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Zone Divide of Three-Dimensional Model for Spraying Application on Industrial Robot

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***Abstract* – Basing on three-dimensional model, we propose a zone divide method which is suitable for spraying application on industrial robot. The method can divide a model into several meaningful zones by means of smart clustering, the divided zones are split or combined according to the rules designed to improve work efficiency. What is more, in consideration of the specific characteristic of spraying work on industry robot, edge detection imposed on zone is adopted to reduce collision between robot and object when it comes to later real spraying.**

***Index Terms* – three-dimensional model, zone divide, smart-clustering, edge detection, spraying**

I. Introduction

Nowadays, every walk of life is experiencing great change from traditional handcraft pattern to automatic mode, high efficiency, level off and self-motion has become marked sign of epoch, spraying implemented on car also witnesses conversion from men-based fashion to robot-based manner. Fully automated of above work relies on instructive automatic zone divide executed on model which is created through retrorse engineering. However, up to now, few methods can give acceptable zone divide result for spraying application, hence, a partition algorithm that meets spraying demands for industrial robot is in urgent need.

Fig.1 Actual spraying environment

Owing to broad application background, common zone divide of model is widely studied. Paper [1,2] advances regional division method basing on k-means clustering, it first sets number of zones and produces initial clustering centres, basing on which each mesh of model is placed in certain zone by various measure criterions including Euclidean distance, afterwards, all the clustering centres are renewed, above procedure is iteratively executed until satisfaction of certain rule. The above method is simple in implementation, yet, its application range is limited as a result of invariable clustering centres. Paper [3] extends watershed method used in two-dimensional picture to three-dimensional model, it includes following procedures:

1. Calculate curvature of each vertex by their neighboring polygonal meshes.
2. Get all points with local minimum curvature.
3. Achieve zones with invariable curvature.
4. Sign each polygonal mesh with certain zone by means of curvatural descending method.
5. Combine zones according to depth information of water in every produced zone.

Paper [4,5,6] completes partition work with analogous method, difference lies in fine improvement in curvature estimation, yet, excessive partition may occur, which is even more serious when there is biggish noise. Paper [7] adopts so-called shape controlling factor to ensure the regular shape of zone ,the factor can be displayed as following expressions:

$$\gamma = \frac{\rho^2}{4\pi\omega} \tag{1}$$

in the above expressions, parameter ρ expresses the perimeter of zone while ω represents the area of zone. The factor is small for regular square and round, but when it comes to narrow rectangle, it is quite big. In the light of above truth, paper [7] ensures the square shape of zone. Yet, the factor also brings two problems: on the first hand, the area of zone is easy in calculating while the perimeter of irregular zone is rather complex in counting; on the second hand, a massive of squares may be created when the factor is applied to narrow part, which induces low efficiency in later spraying.

Paper [8,9,10] lists various segmentation methods, a means called zone growing is also mentioned. Firstly, the fringe of zone is achieved by curvature or other information; secondly, a random selection of seed polygonal mesh is implemented in each zone; thirdly, the growing of zone is continuously executed until the fringe of zone is encountered. The speed of the algorithm is rather soon, yet, a notched zone may lead so-called excessive growing problem, which is even more serious in the presence of biggish noise.

All the mentioned algorithms are designed for common three-dimensional model, when it comes to spray application on industrial robot, none of them can give an acceptable result. For the reason of unique application background, zone divide of model for spraying application on industrial robot calls for strict flatness extent, compactness and other aspects, further, an avoidance of collision between robot and sprayed object should be regarded.

In consideration of above requirement, paper produces valid zones by smart clustering method. In order to reduce the possibility of later collision, several procedures are executed, firstly, fringe polygonal meshes are achieved through the information of neighbors'; Secondly, valid edge lines are gained by fringe polygonal meshes; thirdly, meaningful partition is imposed on zone by valid edge lines, which can be used to reduce the occurrence of collision.

The subsequent part is organized as follows: chapter 2 expounds relevant concepts, chapter 3 recites proposed algorithm, chapter 4 imposes advanced algorithm on several models, meanwhile, a comparison with other algorithms is also made, chapter 5 draws the conclusion from the paper.

