Proceedings of the 24th IEEE International
Symposium on Robot and Human Interactive Communication
Kobe, Japan, Aug 31 - Sept 4, 2015

Shape Modeling of A String And Recognition Using Distance Sensor

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Abstract— The demand is growing that a robot manipulates a deformable object. Scenarios for both of a grasping point and transfer of grasped point are required, in order to manipulate a deformable object by a robot. Therefore, it is important for a robot to recognize its form by using image information. In this paper, three-dimensional points groups of a string are obtained by a camera that has distance measure equipment. A shape model called "point chain model" is obtained from points group based on proposed algorithm. In this algorithm, first, points which are estimated to be outside of target object are removed from obtained points groups. Secondly, points groups obtained from various viewpoints are combined to reconstruct three-dimensional shape of a string. Thirdly, central axes of a string are abstracted from combined points groups. Finally, central axes are chained to construct the point chain model. Effectiveness of proposed algorithm is confirmed by experiment.

I. INTRODUCTION

There are many deformable objects around our living space, such as cloth, rope, towel and so on. If robots work in people living environments, they have to manipulate those deformable objects on housekeeping. On focusing interaction between human and robots, it is troublesome for people to teach robots the sequence of deformable objects manipulation step by step in both of each situation and each object. Therefore, in order to omit those teaching processes, robots are expected to learn the sequence of those manipulation. As a first step of deformable object manipulation, shape recognition method of deformable object is required. If shape recognition is extractly conducted, robots can evaluate their behavior on deformable object manipulation, and they can improve their motion. In addition, the demand is growing that a robot manipulates a deformable object in factory[1].

There are following contents as preceding research regarding deformable object. Shape extraction methods of a string are mentioned in some papers[2][3]. Shape of string is recognized by image analysis, and then knot theory of the string and movement method of robot are proposed[4]. Methods of operation based on feature of deformable objects are calculated and some behavior such as tying of rope and folding of clothes are realized in some papers[5][6]. However, user decides trajectories to manipulate a target object in these papers. In order to manipulate a deformable object by a robot in work environment, the robot has to recognize shape of a deformable object and has to generate
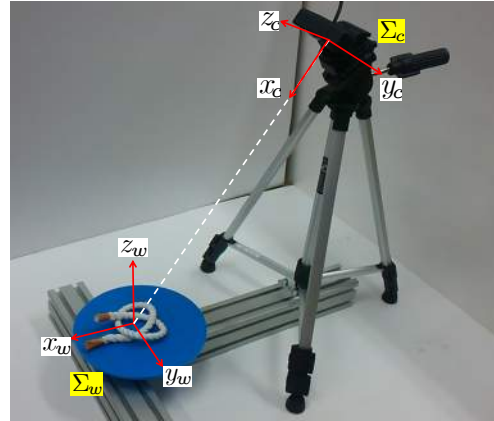
Fig. 1. Experimental environment

trajectories to manipulate a target object according to the shape.

In this paper, three-dimensional points group of a string is obtained in a camera that has distance measure equipment as shown in Fig.1. A shape model called "point chain model" is obtained from points group based on proposed algorithm. In case of three-dimensional points group, it is possible to recognize three-dimensional shape of a deformable object. However, camera occlusion should be solved to reconstruct a shape of a target object from three-dimensional points group. In this algorithm, first, non-target object is removed from obtained points groups. Secondly, points groups obtained from various viewpoints are combined to reconstruct three-dimensional shape of a string. Thirdly, central axes of a string are abstracted from combined points groups. Next, central axes are chained to construct the point chain model. Finally, point chain model is reconstructed by dividing new segments and connecting edges of them. Effectiveness of proposed algorithm is confirmed by experiment.

II. SHAPE RECOGNITION ALGORITHM OF A STRING

In this section, shape recognition algorithm of a string is proposed. Flow chart of algorithm to recognize shape of a string is shown in Fig.2.

