Path Planning for Hospital Internal Drug Distribution with Linear Temporal Logic

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Abstract: - This paper studies the global optimal patrol path planning for drug distribution in hospitals. Owing to the fact that the traditional drug supply mode in the hospital, which has the disadvantages of consuming expensive resources of pharmacy and nursing professionals, this paper proposes an optimal patrol path planning based on linear temporal logic (LTL) for drug distribution. First, according to the actual environmental characteristics of pharmacy departments, construct a weighted transition system model. Second, use LTL language to describe the tasks that the agents need to perform. Next, construct a Product automaton that integrates the environment model and task requirements. Finally, use the path search method based on Dijkstra algorithm to search for the optimal path on the Product automaton, and the optimal path is mapped back to the area transition system, so that the agent receives the running route in the actual environment. The simulation results show that this method can solve the problem that the multi-point supply task and the distribution area are constrained, and guarantees the optimality of the supply path.

Key-Words: - Drug Distribution, Linear Temporal Logic, Path Planning, Multi-point Patrol, Transition System, Büchi Automaton, Product Automaton

1 Introduction

At present, the internal drug circulation management of the second and third class general hospitals in China is basically composed of a central drug store, an out-patient pharmacy, an operation room pharmacy, an in-patient pharmacy, and an emergency pharmacy [1]. Due to the numerous internal drug supply links, many central drug stores with traditional manual distribution mode are struggling to meet the needs of various secondary pharmacies. Meanwhile, the traditional mode not only increases the frequency of drug distributions, but also wastes valuable resources for pharmacy and nursing professionals, so we need an agent logistics system capable of drug distribution to improve hospital drug circulation management techniques, reduce manual operations, improve work efficiency and accuracy.

As the agent for drug distribution is a controlled application under fixed lines and fixed scenes, the core of realizing drug distribution is path planning [2]. However, the traditional path planning methods, such as the artificial potential field method [3], A^* algorithm [4], and ant colony algorithm [5], are mainly focused on satisfying “from location A to location B and avoiding obstacles” such sample task instructions, and cannot plan the optimal path for complex tasks contain time sequence and cyclicity well. Because computation tree logic (CTL) [6] and LTL [7] can conveniently describe complex tasks that include time sequence and cyclicity and so on, the research based on the temporal logic theory [8] is undoubtedly a future direction of development.

In recent years, more and more scholars have begun to study path planning via temporal logic theory [9-11]. Agent planning by computational tree logic was proposed in [12], whereas [13, 14] focused on the behavior of a group of robots based on LTL theory. In [15], the authors have used a LTL fragment as a standard language for vehicle routing problems. In [16], the study of LTL path planning in a time-limited dynamic environment was demonstrated. In [17, 18], individual control and communication strategies via LTL model checking were considered, the authors decompose the task formula with a global specification into independent local specifications that can be treated separately for each robot. And a cooperative motion and partially decentralized task planning solution was proposed in [19], which only considered the behaviors of interdependent agents and no longer considered the entire team.

For path planning research, a lot of attention has been devoted to the problem of patrol surveillance, and many scholars have proposed different methods. In [20, 21], a controller synthesis framework inspired by model predictive control is proposed, where the rewards are locally optimized at each time-step over a finite horizon, and the immediate optimal control is applied. In [22], the authors proposed an embedded control software method that combines LTL specifications to implement path planning with fault tolerance. However, none of the methods proposed in the above literatures can directly solve the problem of multipoint monitoring with complex requirements. Although the literature [23] and [24] constructed a transition system and a Büchi automaton [25], a graph algorithm was used to search out the optimal path and solve the multipoint recurring monitoring problem. However, the method is affected by the order of the task nodes, so that the searched path is not a global optimal path.

