Proceeding of the IEEE
International Conference on Robotics and Biomimetics
Dali, China, December 2019

Alignment of an Unmarked Deformable Sheet Like Object Based on NURBS Fitting

Mengyuan Li, Huangtao Wei and Xin Jiang
Department of Mechanical Engineering and Automation
Harbin Institute of Technology, Shenzhen
Shenzhen, Guangdong Province, China
x.jiang@hit.edu.cn

Yunhui Liu
Department of Mechanical Engineering
The Chinese University of Hong Kong
Hong Kong, China
yhliu@mae.cuhk.edu.hk

***Abstract*— In this paper, we proposed a method to realize automatic labeling task of a flexible sheet like object. It is a demonstration to the similar operations widely adopted in industrial production line such as those in flexible printed circuits assembly. In these operations, it needs to precisely position a specific part within a deformable sheet to a predefined position. In many applications involving such operations, the usage of artificial markers are not allowed and the target may lack enough features for tracking. Thus 3D position of the alignment reference has to be estimated from its contour. The task of aligning an unmarked paper sheet considered in this paper well demonstrates these situations. In this paper, Non-uniform rational B-Splines (NURBS) fitting is utilized for tracking the shape variation of the paper. It is proved that for an unstretchable sheet like object, the fitted NURBS plane can be used in the way of servo control for regulating the shape. It provides a simple way to track the featureless points described with the paper undeformed generally as a sketch. The advantage of the proposed method is verified by successful alignment experiment in which a certain line defined on an undeformed paper sheet is aligned to the predefined position on a box.**

I. INTRODUCTION

With the progress achieved in robot technologies, in many applications it expects that a robot can handle deformable objects. In industrial fields, this need comes from the tasks such as assembly of cables, rubber and plastic parts. In service field, robots are used in laundry folding and food packaging. In newly emerging automatic surgery, robots are considered to perform suturing. However, compared with the tasks characterized by handling rigid objects, the tasks involving handling deformable objects are still considered to be difficult in robot engineering and academic fields. Recently many efforts are being made for tackling the problems in this field.

Technically, many difficulties involved in handling deformable objects lie in real-time measurement of the target shape and servo control for shape regulation. As for the means for measuring the 3D shape of a deformable object, RGB-D sensors are well adopted. In [1], topological state of a tangled rope is estimated by analyzing the point cloud captured by Kinect sensor. In [2], tracking to an elastic object (pizza) is achieved by Kinect. It utilizes the FEM model of the object. In [3], a general tracking method is proposed which utilizes the object model from commercial physical simulation engine (Bullet). In the demonstration achieved in the research, tracking of a flag in a folding process is realized. In [4], the B-Spline surface approximation is used to fit a garment surface. The wrinkle of the garment is found through the B-Spline surface. Then a flattening plan optimized for the largest detected wrinkle is formulated based on a dual-arm manipulator. In [5], the authors use a soft-body-physics model to monitor the deformation of a paper sheet. The monitored shape information is used in the folding task. It is accomplished by introducing a set of tactile and vision-based feedback controllers.

The other difficulty involved in deformable object handling is the shape control necessary in practical applications. This problem is generally formulated as indirectly controlling the position of part of a deformable object. Since these parts are not allowed for direct grasping. Their positions have to be affected indirectly by the gripper grasping one end of the object. Generally, the effect of robot hand motion to the deformation indicated by the movement of the points is expressed by deformation Jacobian matrix. In [6], trajectory control of several points within a cloth is achieved by moving its edge. In order to estimate the effect of robot hand movement to the points inside of the cloth, FEM model of the cloth is utilized. In [7], the effect of gripper movement to the points inside the object is estimated by using a simple way. The proposed method models deformation Jacobian matrix by introducing a decay factor to the matrix derived from rigidity assumption. The decay factor is related to the distance between the feature point and the gripper. In [8], the authors proposed an adaptive way to estimate the deformation Jacobian matrix. It enables applications with no physical models of the object. In [9], force control based on tactile sensor is used for handling a flexible sheet. It helps to achieve the task of turning and removing a thin sheet from a pile of paper on a table.