II. RELEVANT CONCEPTS

There are large number of symbols in following part, so, a detailed illustration is indispensable, the signs used in the paper can be listed as follows:

1. V, E and F denotes vertex set, edge set and polygonal mesh set in the model respectively, while $|V|$, $|E|$ and $|F|$ expresses size of relevant set, the sign S that can be expressed as $\{V,E,F\}$ is the denotation of entire model.
2. T_i whose index is "i" is representative to corresponding zone. V_i, E_i and F_i is vertex set, edge set and polygonal mesh set of relevant zone, while $|V_i|$, $|E_i|$ and $|F_i|$ is respective size. $S=\bigcup_i S_i$, $V=\bigcup_i V_i$, $E=\bigcup_i E_i$, $F=\bigcup_i F_i$.
3. $\forall f_i \subset F, f_j \subset F(i \neq j)$, if there is more than one common vertex, the above two meshes are considered as neighbors and signed as expressions "$U(f_i,f_j)=1$", otherwise, $U(f_i,f_j)=0$.
4. Expressions "$f \subset T_i$" will be validated when mesh f is in zone T_i, $\forall f_i \subset T_i$, parameter $\vec{n_i}$ denotes relevant normal vector, $\forall j \neq i$, the number of meshes who meet relation "$U(f_i,f_j)=1$" is signed N_{f_i}, the average normal vector of meshes who meet above condition is tagged $\vec{f_i}$, while relevant centre point is signed $\overline{P_{f_i}}$, the line that is created by $\overline{P_{f_i}}$ and $\vec{f_i}$ is expressed as l_{f_i} while $P_{l_{f_i}}(f_j)$ is representative to projective point of P_{f_j} on l_{f_i}, $\forall f_i \subset F, f_j \subset F(i \neq j)$, if $U(f_i,f_j)=1$ is met, then $\overline{P_{l_{f_i}}(f_j)}$ is representative to the centre projective point of f_j on l_{f_i}.

III. RELEVANT WORK

Generally speaking, there are always specific application background regarding zone divide, stand or fall relies on certain case. When we are trying to impose spraying on car with industrial robot, the quality and efficiency is the core factor. On the first hand, strict flatness extent can be used to upgrade the quality; on the second hand, in-between points are produced when robot transfers from one zone to another. Hence, the number of divided zones should not be too large. Moreover, the convex shape of zone should be met basically considering collision avoidance.

A. Flow chart of proposed algorithm

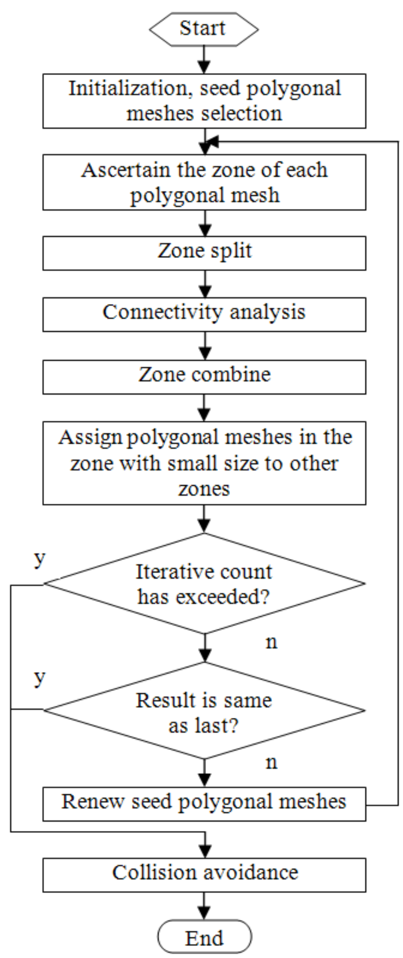

Fig .2 Flow chart of proposed algorithm

B. The initialization of zone numbers

To create initial clustering centres, algorithm gives a specific number of zones first. The scalar of zone is invariable in paper [1], whose application range is limited as a result of changeless number of zones. Conversely, the counts of zones in proposed algorithm are variational, in this way, the advanced algorithm can be employed in various cases. At the same time, the result of developed method is insensitive to initial centre numbers, which will be validated in later experiment.