In shape recognition algorithm as shown in Fig.2, first, non-target object is removed from obtained points groups. Three-dimensional points group of a string is approximately obtained by setting extraction range of points groups in removal of non-target object. Secondly, extra points are removed in statistical outlier removal from points groups obtained by previous processing. Thirdly, normal vectors of
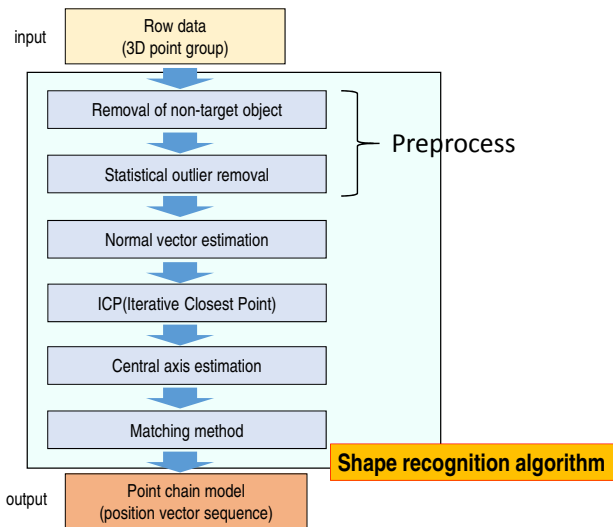
Fig. 2. Flow chart of algorithm to recognize shape of a string

Fig. 3. A target object

Fig. 4. Configuration of a target object and a camera

Fig. 5. Relationship between Σ_c and Σ_w

a target object are calculated in normal vector estimation from points groups obtained by statistical outlier removal. Next, points groups obtained from various viewpoints are combined by ICP(Iterative Closest Point) algorithm. Finally, central axes of a string are abstracted from combined points groups. Point chain model to express shape of a string is made by carrying out these processing in sequence. The detail of processing is explained in section IV.

III. MEASUREMENT ENVIRONMENT

A string used as a deformable object is shown in Fig.3. This string is 8.4[mm] in diameter and 400[mm] in length. Shape of a string as shown in Fig.3 is constituted in various elements such as knot segment, straight segment, circular segment and overlapping segment. Therefore, if this shape is able to be recognized correctly, it may be possible to recognize other various shapes.

Experimental environment is shown in Fig.1. Configuration of a target object and a camera is shown in Fig.4. Circular plate as shown in Fig.1 is attached on rotation stage and a camera is attached in tripod. The distance camera
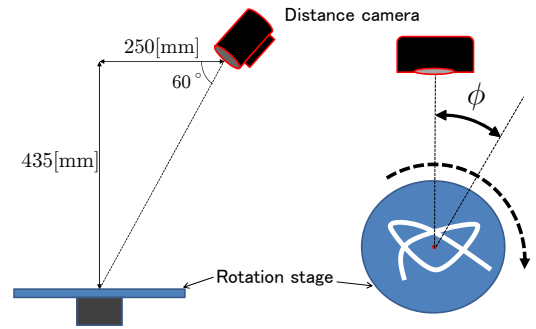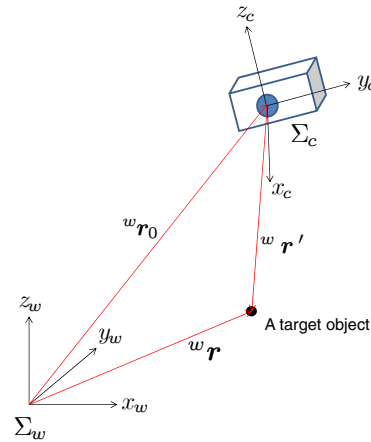
in Fig.1 is Senz3D made by Creative Technology Ltd. The rotation angle is adjusted in detail by reading scale. A target object is measured from various viewpoints as shown in Fig.4. Rotation angle of circular plate is defined as ϕ. Points groups measured in seven viewpoints are obtained by rotating a circular plate from -90 degrees to 90 degrees with respect to each 30 degrees. When points are obtained, the coordinates are converted from camera coordinate system Σ_c to world coordinate system Σ_w as shown in Fig.1. Coordinate transformation based on obtained points groups data is important to combine points groups obtained from various viewpoints by ICP algorithm.

