MOTION PLANNING APPROACH OF A MULTI-FINGERED ROBOT FOR CARTON FOLDING OPERATIONS

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Abstract: The motion planning approach of a multi-fingered robot for carton flap folding operations has been newly developed. This approach considers the loci of the tool center point for carton flap folding operations. Also that considers the pushing or fixing points of the carton flap. This approach is calculated from the rotating angle for carton flap folding and the position of a robot finger tip in contact with the carton surface, using inverse kinematics. And this approach can be adapted to changes of a carton size or a folding position. In cases in which the carton flap is folded using this approach, the robot finger tip touches the carton surface without slipping and moves along circular continuous path. Therefore in case of the rectangular carton box folding, each robot finger moves in each 2.5-dimensional Cartesian frame. In this report, the proposed approach is verified using a prototype robot system. This prototype system consists of two pairs of the robot fingers and rotating mechanism for carton paper. Each finger has a 3-DOF SCARA type robot and a 1-DOF linear motion system. The testing carton boxes can be folded to the desired shape.

1 INTRODUCTION

An industrial robot for assembling is used in various fields, for example mechanical or electrical parts assembling and circuit board testing. Especially, in recent years, the industrial robots are used to handle soft products like a cloth or a paper (Buckingham, 1996). However, for the assembling of carton box which is the one of the soft products operations, the use of robot system is not yet popular.

The carton box is usually assembled with bending some carton flaps and lid, as shown in Figure 1. The carton box is assembled with bending on the various positions and to various directions, even like this simple rectangular shape. So in general, a carton is assembled using the special assembling machine (Kyoto-seisakusho, 2004). Also, the packaging carton is often desired the complex shape or folding procedure based on industrial or artistic design. Therefore, it is difficult to adapt the various kinds of the carton using the conventional assembling machine. So, the robot system with higher dexterity is needed.

For carton box assembling, the robot system with higher dexterity can be adapted to the various changes of carton size, shape or carton folding procedure. In other words, the many parameters of robot control have to be decided for the motion planning. These parameters are the folding or fixing positions, the folding angles with directions and the order of folding operations. Although it is difficult to teach the carton box assembling procedure using conventional robot system, that procedure has to be taught directly, using the "Direct teaching method" (Rosheim, 1994). When that parameter which is the position or the order of folding is changed using that conventional method, it is necessary to teach all motion again. So the conventional method is not useful. Also, some researches have shown the quantification method of a carton assembling procedure (Song, 2001, and Dubey, 2003). In that method, the robot motion locus was not considered with a folding procedure. So the robot motion control method had to be generated, using other procedure.

In this report, the simplified motion planning approach, which realizes the quantification of carton box assembling operations, is newly proposed. And the locus of robot motion is considered to this approach. And the structure of robot system and the

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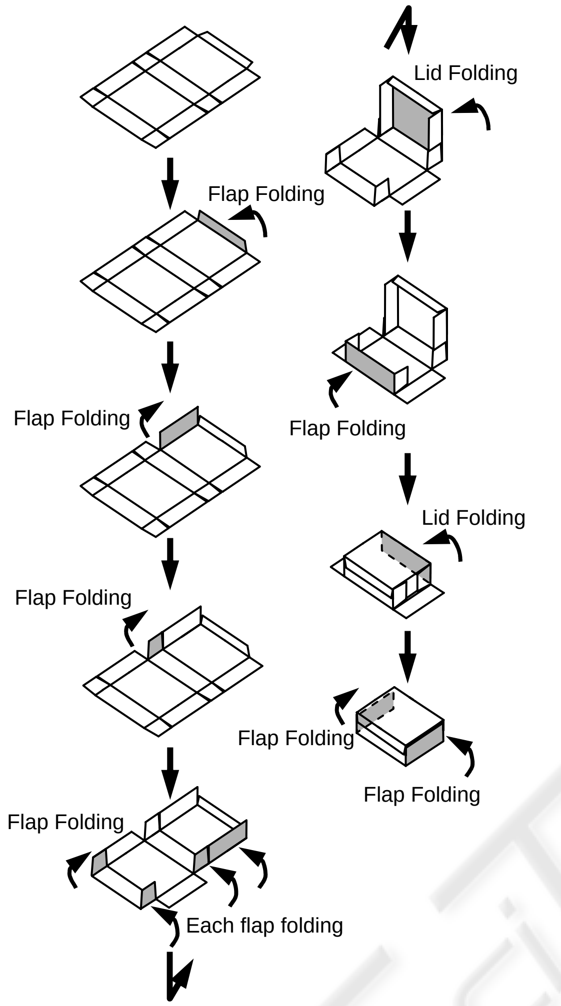