In this paper, automatic alignment of a paper sheet is considered. The task is to mimic one operation in packaging process, in which a box has to be labeled with a paper sheet. The quality requirement is defined as precisely aligning the paper sheet so as to make a specific part of the paper attached to the specified edge of the box. It is assumed that the alignment reference within the paper can not be marked and there are no enough visual features for tracking. This condition

978-1-7281-6321-5/19//$31.00 ©2019 IEEE

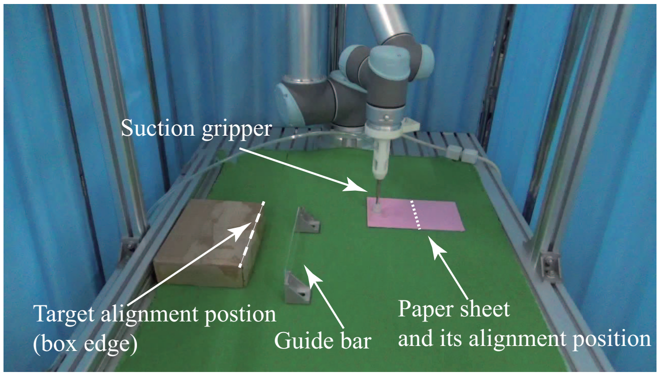


Fig. 1. The platform used for experimental verification

is common in many similar processes in industry. For these tasks, tracking of featureless points on 3D deformable objects are required. In this paper, we propose to use NURBS fitting for this purpose. Since no distinctive visual features are available, the consistence of point tracking between different frames has to be realized considering the 3D contour. The approach adopted in the paper demonstrates that by a well designed NURBS initialization process, the consistence in point tracking can be easily achieved. The correspondence between NURBS coordinate and the Cartesian coordinate defined in flat state is stationary during a whole process involving deformation. This property can help to find the positions for any featureless points on the object. It is proved that for a unstretchable sheet like object, NURBS fitting provide enough precision for tracking featureless points. This property is proposed to be used in the servo control for shape regulation. The work in this paper is expected to help handling those tasks involving shape servo of featureless 3D deformable objects.

The rest of the paper is organized as follows. Section II presents an introduction to the tracking method adopted in the paper. Based on the real-time feature position derived by this method , shape control is implemented. It is to realize the final alignment. Its details are addressed in section III. The verification experiments conducted is introduced in section IV. The paper ends with concluding remarks in section V.

II. Tracking the Deformation of a Paper Sheet

In this research, Non-uniform rational B-Splines (NURBS) is used to describe the deformation of the paper sheet. It is widely adopted in computer graphics for representing continuous surfaces. Since no physical models are assumed in the method, it is proper for the cases where there are unexpected contacts between the object and the environment. A NURBS surface composed of p degree in u direction and q degree in v direction is expressed as:

$$S(u,v) = \sum_{i=0}^{n} \sum_{j=0}^{m} R_{i,j}(u,v) c_{i,j}, \tag{1}$$

where

$$R_{i,j}(u,v) = \frac{N_{i,p}(u) N_{j,q}(v) \omega_{i,j}}{\sum_{k=0}^{n} \sum_{l=0}^{m} N_{k,p}(u) N_{l,q}(v) \omega_{k,l}}. \tag{2}$$

$c_{i,j}$ represent $(m+1)\times(n+1)$ control point positions expressed in Cartesian coordinate, $\omega_{i,j}$ are weights, and $N_{i,p}(u)$, $N_{j,q}(v)$ are the non-rational B-spline basis functions defined on the knot vectors [10]. The variable u,v are the coordinates in NURBS. Given a set of u,v specified, (1) uniquely determines one Cartesian point on the surface.