Relationship between Σ_c and Σ_w is shown in Fig.5. Here, position of a target object based on Σ_w is calculated as follows. Position of Σ_c based on Σ_w is defined as ${}^w\boldsymbol{r}_0$. Position of a target object from Σ_c based on Σ_w is defined as ${}^w\boldsymbol{r}'$. Position of a target object based on Σ_w is defined as ${}^w\boldsymbol{r}$. Equation related to ${}^w\boldsymbol{r}$ is obtained as follows

$$ {}^w\boldsymbol{r} = {}^w\boldsymbol{r}_0 + {}^w\boldsymbol{r}' . \tag{1} $$

Here, unit vector of each axis about Σ_c based on Σ_w are defined as ${}^w\boldsymbol{e}_{xc}$, ${}^w\boldsymbol{e}_{yc}$ and ${}^w\boldsymbol{e}_{zc}$. Position of a target object based on Σ_c is defined as ${}^c\boldsymbol{r}'$. Eq.(1) is transformed as follows

$$^{w}\boldsymbol{r} = {}^{w}\boldsymbol{r}_0 + \begin{bmatrix} {}^{w}\boldsymbol{e}_{xc} & {}^{w}\boldsymbol{e}_{yc} & {}^{w}\boldsymbol{e}_{zc} \end{bmatrix} {}^{c}\boldsymbol{r}' . \tag{2}$$

Rotational matrixes around x, y and z axes are defined as $\boldsymbol{R}_x$, $\boldsymbol{R}_y$ and $\boldsymbol{R}_z$. Those parameters are expressed as follows

$$^{w}\boldsymbol{r} = \begin{bmatrix} x_w & y_w & z_w \end{bmatrix}^{\mathrm{T}} , \tag{3}$$

$$^{w}\boldsymbol{r}_0 = \begin{bmatrix} x_0 & y_0 & z_0 \end{bmatrix}^{\mathrm{T}} , \tag{4}$$

$$^{w}\boldsymbol{r}' = \begin{bmatrix} x' & y' & z' \end{bmatrix}^{\mathrm{T}} , \tag{5}$$

$$^{w}\boldsymbol{e}_{xc} = \boldsymbol{R}_x\boldsymbol{R}_y\boldsymbol{R}_z \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}^{\mathrm{T}} , \tag{6}$$

$$^{w}\boldsymbol{e}_{yc} = \boldsymbol{R}_x\boldsymbol{R}_y\boldsymbol{R}_z \begin{bmatrix} 0 & 1 & 0 \end{bmatrix}^{\mathrm{T}} , \tag{7}$$

$$^{w}\boldsymbol{e}_{zc} = \boldsymbol{R}_x\boldsymbol{R}_y\boldsymbol{R}_z \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}^{\mathrm{T}} , \tag{8}$$

$$^{c}\boldsymbol{r}' = \begin{bmatrix} x'_c & y'_c & z'_c \end{bmatrix}^{\mathrm{T}} . \tag{9}$$

When measurement by a camera is carried out, elements of $^{c}\boldsymbol{r}'$ can be calculated. Therefore, $^{w}\boldsymbol{r}$ is calculated by setting parameters of $^{w}\boldsymbol{r}_0$, $^{w}\boldsymbol{e}_{xc}$, $^{w}\boldsymbol{e}_{yc}$ and $^{w}\boldsymbol{e}_{zc}$. In this condition, points group obtained without preprocess is shown in Fig.6(a).

IV. PROCESSING OF POINTS GROUPS

A. Statistical outlier removal

When three-dimensional points group is obtained, false points are also obtained by external noise and measurement error. These points exist in the place having low density of points group. Because false points may interfere with later processing, these points should be removed. In this paper, searching radius from a basic point is set. After counting number of points existing in searching radius, outlier point is distinguished by the number. Points group obtained by adapting preprocess from Fig.6(a) is shown in Fig.6(b).

B. Normal vector estimation

Algorithm to estimate normal vector is the method which calculate normal vector of each point from the neighboring points. Normal vector is led by calculating a plane from both a basic point of points group and the neighboring points. Relationship between normal vector and position vector is shown in Fig.7.

Here, normal vector of a basic point $\boldsymbol{p}$ existing in points group data is defined as $\boldsymbol{n}$. Next, k points existing around $\boldsymbol{p}$ are searched. Vectors from $\boldsymbol{p}$ to respective neighboring points are defined as $\boldsymbol{q}_i (i = 1, 2, \cdots, k)$. Equation regarding inner product of both $\boldsymbol{q}_i$ and $\boldsymbol{n}$ is defined as follows

$$\boldsymbol{n} \cdot \boldsymbol{q}_i - d = 0 . \tag{10}$$

Here, d shown in Eq.(10) is defined as constant term because inner product of both $\boldsymbol{q}_i$ and $\boldsymbol{n}$ does not necessarily become 0. Equation to evaluate both $\boldsymbol{n}$ and d is defined as follows

$$F(\boldsymbol{n},d) = \sum_{i=1}^{k} \|\boldsymbol{n} \cdot \boldsymbol{q}_i - d\|^2 . \tag{11}$$

