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Navigation in spatial networks: A survey

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HIGHLIGHTS

- We survey the recent advances of the navigation problem in spatial networks.
- The navigation problems in homogeneous and heterogeneous networks are surveyed.
- The cost problem of adding long-range links among nodes is surveyed.
- The spatial orientation based navigation algorithm is surveyed.
- Random walk and transportation processes in spatial networks are briefly surveyed.

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ABSTRACT

The study on the navigation process in spatial networks has attracted much attention in recent years due to the universal applications in real communication networks. This article surveys recent advances of the navigation problem in spatial networks. Due to the ability to overcome scaling limitations in utilizing geometric information for designing navigation algorithms in spatial networks, we summarize here several important navigation algorithms based on geometric information on both homogeneous and heterogeneous spatial networks. Due to the geometric distance employed, the cost associated with the lengths of additional long-range connections is also taken into account in this survey. Therefore, some contributions reporting how the distribution of long-range links' lengths affects the average navigation time are summarized. We also briefly discuss two other related processes, i.e. the random walk process and the transportation process. Finally, a few open discussions are included at the end of this survey.

1. Introduction

Systems with large-scale networking are ubiquitous in real life nowadays, especially with the rapid developments and broad applications of information technology [1–5]. Both theoretical and empirical studies have revealed that network structure and dynamics on networks exhibit interdependent relationships with each other, which is actually an important and fundamental problem in the field of complex networks. Information transport is one type of dynamics that can be commonly observed in real life. Generally speaking, information can be categorized into two classes [6]: the nonspecific information, such as epidemic spreading, rumor propagation etc., in which information is desired to travel all over the network, and the specific information, such as packet delivery on the Internet, vehicle flows on highway networks etc., in which the delivery of information is intended for some specific target. And in this survey, we will focus on the latter one.

In transport dynamics, the navigation problem is the most fundamental issue to our knowledge since the study of navigation can help search targets in communication systems, especially in systems such as the Internet and the highway network whose main function is to transport. Efficient navigation can help search successfully arrive at the targets in a relatively short time while inefficient navigation may result in significant increase in searching time before the search

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arrives at the target. Sometimes search even makes detours around some particular nodes under inefficient navigation which further increases the total navigation time. The simplest navigation scheme is random navigation [7–9], in which the next router is always randomly chosen in the searching process. It is assumed that, in the random navigation, each node does not possess global topological view of the whole networked system. However, the random navigation scheme usually exhibits low efficiency in searching out a short path to target, especially in large-scale networks. On the other hand, if each node possesses global topological view of the whole networked system, the highest efficiency can be achieved with the total navigation time equal to the topological shortest path length [6,10]. However, due to the heavy communication cost and limited storage size, navigation schemes based on global knowledge of network topology are usually not practical in large-size networked systems.

In real life, it can be observed that navigation can usually achieve high efficiency even though each node does not possess global topological view of the whole system. This fact was confirmed by Milgram's famous experiment as early as 1960s [11]. In Milgram's experiment, some participants were randomly chosen from Wichita, Kansas, Omaha and Nebraska. Then he asked each of them to send a letter to a target person in Boston. Note that each participant was not acquainted with the target person. Each participant, and consequently each person receiving the letter, was asked to send it to an acquaintance that they judged to be the closest to the target person. About 20% of the cards reached their destinations, and surprisingly, it was observed that the average path length (i.e. the average number of individuals the letter passes through) was around 5.5. The result of Milgram's experiment gave rise to the "small-world" feature observed in real networks. An important feature of the "small-world" network is that its diameter is bounded by a polynomial in $\log N$ [12–14], in which N denotes the number of nodes. Another example is the neural network, in which each neuron does not have a global view of the detailed inter-neuron connections in the brain. However, each neuron can always send specific signals to appropriate muscles or organs in the body. Moreover, the routing of sensor data in wireless networks [15,16], locating data files in peer-to-peer networks and searching information in distributed database [17] also need efficient navigation algorithms based on available local information that can help find the target in a relatively short time. There have been theoretical studies on designing high-efficiency navigation algorithms in the absence of full knowledge of the whole network topology. For example, in Ref. [18], Carmi et al. proposed an algorithm for navigating messages in which full knowledge of network topology is not available, called the "compact routing" scheme. In this algorithm, each node is assigned with a meaningful name to significantly reduce the amount of information stored at the node. Here, the meaningful name contains the path to the closest hub, i.e. the node with a high degree. The authors of Ref. [18] found that using the proposed algorithm, the length of navigation path is close to the topological shortest path length. Moreover, for scale-free networks with power-law degree distribution, it was found that the proposed algorithm worked particularly well. The authors of Ref. [18] claimed that the "compact routing" scheme is simple and intuitive, and can be applied in the Internet, P2P network and transportation network et al. Other navigation algorithms based on local topological information include the one based on the degrees of neighboring nodes [7,19] etc. Navigation algorithms based on local topological information are specially fit in unstructured networks, in which the precise position of a node cannot be quantified and it is usually difficult to justify whether the next step is toward the target node or far away from the target node. In a word, if in a network, the short path can easily be found by only using local information, then such network is usually called *navigable* or *searchable*.

In some networks such as the Internet [20], the airline network [21] and the power-grid [22], each node in the network has a well-defined position, and between each pair of nodes, there is a definite geometric distance. These networks are embedded in geometric space and therefore we call these network 'spatial networks'. Recently, a few network models have been proposed to mimic the geometric space embedded in network structure [23–32]. These models reveal several important features that can be observed in many real networks. These features include small-world [12], scale-free [33,34] and strong clustering. It has been reported that in real networks, the spatial and topological features are mutually related [4]. Two nodes close to each other are likely to be connected even though both nodes have low degrees, whereas there is no link between two nodes far away from each other even though both nodes have many direct connections. Due to the interdependent relationship between the topological and geometric characteristics in spatial networks, it may be a good choice to utilize geometric information to overcome the scaling limitations of utilizing global topological information for designing efficient navigation schemes in large-size networks. Actually navigation schemes utilizing geometric information can be regarded as local schemes. For each message, the target's location of the message in the geometric space can be affiliated on the message itself. When any node receives the message, the node should know the target's location of the message in the geometric space. Assuming each node also knows geometric locations of all its direct neighbors, each node can easily calculate the geometric distance between each of its direct neighbors and the message's target. Consequently, in the navigation schemes based on geometric information, each node does not have to possess the global knowledge of the whole network topology.

Therefore, in this survey, we mainly review some recent advances of the navigation problem in spatial networks. The rest of this survey is organized as follows. In Sections 2 and 3, we present a few recently proposed geometric-based navigation algorithms on homogeneous and heterogeneous spatial networks respectively. In Section 4, considering the cost of adding additional long-range connections, we review some recent work regarding the effect of the distribution of long-range connections' lengths on the average navigation time in spatial networks. In Section 5, we present some results of the Greedy Spatial Navigation (GSN) algorithm, which is based on the information of spatial orientation. In Section 6, we compare the navigation process with two other kinds of related processes, i.e. the random walk process and the transportation process. Finally, conclusions are drawn in Section 7 with a brief discussion for future work.