Figure 1: Example of an assembling procedure for rectangular carton box

robot motion loci are investigated. Then, the prototype robot system, which consists of two pairs of the robot fingers and the rotating mechanism of carton paper, is tested. Each finger has a SCARA type robot and a linear motion system. And the test carton boxes are folded to verify the validity of that proposed approach and the robot system.

2 MOTION PLANNING FOR CARTON FOLDING OPERATIONS

In general, a carton paper for the packaging box is made from a hard paper, which has similar plastic deformation characteristics like an aluminium bending. Also, it is different from a soft paper like a newspaper. In addition, the outline of that carton paper is usually blanked using cutting machine. And that is usually embossed with folding-lines. Then, the conventional special assembling machine assembles the carton paper which is fixed on the base plate using a vacuum-Chuck or a fixture. In this research, it is assumed that these conditions are applied to investigate the quantification of assembling carton box using the robot system.

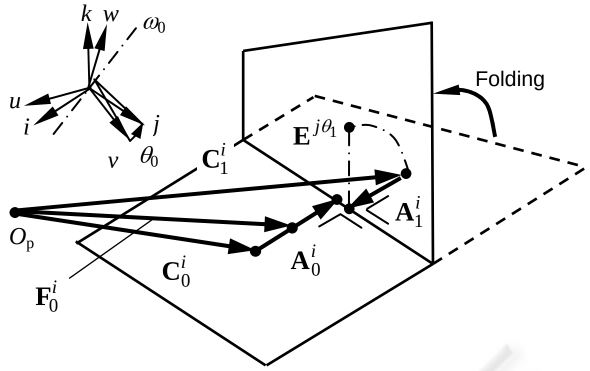


Figure 2: Geometry of a carton flap folding

When we assemble a carton box by folding, we often push the flap using our fingers which slip on that flap. However, the influences of a friction fluctuate by the environment and paper material etc.. In industrial fields for carton box assembling, we should eliminate an influence of that friction. Also the conventional special assembling machine can fold the carton paper without slipping. So it is assumed that the robot finger moves without slipping, too.

A motion of the carton flap folding on the arbitrary position and pose is defined using the polar vector analysis (Makino, 1998) as shown in Figure 2**.** That folding motion is replaced to the rotational motion around the arbitrary axis. And that motion includes the translational motion from origin point. Also for this operation, it is assumed that the carton flap is folded with pushing on the single point. The quantification of a carton paper folding operation which considers these assumptions is investigated.

At first, the initial orientation frame of a carton paper is converted using arbitrary axis rotation $\mathbf{E}^{-\omega_0\theta_0}$. In that figure, the rotating axis of a flap folding is rotated to the *j*-axis on the Cartesian frame. And the folding motion is replaced to the rotating motion of the center of gravity (CGr) of each flap. Each CGr on flap is calculated from each area. In that figure, each CGr is defined as the polar vector $\mathbf{C}^i_0$ and $\mathbf{C}^i_1$ from the origin point O_p. The CGr on a flap is defined as the tool center point (TCP) of a folding operation. In that figure, the pushing point conforms to the $\mathbf{C}^i_1$. Then the distances between the CGr and