In Eq.(11), a plane in $\boldsymbol{p}$ is led by using least-squares method from $\boldsymbol{q}_i$. Appropriate normal vector in $\boldsymbol{p}$ is derived by
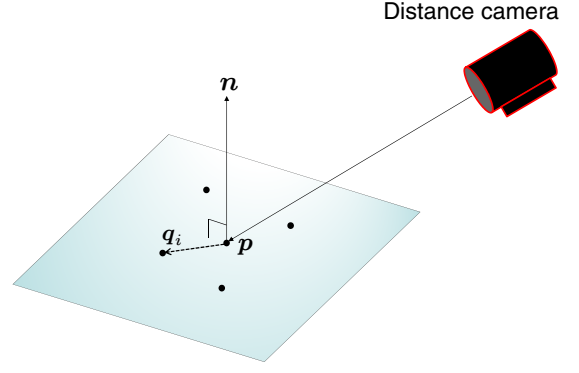

Fig. 7. Relationship between normal vector and position vector

calculating $\boldsymbol{n}$ that minimize $F(\boldsymbol{n},d)$. Equation that led by differentiating partially with respect to d about Eq.(11) is obtained as follows

$$\sum_{i=1}^{k} (\boldsymbol{n} \cdot \boldsymbol{q}_i - d) = 0 . \tag{12}$$

Here, center of points group existing around a basic point is defined as $\boldsymbol{q}_a$. From Eq.(12), equation is transformed as follows

$$\boldsymbol{n} \cdot \boldsymbol{q}_a = d . \tag{13}$$

Equation that Eq.(13) is substituted into Eq.(10) is obtained as follows

$$\boldsymbol{n} \cdot (\boldsymbol{q}_i - \boldsymbol{q}_a) = 0 . \tag{14}$$

Here, $\boldsymbol{n}$ is calculated as main shaft of moment of inertia in points group. Normal vectors of a target object obtained by this algorithm are shown in Fig.6(c).

C. ICP(Iterative Closest Point) Algorithm

It is difficult to extract shape of a whole target object based on points group measured from one viewpoint. So, combination of points groups measured from various viewpoints is expected to construct three-dimensional shape without breakage. In this paper, ICP algorithm is adopted as method that obtained points groups from various viewpoints are combined. Various points groups are not combined sufficiently with only coordinate transformation. Therefore, ICP algorithm is used to reduce error of positions. Rotation matrix is defined as $\boldsymbol{R}$ and translation vector is defined as $\boldsymbol{t}$. Also, corresponding points of two points groups data are defined as $\boldsymbol{x}_i$ and $\boldsymbol{y}_i$. Equation to calculate square error of corresponding points is obtained as

$$f(\boldsymbol{R},\boldsymbol{t}) = \Sigma|\boldsymbol{R}\boldsymbol{x}_i + \boldsymbol{t} - \boldsymbol{y}_i|^2 . \tag{15}$$

