An IoV Route Planning Service Based on LEO Constellation Satellites

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Abstract. With the arrival of Internet of Things, the Internet of Vehicles (IoV) is also developing rapidly. However, the construction of ground network in remote areas is difficult and expensive. Additionally, for urban areas, the traffic situations are sudden, the load pressure of the ground network is too high in this period. This paper introduces a method of IoV path planning based on LEO constellation satellite. The satellite first conducts global situational awareness, the control center makes the initial route and then obtains the optimal path according to Dijkstra algorithm and the Ant Colony Optimization (DiAC). It makes up for the defects of ground communication. Simulation results show that the vehicle network path planning based on STK+MATLAB designed in this paper is feasible and can relieve the ground traffic pressure and network load pressure.

Keywords: LEO constellation · Satellite communications · Internet of vehicles · Route planning · Smart optimization

1 Introduction

With the remarkable development of the Internet of Things (IoT) in recent years, our society has taken another step towards ubiquitous communication [1]. In the smart city scenario, as a smart object with its own processor, computing power and communication capabilities, the vehicle will become indispensable smart device in the future human life due to its rapid growth and high mobility [2–5]. However, the construction of ground network in remote areas such as the central and western regions is difficult and expensive. Additionally, for urban areas, traffic conditions are sudden, during the situation similar to the morning peak, the load pressure of the ground network is too high in this period [6]. Therefore, it is very important to study a path planning for IoV based on LEO constellation satellites.

Internet of Vehicles (IoV) can be seen as the convergence of the mobile Internet and the traditional IoT. As a huge interactive network, IoV technology refers to vehicle-to-vehicle (V2V), vehicle-to-roadside unit (V2R), vehicle-to-infrastructure (V2I), vehicle-to-human (V2H) and vehicle-to-grid (V2G) [7–13]. In addition to safety applications

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in terms of collision avoidance and dissemination of accident data, there is a large amount of research for development that can help the Traffic Information Center (TIC) handle effective route management, route planning, and diversions [14, 15]. Zhang et al. proposed a route planning method based on vehicles and driving environment [16]. Jiang et al. proposed an effective method to cooperative routing [17]. J. Yang et al. proposed to assign multiple TICs to smaller networks in a larger map [18]. Satellite communication is a powerful and achievable supplement to terrestrial communication [19]. Compared with the traditional GEO, LEO has the advantages of low loss, low delay, wide coverage and large order of magnitude [20]. The introduction of 5G satellite communications provides more possibilities for future IoT applications [21, 22]. Therefore, LEO satellite coverage can be used to access the network. It can be seen that the future network is based on LEO satellites.

Based on the above analysis, the research problem is the IoV route planning service based on LEO constellation satellites under complex traffic flow [23–27]. We calculate the current coverage satellite in real time according to the change of time, add the sensor. The satellite realizes the perception of global road conditions through wide coverage, and hands it to the ground control center to formulate a global route planning scheme. Then the UAV, as a mobile communication auxiliary node and an edge network access node, flew to complex traffic areas (such as intersections) to further plan the latest route. In this paper, we proposed a specific algorithm for IoV route planning service based on LEO constellation satellites. Dijkstra algorithm and ant colony algorithm (DiAC) is used to plan the path, which makes the vehicle travel faster and relieves the pressure of ground transportation and network load.

The rest of this paper is organized as follows. Section 2 establishes the mathematical model of the network. The algorithm of route planning is described in Sect. 3. Section 4 illustrates the simulation analysis. We then conclude our work in Sect. 5.

