ARTICLE IN PRESS

Computers & Operations Research ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Computers & Operations Research

journal homepage: www.elsevier.com/locate/caor

Bi-objective data gathering path planning for vehicles with bounded curvature

Douglas G. Macharet*, Jefferson W.G. Monteiro, Geraldo R. Mateus, Mario F.M. Campos

Departament of Computer Science, Universidade Federal de Minas Gerais, Belo Horizonte – MG, Brazil

ARTICLE INFO

Article history:
Received 25 September 2015
Received in revised form
14 April 2016
Accepted 1 July 2016

Keywords:
Data gathering
Traveling salesman problem
Dubins vehicle
Wireless sensor network

ABSTRACT

A Wireless Sensor Network consists of several simple sensor nodes deployed in an environment having as primary goal data acquisition. However, due to limited sensor communication range, oftentimes it is necessary to use a mobile sink node that will visit sensor nodes to gather up their collected data. An important aspect that must be taken into account in this case are the intrinsic limitations of the vehicle used, such as kinematic and dynamic constraints, since most of the vehicles present in our everyday life have such restrictions. Therefore, this work addresses the problem of planning efficient paths, which are length and time of collection optimized for data gathering by a mobile robot with bounded curvature. We propose the use of the classical NSGA-II in order to tackle both objective functions. The methodology was evaluated through several experiments in a simulated environment. The results outperform the classical evolutionary approach to the single-objective problem specially considering the trade-off between overall length and collecting time.

1. Introduction

Wireless Sensor Networks (WSNs) have been the focus of many studies due to their ability to tackle a broad range of applications. This type of network consists of multiple static wireless nodes composed of a processor, memory, a radio-frequency (RF) transceiver, a power source and a set of sensors that collect data from the region of the environment where they happen to be deployed. Depending on the embedded sensor suite, information such as temperature, humidity, acceleration and even sound and images can be acquired.

Unfortunately, a sensor node presents limitations as far as processing, communication range and storage capabilities are concerned. The WSNs community has studied the Traveling Salesman Problem (TSP) in the context of hybrid networks, where mobile sinks with greater processing and communication capabilities travel through the network to capture locally cached batches of data.

The total energy consumption of the new WSN, now composed of fixed and mobile nodes, also needs to be minimized, since mobile nodes will demand power for displacement and for communication. Therefore, it is essential to generate paths that enable the mobile sink node to efficiently collect data from all sensors. The determined path should present the shortest length possible, thereby reducing travel time and energy expenditure, however while still acquiring the maximum information as possible from the nodes.

Recent advances on the research of autonomous vehicles have uncovered a broad range of new problems and prompted new challenges to several classes of already known problems. Among the various issues involved, one well known problem is posed by the mobile robotics basic questions related to navigation: "How does it get to a given goal?". It is directly linked to the strategy (path) being used by the robot to safely achieve a goal position.

In this context, the TSP remains as one of the most studied problems, and several heuristics have been proposed to this NP-hard problem. However, for several real-world scenarios the mathematical formulation of the TSP may be either insufficient or too simplistic to be applied.

Motion planning is crucial to this problem, since kinematic and dynamic constraints play a fundamental role as most of the vehicles present in our everyday life have such restrictions, for example a vehicle with Ackerman geometry (car-like) or fixed-wing Unmanned Aerial Vehicles (UAVs). These vehicles may have one or more constraints associated with their movement, among which may be mentioned minimum turning radius, stall speed, pitch (climb/dive) angle, among others.

Fig. 1 shows examples of different vehicles for military or commercial applications that have such movement constraints. These vehicles can be used in many different tasks such as exploration, surveillance and environmental monitoring.

* Corresponding author.
E-mail addresses: doug@dcc.ufmg.br (D.G. Macharet), willian@dcc.ufmg.br (J.W.G. Monteiro), mateus@dcc.ufmg.br (G.R. Mateus), mario@dcc.ufmg.br (M.F.M. Campos).

http://dx.doi.org/10.1016/j.cor.2016.07.004
0305-0548/© 2016 Elsevier Ltd. All rights reserved.

Fig. 1. Examples of nowadays vehicles which present movement constraints such as mentioned minimum turning radius, stall speed and pitch (climb/dive) angle.

Furthermore, vehicles such as the Predator or the Knock Nevis are not capable, or it is too costly, to stop/restart its current movement in order to acquire data from a sensor for a long period of time.