A. Initialization of NURBS

The initialization of the NURBS fitting is done with the target paper sheet placed on a flat table. Since in this sate the paper sheet is not deformed, its 3D contour reflected in the point cloud is exactly formed as a rectangle surface. The initial NURBS surface is constructed by fitting the point cloud in this state with the NURBS expression. In this state, the directions of u,v are determined by principal component analysis. Thus, the axises of u,v are parallel to the two edges of the rectangle. The value of coordinates u,v are consistent with definition of Cartesian space. The origin is defined as one corner of the paper. It should be noted that generally the coordinate u,v in NURBS has no meaning of Cartesian distance and its origin is not always located in corner of the rectangle. It is not even necessarily inside the paper.

It is necessary to find the corresponding NURBS coordinate for a feature point on the paper sheet defined with it undeformed. In many applications, the design sketch expressed on a flat paper has to be realized when the paper is deformed. It implies to determine the u,v which position is closest to the feature. Denote $c_{ini}(i,j)$ as the point set consisting of the initial control points, then if the object is unstretchable, the point cloud of the deformed object can be well fitted by only changing the control points with the other NURBS parameters unchanged. For a specific feature point on the paper, its u,v coordinate is consistent between different NURBS surfaces corresponding to different moment. In this way, it can locate a featureless point on a deformed object if its u,v coordinate in the initial NURBS surface is known. Since the initial NURBS surface is expressed as a rectangle surface with its axises consistent with its edges, the correspondence between u,v and its Cartesian coordinate is straightforward.

For any deformed state of the object, the most fitted NURBS is determined by manipulating the control points $c_{i,j}$ to minimize the distance D between point cloud containing the paper sheet V_i and the fitted surface as demonstrated in [11].

$$D = \left\| \sum_{i=0}^{n} \sum_{j=0}^{m} R_{i,j}(u,v) c_{i,j} - V_i \right\|_2 \tag{3}$$

B. Isolation of deformation

In the following experiments, variation in object point cloud is resulted from two factors: rigid movement of object and its elastic deformation. They are captured by a Kinect sensors as the point set V_c in the camera coordinate frame. The correspondence between V_c and their Cartesian positions on the paper in the initial state can not be obtained easily. The motion of the gripper has to be considered in the fitting process. In order to maintain the correspondence between u,v

coordinate in the fitted NURBS with that in the initialization phase, it is necessary to distinguish the variation components of point cloud resulted from deformation with that resulted from gripper motion. The correspondence can be guaranteed only if the point cloud component resulted from deformation is put through the fitting process. That is to say if the point cloud is measured from the same view point and they only consists of variation resulted from deformation, then the correspondence will be guaranteed during a whole manipulation process.

In experiments, the extraction of deformation resulted point cloud can be simply achieved if the paper sheet is gripped rigidly without dropping. During the whole process, except the deformation, the paper sheet is static with respect to the gripper. Thus the rigid motion of the paper sheet is consistent with that of gripper, which can be obtained from robot forward kinematics. From the aspect of practical applications, the requirement of always gripping the object without releasing it is not difficult for satisfaction.

In the subsequent experiments, the NURBS initialization is conducted when a suction gripper contact the flat paper sheet on the table for the first time. From that moment the paper sheet is totally constrained until its alignment is finished.

III. Deformation control

With the feature point position measured from the point cloud, it is possible to implement servo for positioning them to specified reference position. This is a problem concerning with shape control of deformable objects. In this paper, the method proposed in [7] is adopted for this purpose. This approach is based on a simplified formulation to deformation Jacobian matrix. For a deformable object, the deformation Jacobian matrix describes the relation between the movement of gripper and the resultant motion of the points on a deformable object.