C. Seed polygonal meshes selection

As initial centre, seed polygonal mesh determines the zone of each mesh by comparing the differences between reviewed mesh and every zone. By and large, related methods can be grouped into two types as follows:

1. Man-machined interactive mode, paper [11] gets seed polygonal meshes by above way. On the first hand, as a result of participating of human, the selection can be made in light of real case, from this perspective, this way is feasible; on the second hand, there are too great works in executing at the presence of complicated model, hence, it is infeasible from this point of view.
2. Automatic mode, this method can be subdivided into two categories further. In the first kind, the fringe of zone is fixed first, later, a random selection of seed polygonal mesh is made in each zone. Accordingly, in the second kind, the vertexes or polygonal meshes are processed by various functions at the beginning. Subsequently, seed polygonal meshes and fringes of zone are got by above filtered result. Obviously, excessive growing problem may happen when there is a notched fringe.

After analyzing existing methods detailed, paper selects seed polygonal meshes in evenness part, the state whether or not a mesh is located in flatness area can be decided by following factors:

1. The variance of normal vectors between reviewed polygonal mesh and corresponding neighbors, it can be estimated by following formula:

$$\sqrt{\frac{\sum_{j\subset\{U(f_i,f_j)=1\}} a\cos\left(\overrightarrow{f_i},\overrightarrow{f_j}\right)}{N_{f_i}}} \tag{2}$$

in above expressions, $$\overrightarrow{f_i}=\frac{\sum_{j\subset\{U(f_i,f_j)=1\}}\overrightarrow{n_j}}{\left\|\sum_{j\subset\{U(f_i,f_j)=1\}}\overrightarrow{n_j}\right\|} \tag{3}$$

2. The error of approximate plane between reviewed mesh and relevant neighbours, it is calculated as subsequent formula:

$$\sqrt{\frac{\sum_{j\subset\{U(f_i,f_j)=1\}}\left\|P_{l_{f_i}}\left(f_j\right)-\overline{P_{l_{f_i}}\left(f_j\right)}\right\|}{N_{f_i}}} \tag{4}$$

The detailed calculating process of factor $P_{l_{f_i}}\left(f_j\right)$ can be referenced in [12].

The cost is estimated by the help of formula (2) and (4), meshes with cost lower than a threshold are regarded as seed polygonal faces. When there are no polygonal meshes meeting demands further, mesh who has the biggest difference with the selected ones will be picked out.

D. Ascertain the zone of each polygonal mesh

The aim of this procedure is the placing of every mesh in fittest zone, while the core of guide line lies in the truth whether or not the result meets later real spraying. In consideration of spraying condition and requirement of spraying, five factors are adopted to determine specific zone of every polygonal mesh:

1. Mean error of approximate plane for the zone.
2. Variance of normal vector for all the polygonal meshes in the zone.
3. The distance between reviewed polygonal mesh and the centre of zone.
4. The angle between the normal vector of considered polygonal mesh and the normal vector of approximate plane.
5. The angle between the normal vector of reviewed polygonal mesh and the correspondingly neighbors.

The first four factors are weighted to calculate cost when the fifth factor is lower than a preset threshold, the zone with lowest cost is considered as the fittest one, in which the reviewed polygonal mesh should be placed.

Of above five factors, the first gives a better estimation when considering the flatness extent of certain zone, therefore, the corresponding percentage should be the largest.

In consideration of the first factor, three steps need to be executed. Firstly, covariance matrix should be calculated with the help of vertexes in the zone; secondly, eigenvalues and accordingly eigenvectors are got on the basis of above matrix; thirdly, the eigenvector of smallest eigenvalue is considered as normal vector of fitted plane, combining with the centre point of zone, ultimate reckoned plane can be achieved.