Search of corresponding points by least-squares method is easily affected by incorrect points. Also, when there are many points, it takes many times to carry out this processing. However, most incorrect points are removed in preprocess.
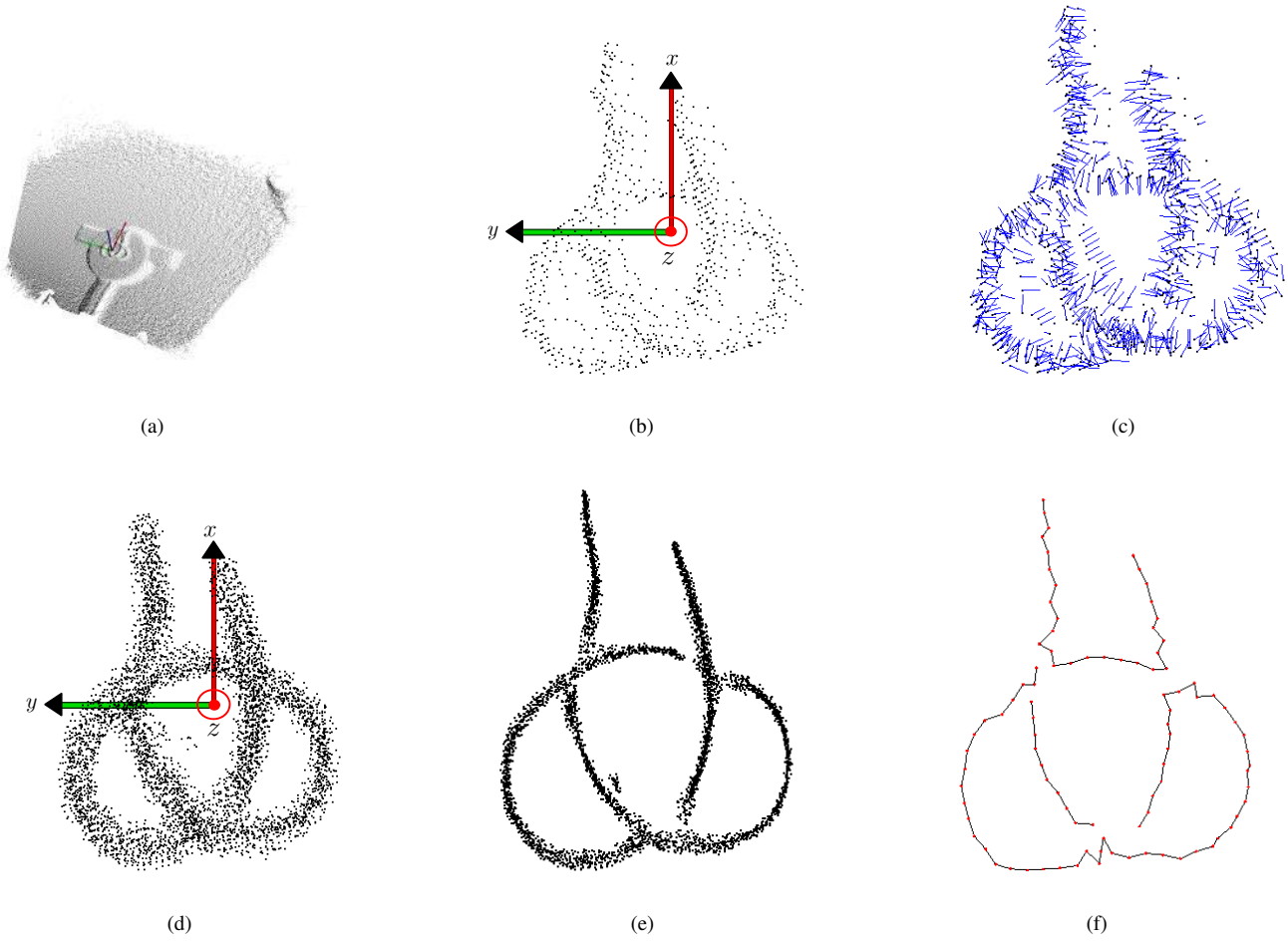
Fig. 6. Points group obtained by shape recognition algorithm

Therefore, it is not time-consuming to search corresponding points. Points group combined by ICP algorithm is shown in Fig.6(d). It is confirmed that various points groups data are combined sufficiently from Fig.6(d).

D. Algorithm to estimate central axis of a string

In this section, algorithm to estimate central axis of a string is described from normal vectors of a target object. If all estimated normal vectors are perpendicular to surface of a target object, central axis of a target object should exist in center of point as shown in Fig.8(a). Number of points obtained by a camera is defined as N. Position vector and normal vector corresponding to the i-th point are defined as $\boldsymbol{p}_i$ and $\boldsymbol{n}_i$ $(i = 1,2,3,\cdots,N)$. Also, number of points obtained by estimating central axes of a string is defined as N_c, position vector corresponding to the i-th point is defined as $\boldsymbol{c}_i$ and radius of a string is r. Equation related to $\boldsymbol{c}_i$ is obtained as follows

$$\boldsymbol{c}_i = \boldsymbol{p}_i - r \cdot \boldsymbol{n}_i . \qquad (16)$$

Center points are calculated against neighboring points existing within distance set from a basic point as shown in Fig.8(b). Number of points existing within $2r$ from i-th
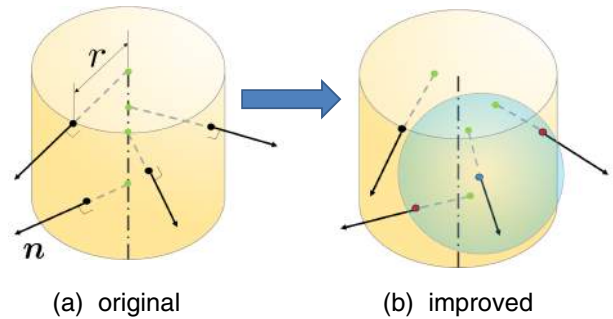