This paper discusses a kind of agents that specialize in drug distribution to reduce hospital pressure and provide efficient clinical distribution services for hospital front-line nurses. In this system, the central drug store collects the drug requirements of subordinate pharmacies, and in conjunction with the current drug inventory, commands the agent to organize drug distribution for each subordinate pharmacy. The problem studied in this paper is that the agent given distribution tasks in multiple sites can achieve path optimization and find the shortest distribution route. Even if the agent patrols in multiple sites, it can still find the optimal route that meets complex tasks. Therefore, according to the actual application requirements for hospital drug distribution, this paper proposes an optimal patrol path planning method based on LTL. According to the geographical location of the pharmacies and the task requirements for drug distribution, this method plans a global optimal patrol route.

2 Path Optimization Method for Drug Distribution via LTL

First, according to the geographic location and environmental characteristics of the pharmacies in each department, the connectivity between all of the distribution task sites is modeled as a weighted transition system, where the transition relationship between state nodes is based on the time required for the agent from one distribution site to another. Second, use LTL language to describe the drug distribution tasks that the agent needs to perform in the practical application. Next, build a Product automaton that contains the environment model and task requirements. Finally, use the path search method based on Dijkstra algorithm to search for the optimal path on the Product automaton, and the optimal path is mapped back to the area transition system, so that the agent receives the running route in the actual environment.

2.1 Environmental Modeling

First, according to actual geographical environmental characteristics of each pharmacy, all fixed supply sites need to be modeled as a finite state weighted transition system.

Definition 1 (transition system) *A transition system is a tuple* $\Gamma = (Q, Q_{init}, \delta, AP, \omega)$, *where* Q *is a finite set of states representing the set of nodes in the weighted transition system;* $Q_{init} \in Q$ *is the initial state, which represents the initial position of the distribution agent;* $\delta \subseteq Q \times Q$ *is the transition function between nodes;* AP *is expressed as a set of finite atomic propositions, namely the set of supply tasks that the agent needs to complete;* ω *represents a weight function that is always positive, namely the time that the agent needs to run from one area to another in real situations.*

For simplicity, a simplified diagram sampled from the actual environment of each pharmacy in a hospital (the transition system shown in Fig.1) can be used to describe the connectivity of all distribution task sites. The weights indicate the time required for the agent to run between pharmacies.

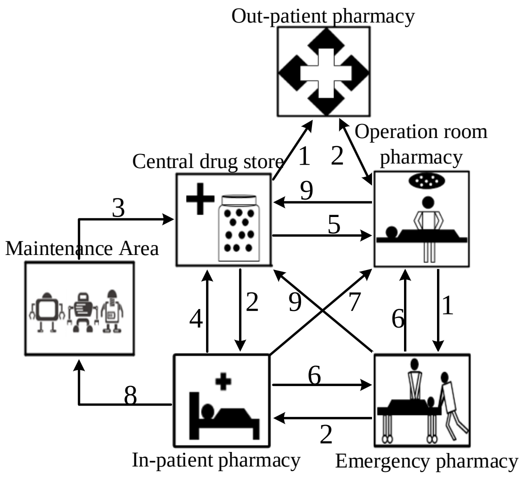

Fig.1 Area transition relation

To facilitate the descriptions about the areas represented by each pharmacy, we use the states Q_0

to Q_5 which indicate the location of each area in Fig.1 to describe the six areas (agent maintenance area, central drug store, Out-patient pharmacy, Operation room pharmacy, emergency pharmacy, In-patient pharmacy), where the node Q_0 serves as the initial position of the agent for drug distribution. Here, we can convert the transition system T of Fig.1 into the form of Fig.2.

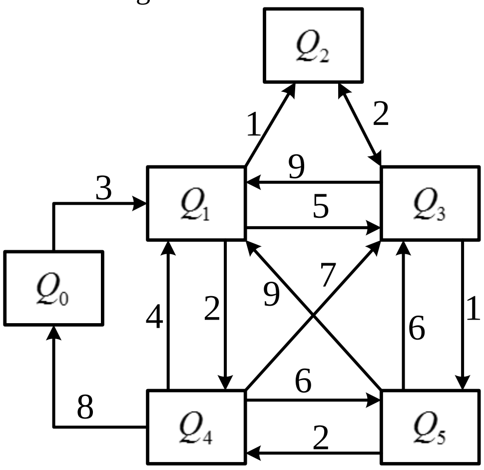

Fig.2 A transition system

In the simulation, the weighted transition system T is constructed by executing the Algorithm 1 according to the transition system connection diagram of Fig.2.

