ROUTE ESTIMATION BY NETWORK VORONOI DIAGRAM IN TAXI-TYPE AGV CONTROL

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ABSTRACT
In flexible manufacturing systems, the importance of automated guided vehicles is increasing because they can respond flexibly to changes in facilities and factory layouts. We propose an autonomous conveyance system for automated guided vehicles based on the operation of a taxi transportation system to solve indefinite and accidental problems. The system focuses on applying traffic engineering knowledge regarding a flexible taxi transportation system. A taxi is a transport unit in a traffic system involving high flexibility in traveling routes and at arrival/departure points. In this report, we suggest quantifying a driving course shape using a network Voronoi diagram. As a result, by using the weighted network Voronoi diagram and the coefficient of variation CV, a correlation is obtained between the variation coefficient CV and the average matching time Ta, and an appropriate path can be arranged to determine the course shape.

1. INTRODUCTION
Flexible manufacturing systems (FMSs) accommodate production of various types and volumes of products. In an FMS, however, changing the factory layout and coping with the problems that arise are difficult. To address these issues, other systems have been proposed. For example, a system that provides an autonomous decision-making function to the components of the manufacturing system has been proposed [1–2]. In this system, the role of automated guided vehicles (AGVs), which control the flow of materials, becomes more important. Therefore, research toward developing such autonomous systems has been extensive. However, systems that can respond to many indefinite elements [3–4] have not been investigated. As the knowledge accumulated in one industry can find an application in other fields, we focused on the movement characteristics of taxis, which can respond in a flexible way to newly generated loads. By analyzing taxi movement characteristics and introducing these into the action rules of an AGV, we had proposed a new AGV system [5–6].

The use of the proposed AGV transport system in general depends greatly on the shape inside the factory. Therefore, in this study, by numericalizing the shape of the driving course, we obtain the relationship between the shape of the course and the proposed AGV transport control system. To analyze the phenomena influenced by distance, we use a network Voronoi diagram for optimization of facility placement to evaluate the course shape.
2. INTRODUCTION OF TAXI MOVEMENT CHARACTERISTICS

2.1. Similarity between traffic and carrier systems
To apply the knowledge of traffic engineering to an AGV carrier system, it is important that the movement characteristics of transportation be superior and the environments similar. Therefore, we focused on the flexibility of the transportation system and the conveyance apparatus. A taxi’s maximum load is smaller than that for a bus or a train, but it offers flexibility in the arrival and departure times and places, as well as the course taken. In the conveyance apparatus of a manufacturing system, the flexibility increases in the following order: conveyor, AGV, and forklift. With an autonomous carrier-type system, the possibilities of full automation as well as a flexible and efficient system are realized.

2.2. Modes of AGV derived from taxi operation
(1) Crawling: Taxis travel around town looking for passengers.
(2) Radio: Taxis are dispatched to the requested location.
(3) Waiting: Taxis wait at busy locations such as train stations.
The basic actions are as follows.

2.3. Basic action rules of taxi-type AGVs
(1) Continuous AGV travel is based on the taxi crawler mode. Therefore, the AGV travels a predetermined course. This course only consists of left turns, which reduces the risk of collisions and wait time. When a product is generated while the AGV is traveling on the predetermined course, another AGV is autonomously sent to a pick-up/drop-off (P/D) location if the P/D nearest to the AGV can be used as a pick-up point.
(2) When a product is generated at a random P/D and selected, an AGV is autonomously sent to that P/D if the AGV closest to that P/D can be used to pick up the product. This action is based on the taxi radio mode. If it is not the closest AGV, the AGV goes to the selected target P/D.

3. SETUP AND EXPERIMENTAL CONDITION

3.1. Setup of path model
The flow path used in the experiment is shown in Fig. 1. By choosing two from e of the path from a, we created seven courses with a constant course length (Fig. 2). The number of intersections in each course is shown in Table 1. Product pick-up and drop-off stations are located in the area surrounded by streets. We assume that the AGVs drive on the left side of the street, as is done in Japan. The delivery of parts to be delivered shall be carried out at the P/D station at ➀-➇, and the P/D shall be chosen randomly. The conveyance performance is evaluated under circumstances with more uncertain factors.
3.2. Setup of evaluation function

A taxi driver picks a route to maximize sales. Sales increase with the riding rate, which is defined as the ratio of the total traveling time with passengers to the total working time. Therefore, an important performance function in taxi transportation is to minimize this time. In an analogous factory situation, reducing the time wasted without machine operation in manufacturing and increasing the operating rate are important. The rate can be improved by minimizing the time from product base to transportation. We define this time as matching time $T_a$ expressed as

$$T_a = T_p - T_g$$

where $T_p$ is the time when a product is picked up and $T_g$ is the time when a product is generated.