E. Zone split

The algorithm advanced in this paper divides the model with iterative mode, the specific zone of each polygonal mesh is decided by the cost information which is brought by adding single mesh to a corresponding zone.

There is a possibility in which the set number of zones is smaller than desired count, obviously, the up-and-down zone will be produced, which goes against real spraying effect, therefore, such zones should be split into valid ones.

The essence of zone splitting lies in the invalid feature of certain zone, to say further, flatness extent is the key factor. Thus, this step is only imposed on zone whose flatness extent is larger than the preset threshold. Firstly, two polygonal meshes whose angle with corresponding neighbors are the first two largest are selected; secondly, splitting plane is gained by above two polygonal meshes; thirdly, real partition is executed by calculated splitting plane.

The following chart gives a description of the above step:

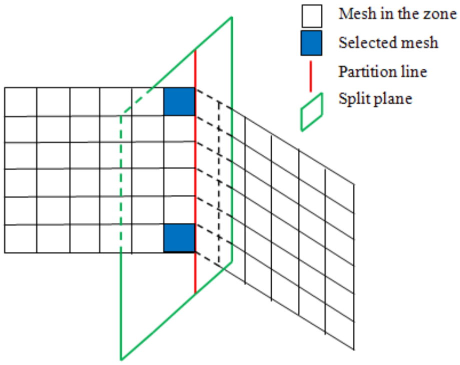

Fig. 3 Zone split

Obviously, an invalid zone is split into two valid ones by the partition plane in Fig.3.

F. *Connectivity analysis*

The spraying of any zone separated by other zones is low in efficiency with the reason of excessive inserted points. Yet, the above situation may occur during the execution of raised partition algorithm, therefore, the method called connectivity analysis should be adopted to overcome the problem.

By the aid of connectivity analysis, invalid zones will be split into several connective ones, by this way, the number of inserted points will be reduced greatly.

Whether or not a single zone is in connective state can be decided as following manner:

$\forall\ T_i \subset S$ and $f_j \subset T_i$, $\exists\ f_k \subset T_i$, if "$U(f_j, f_k) = 1$" is met, the so-called connectivity feature will be validated.

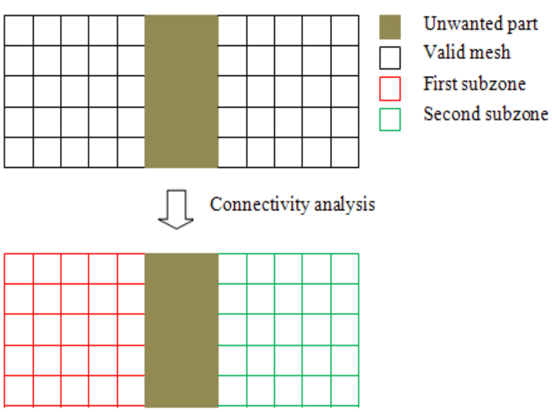

Fig. 4 Connectivity analysis

In above figure, an unwanted part is located in produced zone. Obviously, it does not satisfy connectivity demands, further, if the invalid part is higher than the watched zone, transitional points will be produced when robot is transferring from left to right part in the zone, by the aid of above method, the watched zone is partitioned into two connective ones.

G. *Zone combine*

Contrary to the situation in which split of zone confronts, there is a possibility in which the preset number of zones is larger than the desire one. Meanwhile, zones with analogous flatness extent may be created through previous steps, hence, a combining step is devised to consolidate such zones.

$\forall\ T_i \subset S$, $T_j \subset S$, $\exists\ f_i \subset T_i$, $f_j \subset T_j$, if the relation "$U(f_i, f_j) = 1$" is met, the above two zones will be combined when the error of approximate plane and variance of normal vector are lower than a preset threshold .

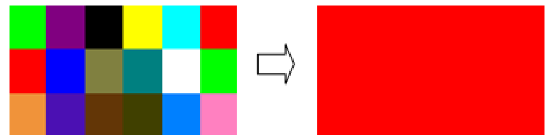

Fig.5 Zone combine

The model in above figure comprises eighteen polygonal faces, meanwhile, there are eighteen clustering centres initially which creates zones with the same counts, by the aid of above procedure, the above zones with fine differences are combined into one single zone.