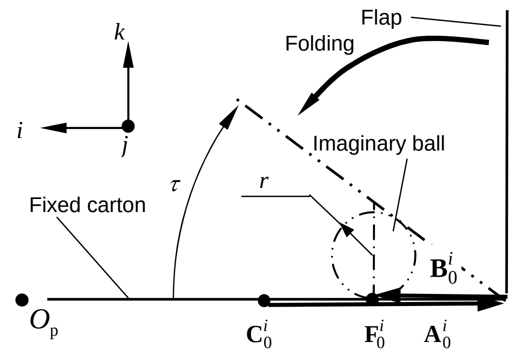


Figure 3: Geometry of a fixing point on carton flap

the folding-line are defined as $\mathbf{A}^i_0$ and $\mathbf{A}^i_1$. So the folding operation is shown as follows:

$$\mathbf{P}_1 = \mathbf{E}^{-\omega_0\theta_0}\left(\mathbf{C}_1^i + \mathbf{A}_1^i - \mathbf{E}^{j\theta_1}\mathbf{A}_1^i\right) \quad (1)$$

In case of a rectangular carton box assembling, each folding axis conforms to the principal axis of the Cartesian frame. And the end point of $\mathbf{A}^i_0$ conforms to the end point of $\mathbf{A}^i_1$. And each distance is same. So, the folding operation is simplified as follows:

$$\mathbf{P}_1 = \mathbf{C}_1^i + \mathbf{A}_1^i - \mathbf{E}^{j\theta_1}\mathbf{A}_1^i \quad (2)$$

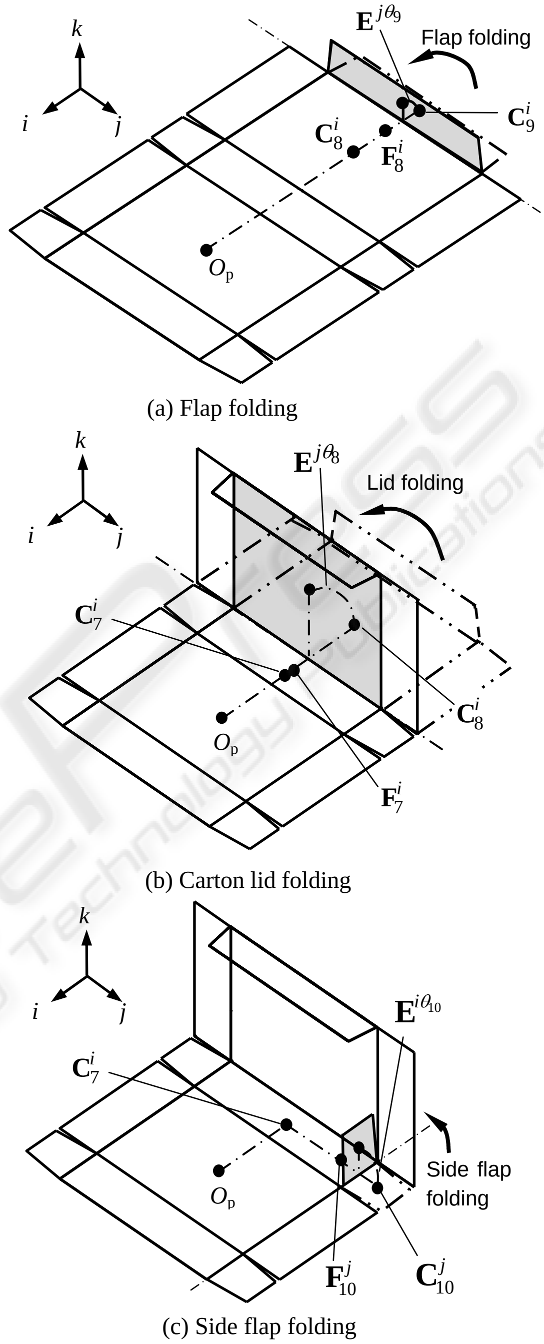
In cases in which the carton paper is folded without slipping, the fixing point for carton flap folding should be near the folding axis line as shown in Figure 3. And when the carton paper is folded along the embossed folding-line, the fixing point and the push point need to be symmetrical with respect to the folding-line, in general. And the fixing point holds a constant point during a folding operation. Also, these points are operated simultaneously. In other words, the two fingers need to co-operate to fold a carton flap.