2 Network Model

To cover certain area on the ground in some period of future time, and provide communication services for path planning under the IoV, we calculate the current coverage satellite in real time according to the change of time and add the sensor. We can obtain the satellite orbit parameters required at time t to cover the area of the sub-satellite point center to get the satellites currently covered. First calculate the latitude of the sub-satellite point. The geo-centric geodetic coordinates (L, B, H) of the sub-satellite point can be obtained from the digital earth. The geocentric coordinates (r, φ, L) are calculated as follows:

$$\begin{cases} \phi = \arctan\left[\dfrac{N\left(1 - e_{\mathrm{E}}^2\right) + H}{N + H}\tan B\right] \\ r = (N + H)\dfrac{\cos B}{\cos\phi} \end{cases} \tag{1}$$

$$\begin{cases} N = a_{\mathrm{E}}/\sqrt{1 - e_{\mathrm{E}}^2 \sin^2 B} \\ e_{\mathrm{E}}^2 = 0.00669437999013 \\ a_{\mathrm{E}} = 6378137\mathrm{m} \end{cases} \tag{2}$$

where B is earth latitude, north latitude is positive, south latitude is negative; L is longitude, east longitude is positive, and west longitude is negative.

When the sub-satellite point is (L, B, H), the satellite's flying height H_S, the satellite's geocentric radial direction $r_s = r + H_s$; the satellite's geocentric spatial rectangular coordinates (x_D, y_D, z_D) are calculated according to Eq. (3):

$$\begin{cases} x_D = r_S \cos\phi \cos L \\ y_D = r_S \cos\phi \sin L \\ z_D = r_S \sin\phi \end{cases} \tag{3}$$

The calculation of the hemispherical coordinates of the satellite at the future t at the center of the hotspot area is the conversion of the above-mentioned rectangular coordinates (x_D, y_D, z_D) of the geocentric space of the satellite into J2000.0.

Using the parameters of the elliptical orbit of the orbiting satellite and the flying height, by solving the system of equations, the velocity components (v_x, v_y, v_z) of the satellite in the hemispherical coordinate system are calculated when the latitude and longitude of the satellite's sub-satellite point at time t are L and B, respectively. The satellite operating speed v at time t can be calculated by Eq. (4):

$$v = \sqrt{\mu(\frac{2}{r_s} - \frac{1}{a})} \tag{4}$$

where $\mu = 3.986004418 \times 10^{14}\ m^3/s^2$.

The satellite moves in elliptical orbit, and gets:

$$\begin{cases} \tan i = \frac{\sqrt{(yv_z - zv_y)^2 + (zv_x - xv_z)^2}}{xv_y - yv_x} \\ e = \sqrt{\frac{(xv_x + yv_y + zv_z)^2}{a\mu} + \left(1 - \frac{r_S}{a}\right)^2} \\ v^2 = v_x^2 + v_y^2 + v_z^2 \end{cases} \tag{5}$$

Among them, the semi-major axis a of the elliptical orbit of the orbiting satellite $a = 7177864.881\ m$, the eccentricity $e = 0.0020$, the orbit inclination angle $i = 98.40°$, x, y, z is the satellite's flat sphere coordinate in epoch J2000.0.

Iterative method is used to obtain (v_x, v_y, v_z). Using mature software, the satellite's orbital parameters $a, e, i, \Omega, \varpi, M$ are obtained from the calculation of the satellite's position and velocity in the hemispherical coordinate system, and input the orbital parameters into the STK for simulation, we can calculate real-time coverage satellite.

3 Route Planning Algorithm

The route planning algorithm DiAC is divided into two parts: initial path planning and path optimization. Our IoV route planning strategy based on LEO constellation satellites is shown in Fig. 1.

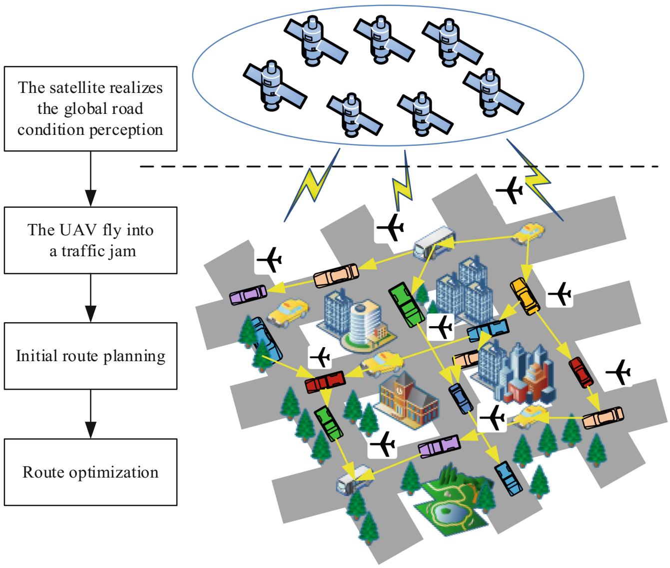

Fig. 1. Route planning strategy.