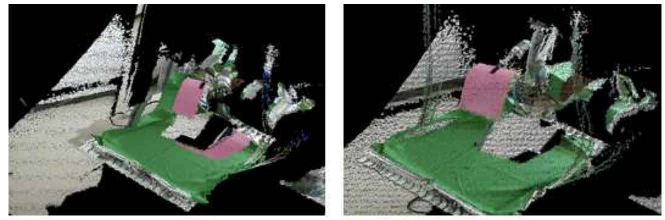
Let $p_i \subset \mathbb{R}^3$ be the position of the ith feature point on the paper sheet. Considering that one end of the paper sheet is gripped by a robot manipulator, then the element of deformation Jacobian matrix with respect to ith feature point is calculated as:

$$J_d(q,i) = w(i)[J_{trans}(q,i), J_{rot}(q,i)] \tag{4}$$

where $w(i)$ is the rigidity decay factor that reflect how the affect of gripper q to ith feature point decays with their relative distance increasing. $w(i)$ is expressed as $e^{-kd(i)}$, where k is a constant factor greater than 0, and $d(i)$ represents the distance between gripper q and feature point i. $J_{trans}(q,i)$, $J_{rot}(q,i)$ represent the translational and rotational elements calculated with rigidity assumption. This formulation utilizes the fact that for a deformable object, the influence of the gripper to points on the object decays gradually as the distance from the gripper to the point increase.

Following the previous description, for feature point i, the corresponding element of Jacobian matrix is formulated as

$$J_{trans}(q,i) = I_{3\times 3} \tag{5}$$



(a) (b)

Fig. 2. The result of color image and depth image registration. (a) The raw point cloud obtained from Kinect. (b) The point cloud after registration.

$$J_{rot}(q,i) = \begin{bmatrix} r & 0 & 0 \\ 0 & r & 0 \\ 0 & 0 & r \end{bmatrix} \tag{6}$$

where r is the norm of the vector pointed from the gripper to the feature i.

Summarizing all the elements of N features, we have

$$J_d(q) = \begin{bmatrix} J_d(q,1) \\ J_d(q,2) \\ \vdots \\ J_d(q,N) \end{bmatrix} \tag{7}$$

For a desired deformation represented as $\dot{P} = [\dot{p}_1, \dot{p}_2, \cdots, \dot{p}_i, \cdots, \dot{p}_N]^T$, the corresponding gripper velocity $\dot{X}$ can be calculated as:

$$\dot{X} = J_d^+(q)\dot{P} \tag{8}$$

Considering the Jacobian matrix of the robot arm $J(q)$, then given specified deformation velocity the corresponding joint velocity is :

$$\dot{q} = J(q)^+ J_d^+(q)\dot{P} \tag{9}$$

IV. Experiment

A. RGB camera and depth camera registration

The point cloud of the paper sheet is segmented by HSI color space, so the color image and depth image need to be registered. The result is shown in Fig. 2, the paper sheet in our experiment is pink. Before the registration, the point cloud contains green color of the table cloth. After the registration, the color image and depth image are registered which is ready for point cloud segmentation.

B. Target point cloud segmentation

The target point cloud of paper sheet needs to be extracted from the environment. As shown in Fig. 3, the raw point cloud of the paper sheet is obtained through HSI color space segmentation. The noise contained in the point cloud is eliminated through radius filtering. The point cloud which contains more than 180 points within in a ball of radius 0.04 meters is reserved. The noise points is well filtered out and the edges of the paper sheet are well preserved. To accelerate the surface fitting process, we downsample the point cloud by voxel filtering. The surface fitting process is done using the data of down-sampled point cloud.

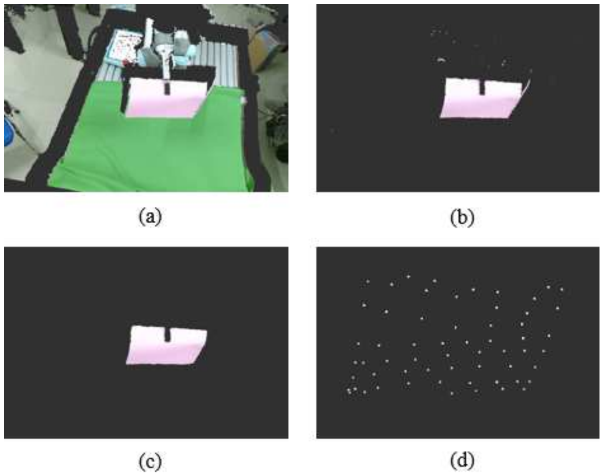


Fig. 3. The result of segmentation. (a) The point cloud after registration. (b) The point cloud after HSI color space segmentation. (c) The point cloud after radius filtering. (d) The point cloud after voxel filtering.