Fig. 8. Image of central axis estimation

point $\boldsymbol{p}_i$ is defined as $\bar{N}_i$. Also, those points are defined as $\boldsymbol{P}_{ik_j}(j = 1,2,3,\cdots,\bar{N}_i)$. Inequation regarding both point $\boldsymbol{p}_i$ and $\boldsymbol{p}_{ik_j}$ is obtained as follows

$$|\boldsymbol{p}_i - \boldsymbol{p}_{ik_j}| \le 2r \ \ (j = 1,2,3,\cdots,\bar{N}_i) . \qquad (17)$$

Here, When $\bar{N}_i$ becomes less than $\bar{N}_{lim}$, points existing in the area may be estimated as outlier. In such a case, it is
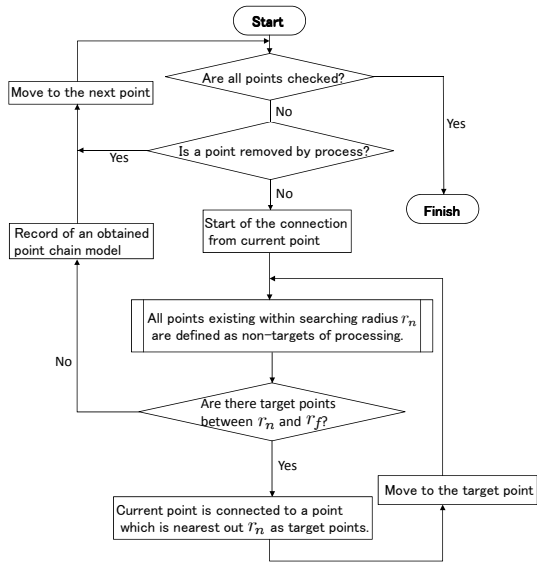
Fig. 9.   Flow chart of matching method

Fig. 10.   Appearance of matching method

considered that central axis estimation of the points does not need to be carried out. Therefore, number of obtained points N_a becomes less than N. Equation related to the m-th point $\bar{\boldsymbol{c}}_m$ is obtained as follows

$$\bar{\boldsymbol{c}}_m = \frac{1}{\bar{N}_i} \sum_{j=1}^{\bar{N}_i} \boldsymbol{c}_{ik_j} \ . \tag{18}$$

Obtained points group by above mentioned processing is shown in Fig.6(e). It is confirmed that most points group is distributed around central axis of a string from Fig.6(e).

V. CREATION OF POINT CHAIN MODEL

A. Algorithm to make point chain model

In this section, algorithm to make a point chain model is described. Matching method is adopted to make point chain model. Point chain model can express a shape of string as sequence. Matching method is carried out based on flow chart shown in Fig.9. Also, appearance of matching method is shown in Fig.10. First, searching radius r_f and neighbor radius r_n from a basic point are set. Next, all points existing within r_n are regarded as non-targets of processing. After then, a basic point is connected to the nearest point existing between r_n and r_f. Sequences of position vector are made by repetitively carrying out these processing. Finally, when there is no point existing within r_f, these processing is finished. It is considered that these processing are able to be dealt with problems such as outlier and dispersion of points.

B. Reconstruction of a whole connected model

Matching method will generate point chain model with cutting and wrong connection on intersection. In order to reconstruct the feasible connection in three dimension under the assumption that there is only one rope in measurement region of distance camera. First, old segments are divided
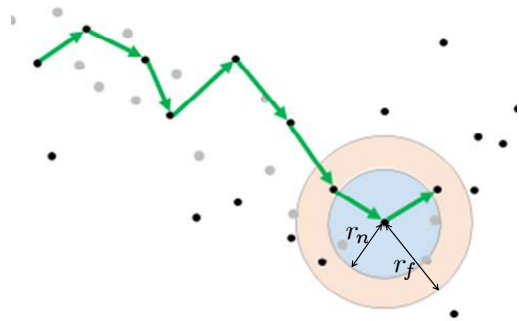
into some new segments which have no intersection in their middle points. The criteria to divide those segments is distance d_i^* which is expressed with equation(19).

