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Multi-goal Pathfinding in Cyber-Physical-Social Environments: Multi-layer Search over a Semantic Knowledge Graph

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Abstract

Multi-goal pathfinding (MGPF) is a problem of searching for a path between a start and a destination that allows a set of goals to be satisfied along the path. In this paper, we address MGPF in the context of ubiquitous environments such as airports, commercial centers and smart campuses that accommodate cyber, physical and social entities from smart objects, to sensors and to humans. The availability of data and services in such environments presents new opportunities for addressing MGPF. More precisely, given a MGPF problem in a pervasive environment, our approach exploits data from various resources, for instance, information acquired from cyber-physical entities located in the environment and from external resources such as the Web in order to solve the problem. In this approach, we propose a knowledge model for describing spatial structures of an environment, cyber-physical-social entities it contains, and relationships among them as a graph, called cyber-spatial graph (CSG). Depending on the set of goals to be satisfied, we dynamically build a graph of goal-location pairs (each goal paired with locations at which it can be satisfied), on top of a CSG creating a multi-layer graph. We adapt A* algorithm into a multi-layer A* that is able to search on both layers. We propose heuristics that exploit the structure and knowledge of CSG to improve the search. Our experiments show significant time efficiency and node expansion reduction in various graph structures when employing the heuristics.

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Keywords: Multi-goal Pathfinding; Search algorithms; Semantic Web; Cyber-Physical-Social environment

1. Introduction

In this information age, from smart phones, to intelligent artificial personal assistants and to smart homes, we are experiencing the shifting towards ubiquitous computing, Internet of Things (IoT) and artificial intelligence. Cyber-physical entities are embedded in social environments of various scales from smart homes, to airports, to smart cities, and the list continues. This paradigm shift supplies us with tremendous amount of useful information and services, thus presenting opportunities to address classic problems in new, different, and potentially more efficient manners.

Pathfinding is a problem that has been studied extensively due to its importance in various fields from robotics to logistics. There are different variations of pathfinding problem [1 2] such as single-agent pathfinding, multi-agent pathfinding in static, dynamic and real-time environments. Numerous techniques have been proposed to address

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this problem[3]. In this paper, we address multi-goal pathfinding (MGPF) in the context of ubiquitous environments accommodating cyber, physical and social (CPS) entities such as sensors, smart objects and humans. In literature, there are two common variants of MGPF. First, given a single start and multiple goals, MGPF is defined as a problem of searching for paths for each start-goal pair, resulting in multiple paths[4]. Second, MGPF is treated as a traveling salesman problem (TSP) in which the aim is to find a path from a start to a number of goals before reaching a destination such as in[5 6]. Our problem is close to the second definition. However, unlike the classical TSP, we have constraints on the order of goals to satisfy. The work in[7] addresses a TSP with partial order constraints. The author proposes two algorithms to solve the selection and ordering of points-of-interests (goals), which are places, for indoor navigation systems. Path computation is based on complete spatial knowledge of an environment, and distance is the sole criterion for path evaluation. In this paper, we address a problem similar to[7], but the specific property of our problem is that satisfying a goal is not limited to passing by a place, but can be any activity carried out via a cyber, physical and/or social entity, which can be mobile and dynamic. The aim of our approach is to solve MGPF by exploiting data acquired from CPS entities in a given environment and from external resources such as the Web. It uses up-to-date and dynamic information from various resources for path computation. We use generic criteria, not limited to distance, and quality of entities, determined using qualitative information from resources, for path evaluation.

To understand the underlying motivation of our approach, consider the following scenario. A traveler, Bob, arrives at an airport. Bob wants to find a path to his departure gate. Bob has a set of activities (goals) he wants to do on his way to the gate: get a trolley for his luggage, check-in, buy a takeout for lunch and find a waiting seat near a power plug to charge his laptop. Using spatial information of the airport, we can find a path to the gate. Information about the airport makes it possible to determine which locations allow Bob to satisfy each of his goals. For example, restaurant is a business which prepares and serves food and drinks to customers in exchange for money. By obtaining that piece of information from the Web, we are able to deduce that Bob can buy lunch at locations of type restaurant. Dynamic and up-to-date information from sensors and smart objects enables us to determine the optimal path for Bob. For instance, instead of going to a trolley area, which is at the opposite direction of his gate, it is possible to locate an available trolley nearby that was left by other people, thanks to data from connected trolleys. We might suggest Bob to take an escalator instead of an elevator because we know that there are too many people in the queue waiting for the elevators or that the elevators are out of service thanks to the feeds from sensors. In addition, information from social entities such as other travelers or personnel can be used to enhance Bob's travel experience. For instance, reviews by travelers (e.g. quality or availability) on restaurants enable us to choose locations that are at Bob's best interests and preferences. Other interesting goals can be to find a person in an airport or to look for help in case of language difficulty, just to name a few.

Considering the aim of the approach, one might ask two challenging questions: (1) Which resources to use to solve a MGPF problem? (2) How to deal with the dynamics, mobility and heterogeneity of CPS entities? The first question is concerned with the discovery of resources that are relevant to a MGPF problem. We address this question via the use of a data model to capture necessary knowledge enabling resource discovery. Regarding the second question, there are existing works that address these issues in the context of IoT. As an example, in[8], the authors propose a multi-agent-based socio-technical network (STN) to manage the complexity of CPS entities. In this paper, our focus is on the conceptual level, and we employ one of the existing solutions such as STN to abstract away the complexity at the lower level. Furthermore, the state of an environment is dynamic. Referring back to the previous example, at time t_0, the elevator might be available, but at t_1, it might become occupied. Such dynamics has influence on the path. Given the fact that an action of satisfying a goal (e.g. buy lunch, check-in) takes a certain amount of time, an optimal pre-planned path may lose its optimality over time. This necessitates en-route planning to keep refining the initial path according to up-to-date information. In this paper, our focus is on pre-trip pathfinding. Our contributions include a knowledge model for abstracting a ubiquitous environment integrating spatial and CPS dimensions, an ontology for describing the model in a machine-readable and extensible manner, an abstraction model integrating goals and spatial dimension as a multi-layer graph, knowledge-based heuristics for improving search processes and a multi-layer A* algorithm adapted for searching over a multi-layer graph.

The rest of this paper is structured as follows. First, we present an abstraction of a ubiquitous environment for MGPF, and formally define MGPF. Second, we present our approach to solving MGPF. Third, we present and discuss experimental results of the approach. Finally, we conclude the paper, and discuss the limitations of the current approach along with some promising directions to address these limitations.