We model the intersection mathematically as a weight map. The congestion of the intersection will be detected by the UAV, based on the detected traffic flow of the current intersection, and the feedback of the current intersection congestion of the vehicle will be fed back to the vehicle to update the intersection weight. Carry out vehicle scheduling and plan vehicle travel paths. Therefore, our task is to quickly find an effective path that can be driven in the route planning of satellite car networking based on the LEO constellation, and to ensure the shortest path length while driving effectively. Therefore, we propose to use Dijkstra algorithm and ant colony optimization (ACO) algorithm (DiAC) to plan the path. Suppose the starting point is S, the destination node is T, and the objective function can be expressed as:

$$L(S, T) = \min[L(N_c, m)] \tag{6}$$

where $L(S, T)$ represents the path length, N_c stands for the number of iterations, $L(N_c, m)$ denotes the path length of the *m-th* ant moving in the second iteration in the path planning process.

Dijkstra algorithm: Dijkstra algorithm has high reliability and robustness. It is often used to solve the shortest path problem in path planning. Therefore, we use the Dijkstra algorithm in the initial path planning as shown in Algorithm.

Algorithm 1: Dijkstra

Input: Distance matrix L between the nodes of each link, the starting point S, The destination node T.

Output: The shortest path from the starting point S to the target node T.

Initialize $M = \{S\}$, $N = \{V_1, V_2, \ldots, V_n, T\}$,

$dist[V_i] = c[V_i][V_j]$

do

$V_k = \min\{dist[V_i][V_j] \mid V_i \in N\}$

$M = M \cup \{V_k\}$, $N = N - \{V_k\}$

For vertex V_k in N

if ($dist[V_k] + L[V_k][V_j] < dist[V_k] + L[V_k][V_j]$)

$dist[V_i] = dist[V_k] + L[V_k][V_j]$

end if

While $N = \varnothing$

return *dist*

end

According to the feasible path in the environment model constructed before, construct the distance matrix L between the nodes of each link. The construction rule of the distance between adjacent nodes is obtained by Eq. (7), and the distance between non-adjacent nodes is set as ∞.

$$L(v_i, v_j) = ||v_i, v_j|| \tag{7}$$

Where v_i and v_j are the $i-th$ and $j-th$ points, respectively.

Set two sets M and N, the role of M is to record the vertices of the shortest path and the corresponding length. The role of N is to record the vertices that have not found the shortest path and the distance between the vertices and the starting node S. According to the shortest path of Dijkstra algorithm, the initial path is planned. The Dijkstra algorithm is as Algorithm 1 shows.

According to the Dijkstra algorithm, the path can be initialized, but the path is not optimal. Next, use the ACO to optimize the path. The new optimal path can be obtained by using ACO algorithm. The goal is to solve some optimal parameters $(\lambda_1, \lambda_2, \ldots, \lambda_n)$ on the link that the initial path traverses, so that the coordinates of each node satisfy Eq. (8).

$$Q_i(\lambda_i) = Q_i^0 + (Q_i^1 - Q_i^0) \times \lambda_i \qquad \lambda_i \in [0, 1], i = 1, 2, \ldots, n \tag{8}$$

Among them, Q_i^0 and Q_i^1 are the coordinates of the two endpoints of the *i-th* link, and λ_i is the scale parameter of the link.