In general, the carton flap is often folded over 90 degrees. When the robot fingers which are just like a human finger are used, the collision avoidance between the carton flap and the carton fixing robot finger has to be considered. So, it is assumed that the robot end-effector has a ball shape to simplify that procedure. This imaginary radius is defined as *r*. And τ is the supplemental angle of the flap folding as shown in Figure 3. And the fixing point is defined as follows:

$$\mathbf{F}_0 = \mathbf{E}^{-\omega_0\theta_0}\mathbf{F}_0^i = \mathbf{E}^{-\omega_0\theta_0}\left(\mathbf{C}_0^i + \mathbf{A}_0^i - \mathbf{B}_0^i\right) \quad (3)$$

$$\mathbf{B}_0^i = \left(\frac{r}{\tan\tau},\quad 0,\quad 0\right)^T \quad (4)$$

There are two procedures to approach this fixing point. To avoid the collision, each robot finger is approached from the same side as an initial finger position with respect to the carton paper. In case of the example which shows in Figure 3, the robot



(a) Flap folding

(b) Carton lid folding

(c) Side flap folding

Figure 4: Geometry of a fixed point on carton flap

finger for fixing approaches from left side. And the robot finger for folding approaches from right side. However, in case of the carton lid folding, the carton paper is folded over itself. There is the possibility that the collision between robot finger and carton lid will occur. In this case, the carton paper is fixed using a fixture or a vacuum-Chuck, instead of a fixing finger. This fixture is similar to the conventional special assembling machine. Using these definitions and conditions, all folding motions can be quantified.

Figure 4 shows the example of a carton flap folding, that carton box has a rectangular shape. The CGr of each flap is defined as $\mathbf{C}^m{}_\mathrm{n}$. And the carton fixing point using robot finger is defined as $\mathbf{F}^m{}_\mathrm{n}$. And for the flap folding, the rotation of each CGr on a, flap is defined as the rotation matrix $\mathbf{E}^{m\theta_n}$. Also the distance between CGr and folding-line is defined as the vector $\mathbf{A}^m{}_\mathrm{n}$. It is assumed that fixing point using vacuum-Chuck conforms to the origin point of a carton paper. The *m* shows the axis direction on the Cartesian frame, and the n shows the number of flap.

In case of a flap folding around the *j*-axis at 90 degrees as shown in Figure 4(a), the folding motion is defined as follows:

$$\mathbf{P}_1 = \mathbf{C}_9^i + \mathbf{A}_9^i - \mathbf{E}^{j\theta_9}\mathbf{A}_9^i \qquad (5)$$

And the fixing point is defined as the constant vector $\mathbf{F}^i{}_8$. And in case of a carton lid folding around the *j*-axis at 90degrees as shown in Figure 4(b), the folding motion is defined as follows:

$$\mathbf{P}_2 = \mathbf{C}_8^i + \mathbf{A}_8^i - \mathbf{E}^{j\theta_8}\mathbf{A}_8^i \qquad (6)$$

The fixing point is defined as the constant vector $\mathbf{F}^i{}_7$. Also, in case of a side flap folding around the *i*-axis at 90degrees as shown in Figure 4(c), the folding motion is defined as follows:

$$\mathbf{P}_3 = \mathbf{C}_{10}^j + \mathbf{A}_{10}^j - \mathbf{E}^{i\theta_{10}}\mathbf{A}_{10}^j \qquad (7)$$

In this case, the fixing point is shifted to the *j*-axis direction from $\mathbf{C}^i{}_7$. So the fixing point is defined as the constant vector $\mathbf{C}^i{}_7+\mathbf{F}^j{}_{10}$.

These vector equations show the folding motions and the operating procedure of carton assembling conforms to the execution order of these equations. It can be adapted to the change required by replacing the order of those equations. In other words, the motion planning approach of a carton assembling can be quantified using some equations and the order of those equations.

3 FINGER MOTION LOCI FOR CARTON FOLDING

The motion planning approach for carton box assembling has been proposed using a newly developed quantification approach of carton flap folding. Next, the loci of robot fingers are investigated using this approach.