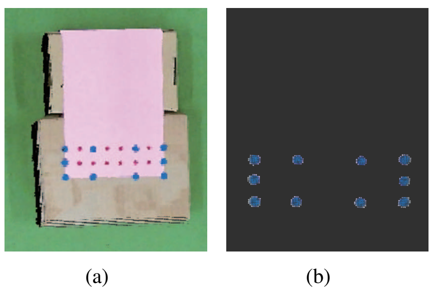


Fig. 4. The point cloud which is used to calculate centroids of the ten blue markers. (a)The initial point cloud. (b) The point cloud after HSI color space segmentation

C. Point cloud NURBS surface fitting

This section contributes to demonstrate the surface fitting result. In order to validate the deformation tracking performance, a marked paper sheet is tracked both by visual feature and by point cloud. As shown in Fig. 4(a), a piece of paper with blue and red markers is placed on two equal-height cartons. The size of the paper sheet is 14 cm $\times$ 20 cm. The marker points are attached on the corners in 2 cm $\times$ 2 cm grid.

In this test, the positions of the blue markers are used for accuracy comparison purpose. The red markers are used to confirm the fitted NURBS, since they are sampled in u, v coordinate and expressed as the cross points on the overlapped grid as shown in Fig. 5.

As shown in Fig. 4, the positions of ten blue marker points are obtained by recognizing its centroid from visual features. Their results are used as the true value of the marker positions. At the same time, the NURBS surface obtained from surface fitting is sampled by using deBoor algorithm, and it also provides estimates to the markers positions. When one of the carton boxes is removed, the paper sheet will bend. We can then compare the fitting accuracy before and after bending. The comparison results are shown in Fig. 5 and it can be observed that the markers almost coincide

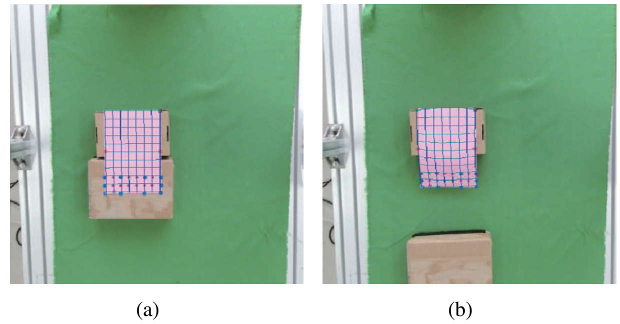


Fig. 5. The result of NURBS fitting expressed as overlapped u,v grid. (a) The initial state. (b)The state after a carton is removed.

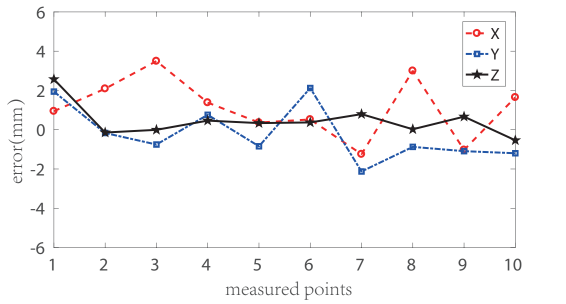
with the rendered NURBS grid. It indicates high precision of NURBS based tracking. The tracking errors of the ten marker points are summarized in Fig. 6. The graph (a),(b) represent the errors in the initial state and that measured in bended state respectively. It can be confirmed that the error fluctuation range in initial state is smaller than that in bended state. With the paper sheet bended, the average error increases slightly and the fluctuation of the error increases significantly. However, the range of fluctuation is no more than 3 mm. Considering that the average error of Kinect V2 in this range is about 2 mm, the tracking performance with NURBS fitting is almost the same as that of feature based measurement. Through this experiment, we can see that there is a good correspondence between paper and the fitted NURBS surface. The feature point positions obtained from NURBS fitting are precise enough.