In this paper we present a solution to the problem of generating efficient paths for data collection in WSNs using a vehicle with movement restrictions as a mobile sink node. The problem at hand is modeled as a generalization of the classical TSP with two objective functions, since we aim to determine a minimum length circuit whilst maximizing the collecting time at each node. The proposed methodology is based upon the use of the well known multiobjective evolutionary algorithm NSGA-II.

Fig. 2 illustrates the problem addressed here, allowing a better visualization of the key issues described previously. It is presented a sample distribution of nodes in the environment and a data gathering tour. The main objective is to reduce the overall length, however while still maximizing the collecting time within a node's communication range (depicted in red).

The remainder of this paper is structured as follows. A review of the literature is presented in Section 2; in Section 3 initially we provide the problem formalization, next we discuss the proposed methodology; numerical results for different scenarios and statistical analysis are shown in Section 4. Finally, in Section 5 we draw the conclusions and discuss avenues for future investigation.

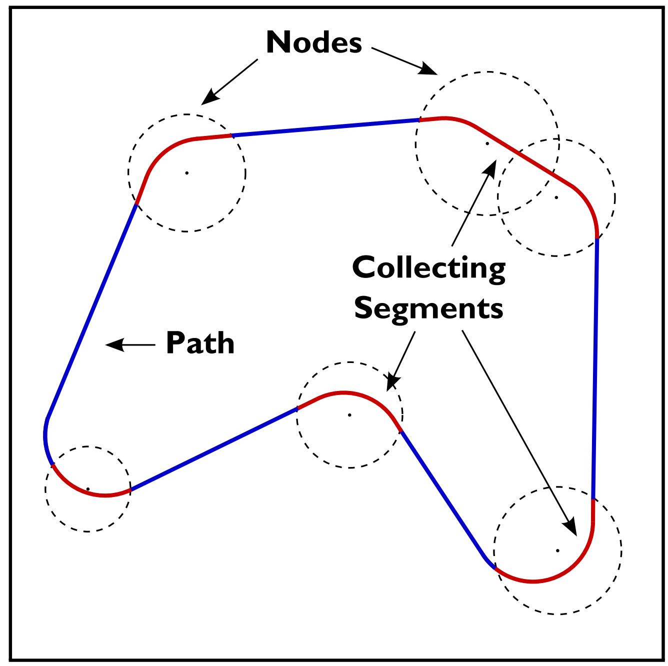

Fig. 2. Example of the bi-objective data gathering path planning for vehicles with bounded curvature. It presents a sample distribution of nodes and their communication range (dashed circles). The red segments represent the parts of path where the vehicle is capable of acquiring data from a certain node. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

2. Related work

Finding feasible routes for mobile agents that are either length or time optimized is essential and of great importance, and has been the goal of several research fields, especially in the context of WSNs and Robotics. Therefore, it is possible to find many works on the subject in the literature [1,2].

The Traveling Salesman Problem (TSP) is a fundamental combinatorial optimization problem and has been widely studied [3]. The problem at hand is to determine the shortest path (sequence of visit) that passes through a set of previously defined points (cities), starting at any point and returning to the starting point after visiting all points once. More formally, the problem is to determine the shortest Hamiltonian cycle [4].

Since it is a NP-hard problem, the solutions adopted are often heuristics. Due to its complexity, the time for calculating instances of a few dozen points may become prohibitive if the application demands a result within a short period of time. Thus, it is possible to choose between solution quality or efficiency. Among the main and most used heuristics we can mention the algorithms of Christofides [5] and Lin–Kernighan [6].

One of the main shortcomings when using the classical model proposed by the TSP in robotic systems is the fact that this model does not incorporate information regarding the targets to be visited or restrictions of the vehicles used, for example the minimum turning radius. Because of this, several studies suggest generalizations to the TSP incorporating certain restrictions, for example, regarding the vehicle or the environment, making it more comparable to real world scenarios.

Taking just the curvature constraint into account, most planners focusing on generating minimum length paths for vehicles with movement restrictions make use of Dubins curves for modeling the routes. In its seminal work, Dubins showed a way to calculate the shortest path between two points with assigned orientations in the two-dimensional space, considering a vehicle with a curvature constraint [7]. There are basically two types of paths: the short case (CCC) and the long case (CSC), or a subpath of a path of either of these two types. The first one is a composition of three arcs (C) with the minimum turning radius (ρ), while the other includes a straight line (S) between arcs. Fig. 3 shows examples of Dubins curves connecting different configurations.

Even though there exists a closed form solution to compute the length of a Dubins curve [8], the problem of calculating a circuit through a set of points turns out to be quite a challenge, since the orientation at each visited point must be taken into account.