Table 1 Algorithm 1

Algorithm 1 Construct weighted transition system
(1) Define the number of nodes N in the transition system according to the total number of transition system vertices in Fig.2
(2) Define the initial position node of the state transition system according to the starting position of the agent in the actual environment
(3) Define observed states T.obs based on task area
(4) Construct an initial matrix, all assigned INF, and supplement the adjacency matrix based on the connectivity between the pharmacies and the time between any two areas
(5) Define the nodes that need to be monitored according to the task requirements for drug distribution

2.2 Task Description

When the central drug store receives orders from lower-level pharmacies, the agent needs to select the optimal route for drug distribution according to actual needs. As a mission specification language, we use LTL to describe the task requirements, for its resemblance to natural language, and expressive power.

Definition 2 (LTL formula) *A LTL formula is the combination of atomic propositions in the transition system, the Boolean connectives [$\neg$(negation), $\wedge$ (conjunction), $\vee$ (disjunction)] and the temporal operators [G(Always), F(Eventually), X(Next), U(Until)]. For example, XQ indicates that the area corresponding to state Q is the next target position that the agent needs to reach. $Q_1\, U\, Q$ indicates that the agent for drug distribution must pass the area corresponding to state Q_2 and then reaches the area corresponding to Q_1.*

This paper aims at the distribution task of a temporary adjustment situation in the emergency department. In view of the fact that the emergency department is the department with the most concentration of patients with acute and severe diseases, there may be in urgent need of certain drugs in the rescue process and the emergency pharmacy cannot supply due to drugs shortage, at this moment, we need the agent to temporarily deliver drugs from the central drug store to the emergency pharmacy. Since there may be a variety of unexpected conditions during the rescue process, it may be necessary for the agent to execute a command that patrols between the central drug store and the emergency pharmacy. Due to the characteristics of the LTL formula describing the mission requirements, we can describe the mission between the central drug store (Q_1) and the emergency pharmacy (Q_5) as

$$\phi = GFQ_1 \;\&\; GFQ_5 \qquad (1)$$

2.3 Automata Construction

Definition 3 (automaton) *An automaton is a tuple $A=(S,S_{init},\Sigma,\delta,T)$, where S is a finite set of states; $S_{init}\in S$ is an initial state; Σ indicates an input alphabet; $\delta \subseteq S\times\Sigma\times S$ is a transition function; $F\subseteq S$ is a set of accepting conditions. Any automaton $(S,S_{init},\Sigma,\delta,F)$ can be viewed as a graph (V,E) with the vertexes $V=S$ and the edges E given by δ in the expected way.*

In order to obtain an optimal path that satisfies the weighted transition system and LTL task formula, it is necessary to construct a network topology that integrates environment model information and task requirement information. The construction method requires the following two steps:

(1) Build a Büchi automaton

LTL task formulas and automata have corresponding relations. After getting the task requirements as shown in formula 1, it is necessary to convert the LTL expression into text form through a tool (LTL2BA), and then convert the text into a matrix by the string processing and finally convert the adjacency matrix to its corresponding chart form (Büchi automaton).

We can obtain the corresponding Büchi automaton as shown in Fig.3 by the transition system T and the task formula 1, while T in the Fig.3 represents all the states in the transition system.