D. Alignment of unmarked paper sheet

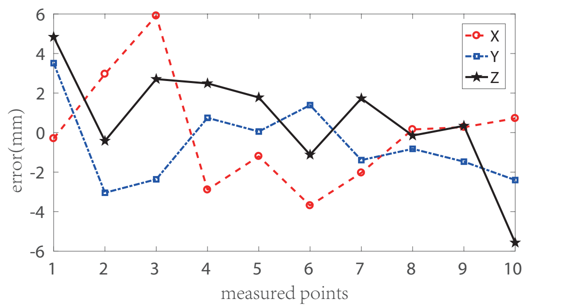
The initialization of NURBS surface is conducted when the suction gripper contact the paper sheet placed on the table for the first time. Fig. 7 demonstrates the process. After the paper sheet is sucked by the gripper, the rigid movement of the paper sheet will be consistent with robot gripper.

Based on the verification results of the NURBS fitting, an experiment of paper sheet alignment is conducted. As shown in Fig. 1, the experiment is designed to mimic operations well adopted in box packaging task. In the experiment, the manipulator has to pick up the paper sheet on the table and then attach it to the box. In order to guarantee packaging quality, it requires that a virtual line on the paper to be aligned to the edge of the box. This virtual reference line on the paper can not be marked. Thus its position can not be recognized by vision. Beside the box, there is a guide bar used for assisting the alignment. The final alignment is realized with one edge of the paper sheet constrained by the guide bar. The position of the reference line on the paper is determined by connecting its two end points estimated from the fitted NURBS surface. The end points Cartesian position with respect to the paper are measured in advance with the paper undeformed.

Before the experiment, the target paper sheet is placed on the table. Then it is sucked by the gripper. At the moment, the relative position between gripper and paper sheet is



(a) The errors of marker position measurement in initial state of paper sheet.



(b) The error of marker position measurement in bending state of paper sheet.

Fig. 6. The errors of marker position measurement in the state before and after the paper sheet is bended.

Fig. 7. After gripper suck the paper sheet, the rigid motion of the paper sheet is consistent with that of the robot arm.

fixed. And at the same time, the initial NURBS surface is established. In the next phase, the paper sheet is moved to the box with its edge constrained by the guide bar. In the final phase, the alignment is realized by triggering the shape servo control described in IV. In the control, real-time positions of the two reference points on the virtual reference line is obtained from fitted NURBS surface.

The whole process of the alignment is shown in Fig. 8. In order to visualize the result, the positions of the two reference points are marked by red circles on the video. The parameter k in (4) is determined from simulations conducted in advance. The parameter k which makes the simulated paper behavior fit the actual one best is chosen. The process of the deformation control is shown in Fig. 9. The two reference points are controlled to follow a specified trajectory towards the final positions of on the box edge. The duration of the final alignment is 5 seconds. The Fig. 9 demonstrates that the trajectory of the points on the paper

Fig. 8. Paper sheet alignment. (a) The initial state of paper sheet, the two red points on the paper are the points to be aligned. (b) The end state of the paper sheet, the red points are aligned to the edge of the box.