H. *Collision avoidance*

The result gained from proposed algorithm is applied to later real spraying. Meanwhile, the losses are huge when there is a collision between working robot and sprayed body, it is true that real spraying paths are created on the basis of produced zones. Furthermore, in order to avoid collision between robot and sprayed body, large number of intermediate points will be created which induces low efficiency, it is propitious to both later process and real spraying when a step is used to avoid latent collision at dividing stage.

We remove a majority of latent collisions by mastering the shape of created zone, obviously, collision is more likely when the shape of zone is concave.

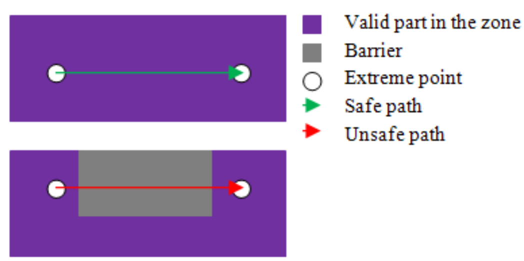

Fig.6 Collision instance

Both safe path and unsafe path are shown in above figure, a conclusion can be drawn easily, to be a valid zone, there are two conditions to be met, on the first hand, the zone must be in convex shape; on the second hand, inner zone should not exist in reviewed one. For above reason, paper employs meaningful partition lines to divide invalid zone into several convex ones.

In order to achieve effective partition lines, the margin of zone should be decided firstly, paper obtains the margin of zone by contiguous feature of polygonal meshes, any face that shares common edge with no bigger than three polygonal meshes is considered as fringe of zone, with the help of above polygonal meshes, meaningful segmentation lines can be estimated. The method in which straight lines are fitted by points are various, among the rest, Hough transformation [13] is widely applied owing to its robust to noise and other favorable features. A dimension reduction step is adopted to extend its applied range from two dimensional picture to three dimensional model.

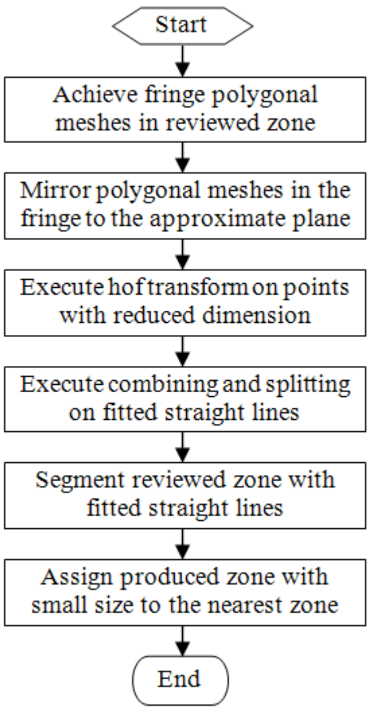

Fig.7 Flow chart of collision avoidance

In above figure, the combining step refers to merge lines with fine differences while the splitting process is pointing at dividing the fitted line into several more precise ones.

In the process of splitting, all the polygonal meshes that have a smaller distance with each other are placed in a single line. With the help of the direction of neighbors, invalid faces can be deleted from the fitted straight line, any line that has a small number of faces will be deleted. So far, ultimate splitting straight lines have been acquired, by the aid of above lines, the zone can be segmented into several valid ones.

After executing above procedure, the zone in Fig.6 can be processed into the following result:

Fig.8 Processing result

Obviously, the invalid zone is segmented into three valid ones in Fig.8.

IV. Experiments and Results

In this section, we first test algorithm's robust to initial number of zones, further, a comparison with other common algorithms is made on several car-alike objects, meanwhile, exhaustive analysis is made upon the dividing result.

A. Invariance to initial number of clustering centres

To explain the essence better, a typical car-alike model is tested by advanced algorithm without the last step.