The point touched with the TCP of robot finger rotates around the folding-line at the required angle. This motion locus has a circular locus, in any folding operations. And all motions of a robot finger are regarded as the planar motion. This plane is defined as "Folding-plane". Especially for

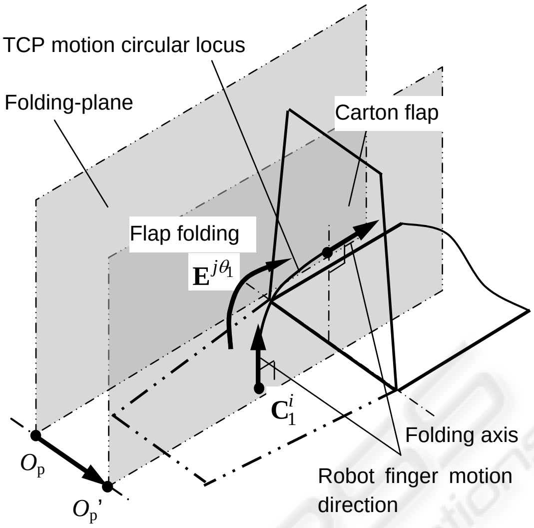


Figure 5: Geometry of a tool center point (TCP) motion and a "Folding-plane"

rectangular carton box assembling, the Folding-plane is moved linearly to include each TCP's locus, as shown in Figure 5. And in case that the carton flap folds around the arbitrary folding-line, that plane can conform to the motion locus by translating along some axes and by rotating around some axes. Then, the carton box is assembled by robot finger, the influence of a finger slip on a carton paper needs to eliminate as much as possible. So, the robot finger maintains the perpendicular pose to the carton flap during the folding operation. And the robot finger needs to avoid a collision at the other section of a carton paper. So it is the most simplified and useful approach to conform the pose of a robot finger tip and the tangent direction of a motion locus.

For the assembling of rectangular carton box as shown in Figure 1, the degree of freedom (DOF) of a robot finger needs the 2-DOF of the position and the 1-DOF of the pose on a Folding-plane. And the Folding-plane needs to include the motion locus. So the translation and the rotation mechanism on a robot base section are needed. However when that robot system consists of the robot finger without the rotating mechanism, that robot system needs two pairs of robot fingers to realize the same carton folding operation. These pairs should be assigned on the perpendicular location.

On the other hand, a robot finger fixes a carton paper to avoid the releasing of the carton paper from fixed base which is caused by the elastic deformation of that paper, during that paper fixed operation. A robot finger should avoid the collision with other sections of carton paper during that operation. So, the pose of the robot finger which fixes a carton paper needs to consider a folding

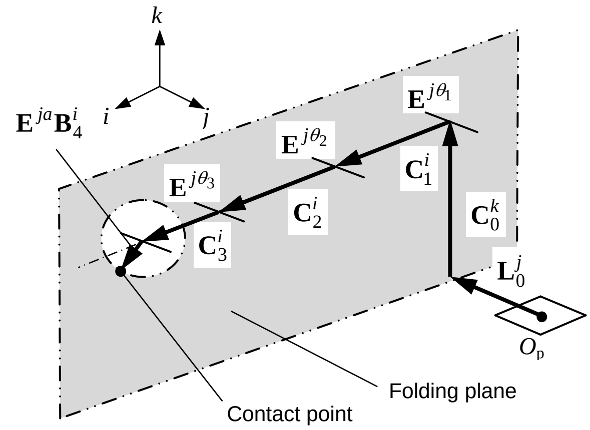


Figure 6: Vectors geometry of a robot finger

angle. In cases in which the robot finger folds the carton flap at 90 degrees, as shown in Figure 5, the robot finger with vertical pose of that finger tip can fix that carton paper.