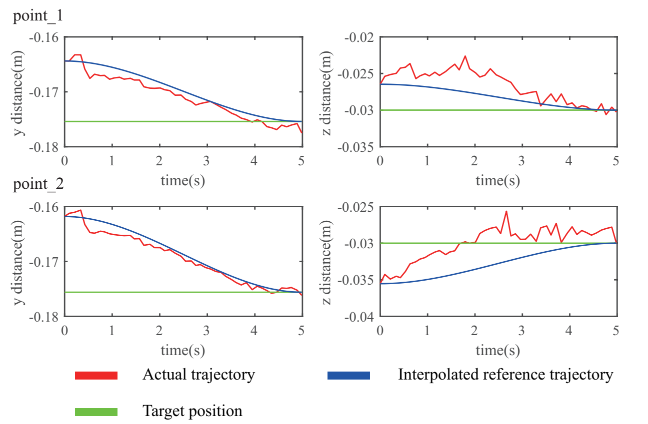


Fig. 9. The process of final alignment. The red line indicates the actual trajectory of the feature points on the paper sheet. The green line indicates the target alignment position on the box edge. The blue line indicates the interpolated reference trajectory for the feature point to follow.

follow approximately the specified one. The low response is due to the low servo rate achieved by ROS.

The trajectory of the gripper and the points on the paper during the whole experiment is demonstrated in Fig. 10. From the figure we can confirm that the motion of the points on the paper sheet is not completely consistent with the gripper because of the deformable property.

V. CONCLUSIONS

In this paper, we proposed a method to realize automatic labeling task of a flexible paper sheet. A robotic realization of the task involves solving problems on deformable object sensing and shape control. Different from the other related work, the target paper sheet has no distinctive visual features on it. Thus if part of the object is needed to be tracked, vision based recognition will not work. This problem exist in many similar tasks, in which tracking and positioning featureless points previously defined in an undeformed state of object are essential. In this paper, Non-uniform rational B-Splines (NURBS) fitting is utilized for tracking the shape variation of a sheet paper. It is proved that for an unstretchable sheet like object, the fitted NURBS plane can be used in fashion of servo control for regulating the shape change. It provides a simple way to track the featureless points previously