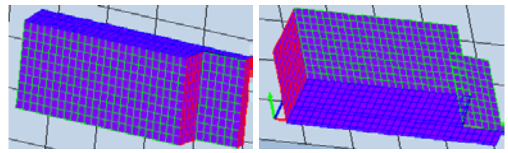

Fig.9 The splitting result when the initial number of clustering centres is twenty

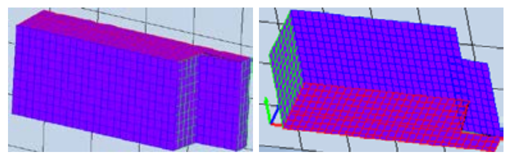

Fig.10 The splitting result when the initial number of clustering centres is five

Obviously, the results are stable whenever the initial number of clustering centres is twenty or five, in conclusion, the segment result is independent of initial number of centres.

B. Experiments on several typical models

In this section, two models are tested on several dividing algorithms including advanced method.

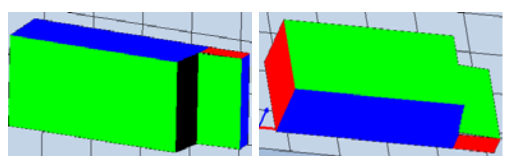

Fig.11 The splitting result of advanced method

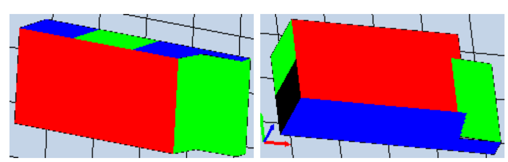

Fig.12 The splitting result of k-means method

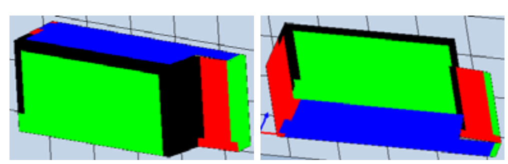

Fig.13 The splitting result of watershed method

The above shows the different segmentation results from three partition algorithms, the result gained from advanced algorithm is basically the same as desire one. Meanwhile, the lateral part is divided into two zones with convex shape, which is induced by collision avoidance procedure. In contrast, other two methods give a worse result.

Fig.14 Result of proposed algorithm

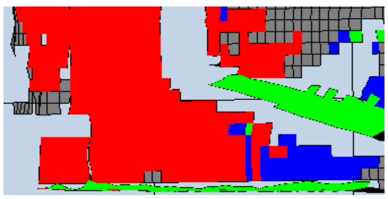

Fig.15 Result of k-means algorithm

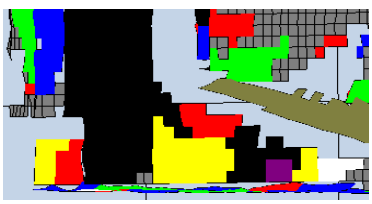

Fig.16 Result of watershed algorithm

The model in above three figures is local of an actual car-alike object, the grey meshes represent the part that is not need to be processed.

Obviously, the proposed algorithm gives the best result in which every produced zone is fit for spraying, zones tagged by digit 1, 2 and 3 are lower than the part encircled by red ellipse, meanwhile, there are fine differences between them, without the execution of collision avoidance step, the above zones will be combined into one single zone, which may induce collision when robot is moving in the combined one, after executing the final step of raised method, three convex zones are produced, which avoids later collision. The k-means method gives a bad result for the reason of invariant centre counts. A better result is gained by the aid of watershed method, however, there are serious excessive partition problem.

V. Conclusion

In this paper a zone divide technique is proposed to partition three-dimensional model into several meaningful zones. The method can extract approximate plane from the model, on the basis of polygonal patches in the fringe of zone, a further segmentation is executed for the purpose of collision avoidance.

The proposed algorithm in this paper is suitable for spraying object with similar shape as car. In the near future further improvement on the method will be made aiming at more wide in adaptability. More powerful algorithm will be developed to extent its application range from car-alike model to object with random shape.

Acknowledgment

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