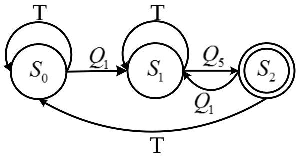

Fig.3 Büchi automaton

(2) Build the Product automaton

We can obtain a feasible network topology map (Product automaton) as shown in Fig.4 via the Cartesian product of the finite state weighted transition system model in Fig.2 and the automata chart obtained in Fig.3. Here, the biggest role of the Cartesian product function is to connect any two unrelated diagrams. According to the definition of Cartesian product, it can be known that the network topology of Product automata not only satisfies the actual environment characteristics of the distribution sites, but also satisfies the various carrying task requirements.

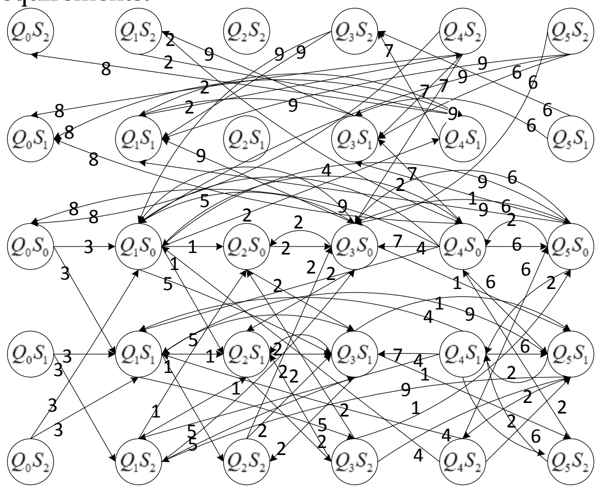

Fig.4 Product automaton

Remark 1 *The Product automaton combines actual environmental model with complex task requirements. The transition relationships between the 18 states* ($Q_0S_0, Q_0S_1, Q_0S_2, Q_1S_0, Q_1S_1, Q_1S_2, Q_2S_0, Q_2S_1, Q_2S_2, Q_3S_0, Q_3S_1, Q_3S_2, Q_4S_0, Q_4S_1, Q_4S_2, Q_5S_0, Q_5S_1, Q_5S_2$) *on the network topology are determined by the transition system T and the Büchi automaton.*

2.4 Optimal Path Optimization Method

Since the above-mentioned task formula for drug distribution is $\phi = GFQ_1 \,\&\, GFQ_5$, in order to find the optimal patrol path, the first step is to determine whether a closed loop including states Q_1 and states Q_5 could be found in the task feasible network topology of the Product automaton, then find out the optimal patrol route with the shortest running time by optimal path optimization method based on Dijkstra algorithm. That is to say, we firstly need to determine whether there is a closed loop in all the path combinations of initial state Q_1 and end state Q_5. At the same time, calculate the time required for the optimal route that meets the task requirements and obtain the specific vertex order.

The optimal path search algorithm for drug distribution is as follows:

Table 2 Algorithm 2

Algorithm 2 Optimal path search algorithm based on Dijkstra
Input: two patrol sites (s, e) for drug distribution, weighted transition system T, task formula ϕ **Output:** the minimum time required from the start location to the end location and the specific route that the agent for drug distribution needs to perform (the vertices are sorted in order) (1) Call the transition system T (2) Build a Büchi automaton: convert the task formula into an automaton chart by using the LTL2BA tool (3) Build a product automaton: make Cartesian product of the transition system T and the Büchi automaton to get the product automaton network topology (4) Write an input function to enter the task patrol sites for drug distribution (5) Execute the command statement in MATLAB [time, path]= dijkstra(A, s, e) to call the Dijkstra algorithm, where time represents the sum (time) of the weights of the shortest path to be run, and path indicates the vertices sequence of the shortest path (6) Define screen output statements which relate to the total time of the shortest path and the vertex sequence of the shortest path (7) Run the program segment and input the patrol sites to return the cost and the vertices sequence of the corresponding optimal patrol path, and get the optimal route in actual environment

By executing Algorithm 2, the optimal path that meets the task requirements can be searched on the task feasible network topology, and the result is shown in Fig.5. Since the time and weight of running this path are the minimum and the number of path nodes is the minimum, it can be judged that this patrol path is the optimal patrol path.