3.3. Experimental condition

We simulated the AGV’s run using the production simulation software QUEST created by DELMIA (Fig. 3). The data obtained by this production simulator includes the average occupancy rate of the simulation time, elements (constituent elements on the physical distribution route, such as AGV, Buffer, and Source), the average staying time of the package, the maximum waiting time, the minimum waiting time, or the total number of parts that have been transported are output. By using this production simulator, since the operation status and result are displayed in real time, it is possible to visually grasp the transportation stroke of each AGV, and it is possible to find a solution for achieving high-efficiency transportation.

In this report, we adopt the taxi crawler mode, which is the basic mode of operation of the taxi-type AGV. As an evaluation function, the average matching time $T_a$ was measured. Experimental conditions in the simulation are shown in Table 2.

### Table 1 The ratio of T-junctions and crossroads.

<table>
<thead>
<tr>
<th>Course</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>e</th>
<th>f</th>
<th>g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of crossroads</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Number of T-junctions</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>

### Table 2 Experimental condition.

<table>
<thead>
<tr>
<th>Product interval[s]</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of product</td>
<td>1000</td>
</tr>
<tr>
<td>Number of AGV</td>
<td>4</td>
</tr>
</tbody>
</table>

4. QUANTIFICATION OF COURSE SHAPE

4.1. Introduction of network Voronoi diagram

One of the widely used geometric analysis methods is a network Voronoi diagram [7]. A network Voronoi diagram is useful for analyzing phenomena affected by distance, which is based on network space, which is a set of connected line segments instead of a planar space. The Manhattan distance of two points $p$ and $q$ is represented by $d(p, q)$. Equation (2) represents a network Voronoi region of $p_i$ for a set of finite number of points specified on a plane $P = \{p_1, p_2, ..., p_n\}$, and the network Voronoi regions $V(p_1), V(p_2), ... V(p_n)$ comprise a network Voronoi diagram. When a plurality of nodes are given as base points, if a distance from an arbitrary point on the edge to a base point is considered and is closer than a point on any other edge, that base point is referred to as a base point to which the edge belongs. As a result, all edges can uniquely determine the points to which they belong. Hence, there may be cases where all of the edges belong to the same base point and the belonging points are changed in the middle of one edge. A point at which a belonging point changes in the middle of one edge is called a boundary point. The base point in this report was taken as a branch point. This is because the branch point has information on the course shape and its positional relationship affects the transportation. An example of a network Voronoi diagram is shown in Fig. 4.

$$V(p_i) = \left\{ p \in R^2 \mid d(p, p_i) \leq d(p, p_j), j \neq i \right\}$$

![Figure 4: Network Voronoi diagram example.](image-url)
4.2. Course shape evaluation method

Consider the influence of the edge length \( l_i \) belonging to each base point of the network Voronoi region created by the network Voronoi division on the course shape. Figure 5 shows a square-shaped course with maximum paths. In the course shown in Fig. 5, if base points are placed only at branch points, the edge lengths \( l_i \) of all the network Voronoi regions become equal. Therefore, in the network Voronoi division, branching points on the course are evenly arranged as the variation of the edge length \( l_i \) is smaller, indicating an excellent course shape. Therefore, the variation coefficient \( CV \) that takes into consideration the dispersion of the edge length \( l_i \) is defined in Eq. (3), where \( \sigma \) is the standard deviation of the edge length \( l_i \) of the network Voronoi division, and \( x \) is the average value of length \( l_i \) respectively. \( CV \) is a value obtained by dividing the standard deviation by the average value, and is a dimensionless numerical value used for comparatively evaluating the relationship between the data and the variation with respect to the average value. The course shape is quantified using Eq. (3).

\[
CV = \frac{\sigma}{x}
\]  

(3)

Figure 5: Course model with path of maximum number.

5. RESULTS AND DISCUSSION

5.1. Variation coefficient \( CV \) and average matching time \( T_a \)

The relationship between the average matching time \( T_a \) and the variation coefficient \( CV \) in the network Voronoi division is shown in Fig. 6. As shown in Fig. 6, a positive correlation was obtained for Courses A, B, and C with 5 base points, and a negative correlation was found with respect to Courses D, E, F, and G with 6 base points. The coefficient of variation \( CV \) is smaller with less variation, indicating an excellent course shape, hence, it is conceivable that \( CV \) and \( T_a \) have a positive correlation. For the three courses where positive correlation was seen, an appropriate analysis was made, but for the course with 6 base points, the result was the opposite. This is considered to be due to the fact that the cross viability and the base point of the T junction are not distinguished when analyzing the network Voronoi diagram.

Figure 6: The relationship between average matching time \( T_a \) and \( CV \).