$$d_i^* = \min_{j \in J \ \cap \ i \in J} \ d(i,j), \tag{19}$$

$$d(i,j) = \|\bar{\boldsymbol{c}}_i - \bar{\boldsymbol{c}}_j\|, \tag{20}$$

here, i and j are indexes of element points of chain model. Also, J indicates subset of certain segment that includes j-th element point. By plotting d_i^* for index of each element, we can find local minimum. The local minimum indicates that the point has other segments in neighborhood to connect on intersection. Therefore, old segment should be divided at local minimum of d_i^*. Secondly, two edges of whole rope are selected from edges of new segments. The most far two points are selected as edges of whole rope. Next, four edges of new segments are combined as candidates of intersection. Based on distance of each edge, the closest four points are selected. Finally, two couples on one intersection are connected based on the similarity of direction of each edge. After each couple of edge is connected, new segments are punished, and a whole connected rope model is established.

C. Experimental result and consideration

Appearance of point chain model obtained by matching method is shown in Fig.6(f). In Fig.11, minimum distance d_i^* for each element point is plotted. Originally the point chain model has three segments, and the number of new segments became seven after dividing by proposed algorithm. And, divided segments are illustrated in Fig.12, where edges of new segments are marked with circles. Those edges are concentrated on intersection, and they can be clearly grouped with four elements, except two edges of whole rope. Finally, reconstructed point chain model of whole rope is illustrated in Fig.13. Because edges of new segments are connected based on direction of them, the connection on straight line are selected. The straight connection is feasible in ordinally case, because the shape without acute angle realizes minimum state of potential energy. Appearance of point chain model is also shown in attached video.
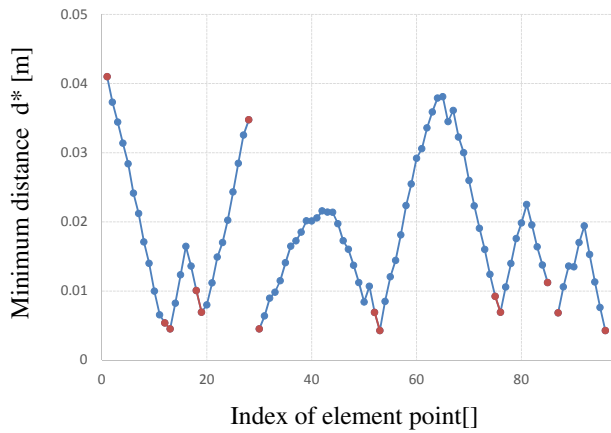
Fig. 11.   Minimum distance d^* and devision of segment
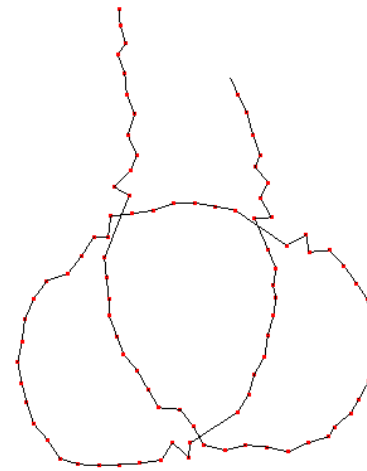

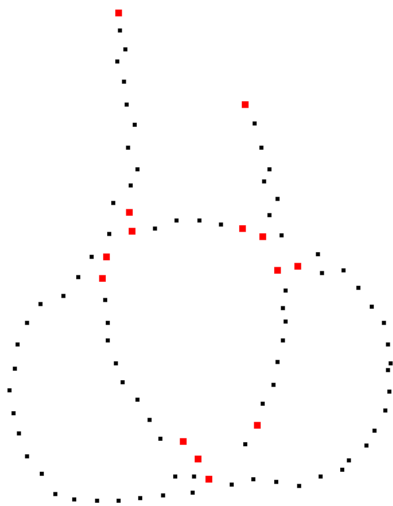Fig. 13.   Reconstructed point chain model of whole rope

Fig. 12.   New segment divided by proposed algorithm: Here, dot points express element points and circles express edges of new segments

VI. Conclusions

In this paper, three-dimensional points groups of a string were obtained by a camera that has distance measure equipment. And then algorithm to recognize shape of a string from points groups was proposed. Three-dimensional points group of a string was obtained accurately in ICP algorithm by preprocess. Also, it was confirmed by this experiment that both central axis estimation and matching method are effective to reconstruct shape of linear deformable object.

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