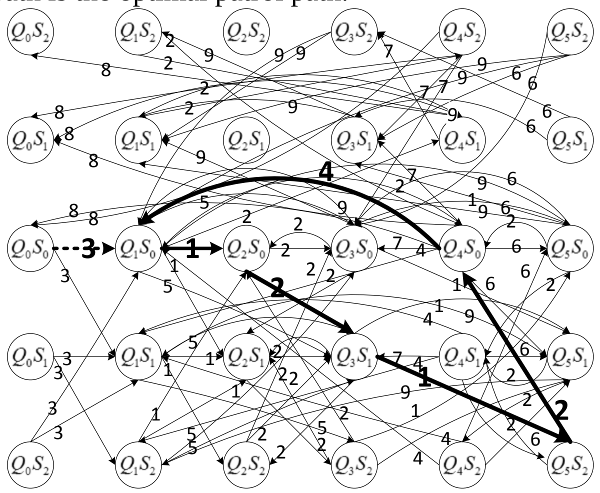

Fig.5 The optimal path on Product automaton

Remark 2 *The network topology merges the weighted transition system information and Büchi automaton information, and we can search the optimal path that satisfies both the environmental information and the specified task on the network topology.*

After obtaining the optimal patrol path $(Q_1S_0 \rightarrow Q_2S_0 \rightarrow Q_3S_1 \rightarrow Q_5S_2 \rightarrow Q_4S_0 \rightarrow Q_1S_0)$ shown in Fig.5, and the path node sequence in the actual environment can be obtained, as shown in Fig.6. According to Fig.6, it can be learned that when the agent executes a command that circulates between central drug store and emergency pharmacy, the agent will select an optimal path by the path planning method based on LTL. The optimal patrol route, namely (Maintenance area $\rightarrow$ Central drug store $\rightarrow$ Out-patient pharmacy $\rightarrow$ Operation room pharmacy $\rightarrow$ Emergency pharmacy $\rightarrow$ In-patient pharmacy $\rightarrow$ Central drug store $\rightarrow \ldots$).

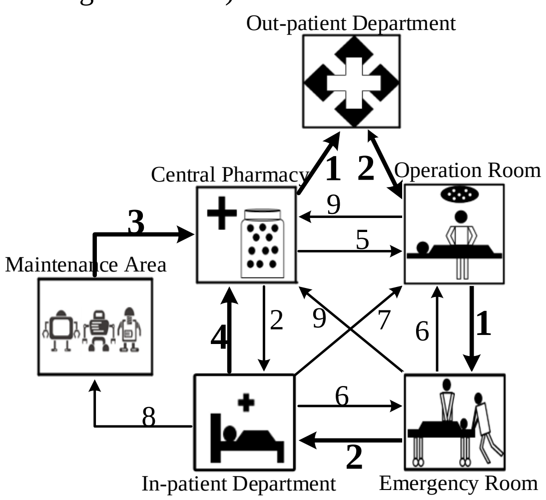

Fig.6 The optimal path in the actual environment

Remark 3 *In the weighted transition system T of the actual environment, there always exists a path corresponding to an arbitrary path that meets the task requirements searched out on the feasible network topology, and the path satisfies the task requirement while ensuring the path optimality.*

3 Conclusion

This paper proposes a global optimal path planning method for drug distribution based on LTL. With a more efficient and accurate mode to distribute drugs, it can effectively reduce the circulation cost for drugs and improve the service level of circulation. However, in the process of realizing this research, we need to fuse the actual environmental model with the Büchi automaton chart, so that the state number on feasible network topology is the product of the state number of transition system and Büchi automaton. So, as for the large number of distribution sites, it is clear that the computational complexity of this path planning method will be very large, which in turn will result in limited search efficiency. Therefore, for this research, the direction of future efforts can be devoted to reducing the complexity of the algorithm.

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