However, the carton paper usually has the "Spring-Back" characteristic which is just like stainless-steel. So, the supplemental angle for the flap folding is defined as the 45-90degrees. And the robot end-effector has a ball shape. So, this condition and Equation (4) should be considered to the pose of the robot finger which fixes the carton paper. Also, to adapt to the various folding operations each robot finger has a same finger structure. And they are installed to make face to face location. Then, they are symmetrical with respect to the carton paper or working-area. And the Folding-plane of a folding motion conforms to that plane of a fixing motion. Both translational mechanisms move simultaneously.

4 KINEMATICS OF A ROBOT FINGER

Considering the proposed motion planning approach, and the robot finger motion on that Folding-plane, the robot finger consists of a 3-DOF serial link and a translational mechanism. On that Folding-plane, the SCARA robot folds a carton flap as shown in Figure 6. That robot finger has the simplest structure that is the minimum DOF. The position **P** and pose **E** of a robot finger are defined using the polar vector analysis shown as Equation 8 and 9.

$$\mathbf{P} = \mathbf{L}^j_0 + \mathbf{C}^k_0 + \mathbf{E}^{j\theta_1}\left(\mathbf{C}^i_1 + \mathbf{E}^{j\theta_2}\left(\mathbf{C}^i_2 + \mathbf{E}^{j\theta_3}\left(\mathbf{C}^i_3 + \mathbf{E}^{j\alpha}\mathbf{B}^i_4\right)\right)\right) \quad (8)$$

$$\mathbf{E} = \mathbf{E}^{j\theta_1}\mathbf{E}^{j\theta_2}\mathbf{E}^{j\theta_3}\mathbf{E}^{j\alpha} \quad (9)$$

Each linkage length is defined as $\mathbf{C}^k{}_0$, $\mathbf{C}^i{}_1$, $\mathbf{C}^i{}_2$ and $\mathbf{C}^i{}_3$. Also each robot joint rotation is defined as $\mathbf{E}^{j\theta_1}$, $\mathbf{E}^{j\theta_2}$ and $\mathbf{E}^{j\theta_3}$. The origin point O_p conforms to the start point of the translational motion $\mathbf{L}^j{}_0$. The robot finger tip has a spherical shape. When that robot finger folds a carton flap, the contact point is on the extended vector of the $\mathbf{C}^i{}_3$. And in cases in which the robot finger fixes a carton paper, this finger tip has an inclined pose at τ'. In other words, the contact point on each finger tip is different. So the contact point from a finger center is defined as $\mathbf{E}^{j\alpha}\mathbf{B}^i{}_4$. Also the spherical shape radius of a robot finger is defined as $\mathbf{B}^i{}_4$. In case of a folding operation, the contact point is on the extended vector of the $\mathbf{C}^i{}_3$, it is α=0. And in case of a carton fixed operation, that is $\alpha=\tau'$.

The folding operation is independent of the translational operation for the Folding-plane. So, the kinematics of that robot system can be regarded as the two individual analyses; the one is the robot finger section and the other is the translational mechanism section. For the forward and inverse kinematics of the robot finger as shown Figure 6, the 3-DOF type SCARA robot and the 1-DOF linear motion mechanism are analyzed. In general, the SCARA robot has two solutions which are the "Right hand solution" and the "Left hand solution" (Furuya et al., 1983). The robot finger for the carton fixing operation usually uses the opposite solution to that folding operation. And the solution doesn't change during the folding or fixing operation.

In cases in which the carton flap folds on the arbitrary position and the pose, the carton paper rotates to conform that folding-line to the motion direction of that translational mechanism; the position and pose shown as Equation 8 and 9, rotate around the arbitrary axis. In case that carton paper is rotated around *k*-axis of the Cartesian frame that is popular for carton folding, the position and posture of a robot finger are changed to the **P′** and **E′**, shown as Equation 10 and 11.