Ant colony optimization (ACO): The basic principle of ant colony algorithm is that during the foraging process of ants, the probability of the next path selection is determined by the pheromone concentration and the heuristic information on the path between the ants. Path selection is determined by this probability. The path transition probability formula is as follows:

$$P_{ij}^{k} = \begin{cases} \dfrac{[\tau_{ij}(t)]^{\alpha}[\eta_{ij}(t)]^{\beta}}{\sum\limits_{s \in allowed_k} [\tau_{ir}(t)]^{\alpha}[\eta_{ir}(t)]^{\beta}} & s \in allowed_k \\ 0 & otherwise \end{cases} \tag{9}$$

$$n_{ij}(t) = \frac{1}{d_{ij}} \tag{10}$$

where $allowed_k$ is the node set that the *k-th* ant can choose next. $\tau_{ij}(t)$ is the pheromone concentration on the path from the current node to the next node at time t. α is the pheromone heuristic factor, and β is the expected heuristic factor. $\eta_{ij}(t)$ is the heuristic function on the path from the current node to the next node at time $t.d_{ij}$ is the distance from the *i-th* node to the *j-th* node.

In order to avoid the influence of pheromone changes on node selection, all ants need to update and adjust the pheromone according to formula (12) after completing a detailed search.

$$\tau_{ij}(t+1) = (1-\rho)\tau_{ij}(t) + \rho\Delta\tau_{ij}(t, t+1) \tag{11}$$

$$\Delta\tau_{ij}(t, t+1) = \begin{cases} \dfrac{Q}{L_k} & ij \in L_k \\ 0 & otherwise \end{cases} \tag{12}$$

where ρ is the volatilization rate of pheromone. $\Delta\tau_{ij}(t, t+1)$ is the pheromone concentration increment. Q is the pheromone intensity, which is a constant greater than zero. L_k is the path length of the k-th ant in this search. So, the ant colony algorithm is used to optimize the initial path. The process is as follows:

Step 1: Initialize the parameters of the ant colony algorithm;
Step 2: Start the path search, select the next node according to the current node information and the next node selection principle;
Step 3: After selecting the next node, update the local pheromone on the path that the ant has just passed;
Step 4: Judge whether the ant reaches the target node, if true, jump to the next step, otherwise repeat step 2;
Step 5: Search the optimal path for the current search, update the global pheromone;
Step 6: Judge the number of iterations and end the search if true, otherwise repeat step 2.

4 Simulation Analysis

The whole scenery is first built in the STK, including the low-orbit constellation satellite network and the ground scenery. Choose the ground scenery as Beijing in the STK. In the ground scenery, we select nine intersections to create a total of 74 cars, and a uniform UAV with sensors near each intersection as shown in Fig. 2.

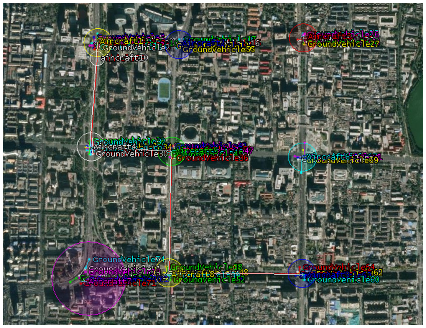

Fig. 2. Path planning results.

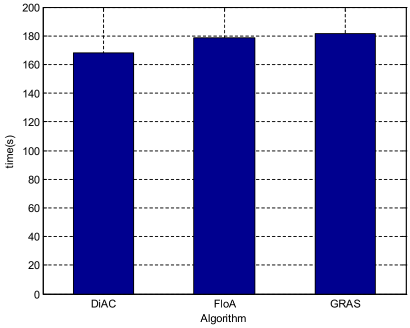

Fig. 3. Comparison of the same scale same congestion of intersection.

Taking the path planning of a car as an example, Fig. 2 shows the result of the path planning of the car from junction 1 to junction 9. Based on the DiAC algorithm, the optimum path from intersection 1 to intersection 9 is obtained, which is $1 \rightarrow 4 \rightarrow 5 \rightarrow 6 \rightarrow 9$. Ground traffic pressure and network load pressure are alleviated by vehicle network path planning algorithm based on low-orbit constellation satellite.