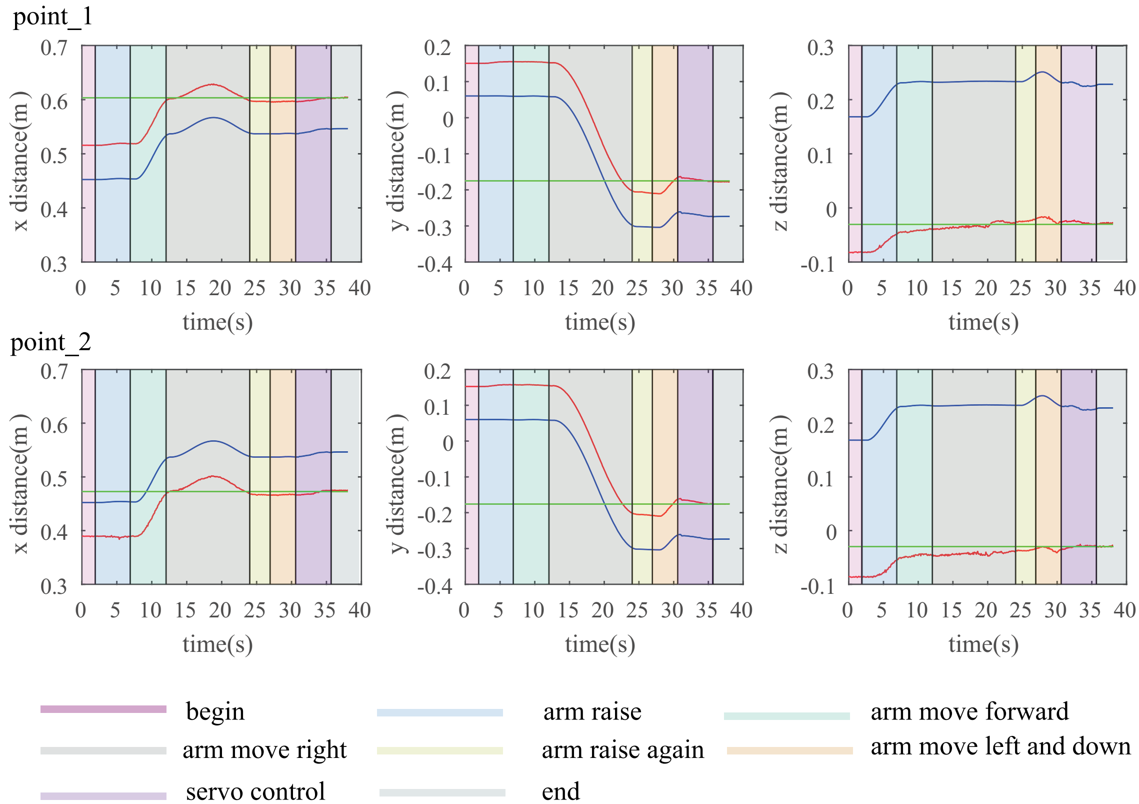


Fig. 10. The whole process of the motion. Blue line indicates the motion of the gripper. The red line indicates the motion of the feature points on the paper sheet. The green line indicates the target alignment position on the box.

described in undeformed paper sheet. The advantage of the proposed method is verified by successful paper alignment experiment in which a specific line defined in an undeformed paper sheet is attached on the predefined position on a box.

ACKNOWLEDGMENT

This work was supported by the Shenzhen Fundamental Research grant (JCYJ20170811155308088) and National Natural Science Foundation of China (Grant No.61873072), National Natural Science Foundation of China(Grant No. U1713202).

REFERENCES

[1] W. Lui and A. Saxena, "Tangled: Learning to untangle ropes with rgb-d perception," in *Proc. of IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, 2013.

[2] A. Petit, V. Lippiello, and B. Siciliano, "Real-time tracking of 3d elastic objects with an rgb-d sensor," in *Proc. of IEEE Int. Conf. on Robotics and Automation*, 2015, pp. 3914–3921.

[3] J. Schulman, A. Lee, J. Ho, and P. Abbeel, "Tracking deformable objects with point clouds," in *Proc. of IEEE Int. Conf. on Robotics and Automation*, 2013.

[6] T. Wada, S. Hirai, S. Kawamura, and N. Kamiji, "Robust manipulation of deformable objects by a simple pid feedback," in *Proc. of IEEE Int. Conf. on Robotics and Automation*, 2001, pp. 85–90.

[4] L. Sun, G. Aragon-Camarasa, S. Rogers, and J. P. Siebert, "Accurate garment surface analysis using an active stereo robot head with application to dual-arm flattening," in *Proc. of IEEE Int. Conf. on Robotics and Automation*, 2015, pp. 185–192.

[5] C. Elbrechter, R. Haschke, and H. Ritter, "Folding paper with anthropomorphic robot hands using real-time physics-based modeling," in *IEEE-RAS International Conference on Humanoid Robots*, 2012.

[7] D. Berenson, "Manipulation of deformable objects without modeling and simulating deformation," in *Proc. of IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, 2013, pp. 4525–4532.

[8] D. Navarro-Alarcón, H. Y, Y. L. Z. Wang, F. Zhong, T. Zhang, and P. Li, "An adaptable robot vision system performing manipulation actions with flexible objects," *IEEE Trans. on Robotics*, vol. 32, no. 2, pp. 429–441, 2016.

[9] K. Sugiman, M. Ohka, and M. A. bin Mat Jusoh, "A basic paper handling task experiment using tri-axial tactile data," *Procedia Computer Science*, vol. 105, pp. 270 – 275, 2017, 2016 IEEE International Symposium on Robotics and Intelligent Sensors, IRIS 2016, 17-20 December 2016, Tokyo, Japan. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1877050917302442

[10] L. Piegl and W. Tiller, *The NURBS Book*, 2nd ed. New York, NY, USA: Springer-Verlag, 1996.

[11] M. Thomas, R. Andreas, P. Johann, Z. Michael, and V. Markus, "Geometric data abstraction using b-splines for range image segmentation," in *Proc. of IEEE Int. Conf. on Robotics and Automation*, 2013, pp. 148–153.