5.2. Number of base points and average matching time \( T_a \)

The relationship between the number of base points, \( N \), and \( CV \) is shown in Fig. 7. From Fig. 7, a negative correlation was seen in \( CV \) excluding Course A. As for Course A, since it is a symmetrical course as compared with other courses, it is conceivable that the standard deviation of the edge length \( l_i \) becomes small and the value of \( CV \) sharply drops. Before analyzing the course shape with \( CV \), we assumed that \( CV \) is a value obtained by dividing the standard deviation by the average value, so that it is not affected by the base point, but from the result of Fig. 7, \( CV \) shows a tendency of negative correlation. From this, it can be considered that the network Voronoi diagram analysis is not suitable for comparing courses with different base points. Therefore, it is understood that there is no correlation when comparing all courses in Fig. 6.

Figure 7: The relationship between the number of base points and \( CV \).
5.3. Difference between crossroads and T-junctions

We will look at the difference between crossroads and T-junctions. From Fig. 6, Courses A, B, and C having a crossroad tend to have a shorter average matching time $T_a$ than Course D, E, F, and G having only T-shaped paths. In Fig. 8, in the case of a crossroad, there are three kinds of paths with respect to the traveling direction, and since there are four traveling directions with respect to the crossroads, there are twelve paths in total. As for the T-shaped route, there are two ways to travel in the direction of travel, and there are three directions of travel for the T-shaped road. Therefore, the total number of passes in the crossroads and T-junctions with a total of six passes will be twice different, and since the crossroads have up-and-down and right-and-left paths, it is thought that this result was obtained. In addition, since we do not distinguish crossroads and base points of T-junctions when analyzing network Voronoi diagrams in this work, it is assumed that a correlation with $T_a$ is difficult to obtain when there are multiple intersections on the course. Therefore, it is thought that improvement will be achieved if weight points are attached to the base points for each type.

5.4. Introduction of weighting in network Voronoi diagram

In this work, we adopt the method of placing base points at branch points, but as shown in Fig. 8, there are mainly two types of T-junctions and crossroads at branch points. As seen from Fig. 8, there are six outputs (outlets) for the three inputs (inlets) for the T-junction, so there are six paths in total. For crossroads there are 3 outputs for 4 inputs, and we have a total of 12 passes. Therefore, the crossroads will own twice the paths of the T-junction; hence, it is inappropriate to evaluate them as the same base point. Therefore, as shown in Fig. 9, we consider the crossroads to be two T-junctions, and weight them by placing two base points. Since the coefficient of variation $CV$ decreases in proportion to the number of base points, this weighting is considered to be effective.

5.5. Influence of the weighted network Voronoi diagram

The relationship between the average matching time $T_a$ and the variation coefficient $CV$ in the network Voronoi division and the weighted network Voronoi division is shown in Fig. 10. In Fig. 6, correlation was not found in $T_a$, but in Fig. 10, on giving weight to the crossroads, positive correlation was obtained except for Course G. By weighting, it is understood that the base points of the crossroads are increased to two, and the values of the coefficients of variation of Courses B, C having crossroads are small.

As the coefficient of variation $CV$ decreases in proportion to the number of base points, in the case where the position of the branch point is changed under constant course length as in this report, as shown in Fig. 2, the T-junction and crossroads As the number of population emerging changes, we could not analyze properly with ordinary network Voronoi diagram. However, as a result of weighting, the number of base points of the crossroads increased to two, the number of base points of all courses became equal, and it was possible to evaluate equally. From this, it is considered that the weighted network Voronoi diagram is effective in quantifying the course shape. Therefore, by using the weighted network Voronoi diagram and the coefficient of variation $CV$, an appropriate path can be arranged and the optimum course shape can be determined.
5.6. Influence of Course G

Figure 11 shows the relationship between average matching time $T_a$ and $CV$ in the weighted network Voronoi diagram. Since it is an index that measures how properly the branch point is arranged in the course shape by placing the base point at the branch point and performing the network Voronoi division, it can be said that correlation with $T_a$ is not exactly obtained. Therefore, Course G is considered to be an outlier. There is a positional relationship of P/D as correlated with $T_a$, and it is expected that correlation with $T_a$ will appear if the network Voronoi diagram is performed again with P/D as a base point.

![Figure 11: The relationship between average matching time $T_a$ and $CV$ in the weighted network Voronoi diagram.](image)

6. CONCLUSIONS

We suggested a novel method to estimate a driving course shape in taxi-type AGV transportation system based on the network Voronoi diagram. The following conclusions are obtained.

1. By using the weighted network Voronoi diagram and the coefficient of variation $CV$, an appropriate path can be arranged and the optimum course shape can be determined.

2. Analysis using the network Voronoi diagram was found to be inappropriate for quantifying and comparing course shapes with different base points.

3. In the crossroads and T-junctions, the number of passes has been doubled, and for courses containing crossroads it turned out that the average matching time $T_a$ tended to be shorter.

4. By weighting the base points of the crossroads, a positive correlation was obtained with the average matching time $T_a$ and coefficient of variation $CV$ for all courses except Course G.

REFERENCES