In order to evaluate the effect of the proposed DiAC algorithm, the Floyd-Warshall algorithm (FloA) and a method for calculating shortest path by using graphshortestpath (GRAS) are also built in MATLAB for comparison. In order to ensure that the evaluation results are reasonable, we take the average value after several times of each experiment. Firstly, evaluate the time required for the planned route at the same scale intersection (take 9 intersections as an example) and the congestion degree of the same intersection with the three methods.

As can be seen from Fig. 3, the time required by the car to plan the path according to the three methods is similar, and the proposed algorithm DiAC is slightly better than the other two algorithms. This is because in the DiAC method, when the car judges the next target intersection at any intersection, it can find the best next intersection. However, since the number of intersections is 9, the traffic situation is not very complicated at this time, so the results of the three algorithms are similar.

In order to evaluate the continuity of the algorithm, we considered the time required for the car to travel according to the path planning algorithm at the number of intersections of different sizes. The time obtained by the three algorithms at intersections of different sizes is shown in Fig. 4. It can be seen that the time under the three algorithms increases with the number of intersections. This is because the more complicated the intersection, the longer the car will travel, which is in line with our common sense of life. Among the three algorithms, the path planned by the DiAC algorithm requires less time. Since the DiAC algorithm is in the process of pathfinding, not only the shortest path but also the optimal path is considered, so when there are more intersections, the selected path can make the car travel faster.

Then, we compared the travel time of cars with different road congestion levels at the same intersection scale. The degree of road congestion can be expressed by the weight of each edge. The specific results are shown in Fig. 5. Here, nine intersections are used

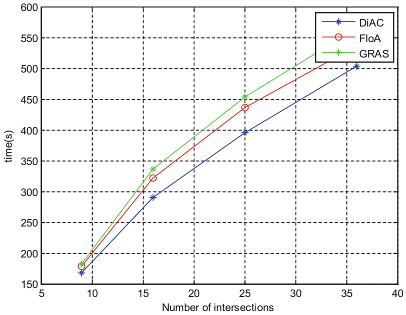

Fig. 4. Comparison of the different number of intersections.

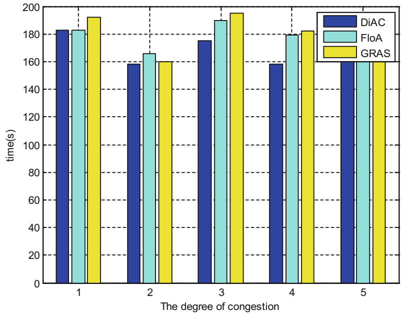

Fig. 5. Comparison of the different congestion of intersection.

as examples to illustrate the problem. It can be seen that the car travel time is different under different congestion levels.

Among them, the travel time of the car obtained by the proposed DiAC method is lower than the other two. Shows the universality of the algorithm. When the degree of congestion changes, the proposed algorithm performs better than the other two methods. This is because the calculation speed and accuracy of the proposed DiAC algorithm path search are considered. As the degree of congestion changes, the importance of these two indicators becomes more and more prominent, thereby achieving a relatively uniform time change.

5 Conclusion

The LEO constellation satellite-based IoV is a supplement and extension to ground vehicle networking, which can greatly expand the coverage of ground IoV. Especially at the intersection, due to the complex road conditions, large traffic flow, the realization of intelligent traffic control requires a large number of concurrent connections and data calculations, intersection base stations are likely to overload, so there is an urgency to get the help from satellites and UVAs. Satellites and UAVs can cooperate with each other to achieve real-time control of vehicles within the coverage area and help base stations to relieve traffic pressure at the intersection. This paper introduces a method of IoV route planning based on low-orbit constellation satellite to provide the service of vehicle route planning. For providing path planning services, the satellite first carries out global situational awareness, and the control center formulates the initial route according to the Dijkstra algorithm, and then obtains the optimal path according to the Dijkstra algorithm and the ant colony algorithm (DiAC). Simulation results show that the design of STK+MATLAB IoV route planning based on LEO constellation satellite can be realized, which can efficiently relieve ground traffic pressure and network load pressure.

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