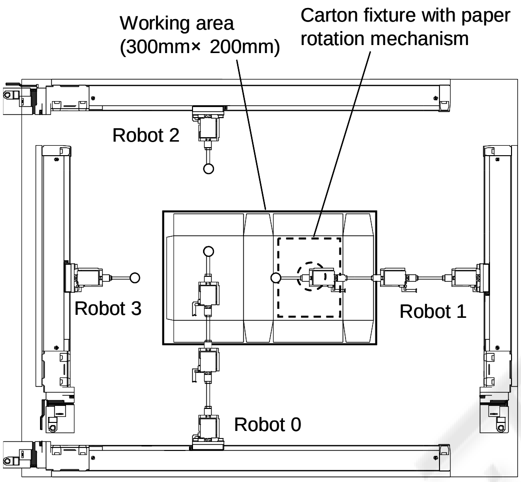
$$\mathbf{P}' = \mathbf{E}^{k\lambda}\mathbf{P} \quad (10)$$

$$\mathbf{E}' = \mathbf{E}^{k\lambda}\mathbf{E} \quad (11)$$

5 PROTOTYPE ROBOT SYSTEM

Considering the proposed motion planning approach for carton box assembling and the circular motion for robot fingers, the prototype of a robot system has been made. That system consists of two pairs of the 3-DOF SCARA robot fingers with the 1-DOF translational motion mechanism and rotating mechanism of carton paper, as shown in Figure 7(a). Each robot finger moves simultaneously in a single working area as shown in Figure 7(b). Each finger is installed to make face to face location. And each

(a) Structure



(b) Robot assignment and working area

Figure 7: The multi-fingered robot system with carton paper rotating mechanism

pair of that finger is placed to make perpendicular location. Also, each pair of translational motion mechanism which is installed to make parallel location moves simultaneously, too. The rotating mechanism around *k*-axis on Cartesian frame with the vacuum-Chuck which fixes a carton paper on carton base section is installed under that working area. Therefore, we can test two approaches using this prototype system. The one is the approach of two pairs of robot fingers, and another is the approach of a pair of robot fingers with a rotating mechanism.

Each finger has small and light-weight joint actuators which consist of an AC servo-motor, encoder and Harmonic-drive reducer (Umetsu et.al.1993). And that size is 30mm diameter with length 30mm and the weight is the 70gf. That actuator uses to the rotating mechanism for carton paper, too. Then, each link of a robot finger has a cylindrical shape made from steel to minimize a collision at the other section of carton paper. That

Table 1: Specifications of a prototype robot system

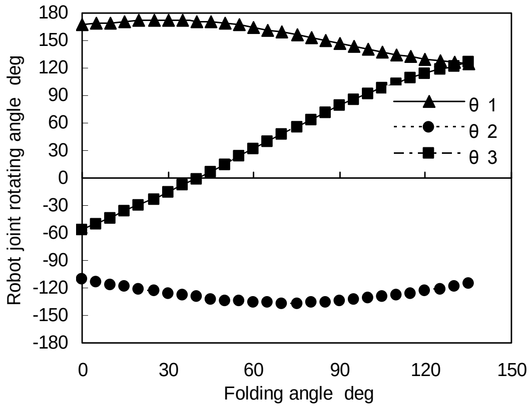
Items	Values
Robot finger type	3-DOF SCARA type
Finger 1st and 2nd link	130mm
Finger 3rd link	50mm
Finger actuator	Hybrid motor-reducer type
Max. speed	22.5rpm
Motor	AC servo-motor, 1.4W
Encoder	128p/r
Reducer	i: 1/80, Harmonic Drive
Tool head diameter	6.5mm
Tool head material	Butadiene rubber
Rotating mechanism	*k*-axis rotating
Linear actuator	Ball screw type, lead 8.0mm
Max. speed	600mm/s
Motor	AC servo motor, 30W
Encoder	2000p/r
Stroke	Robot0, 2: 400mm, Robot1. 3: 200mm

diameter is the 4mm; it is smaller than the joint diameter. Also, the finger tip has a ball shape which is made from the Butadiene rubber to eliminate the slipping on a carton paper. That diameter is the 6.5mm. And also the translational mechanism consists of a ball screw with an AC servo-motor and a linear guide slide system (THK, 2004). The specifications of these actuators are shown in Table 1. Furthermore, all axes of the robot system are controlled synchronously by the command PC. That control data are communicated using a parallel communication protocol.

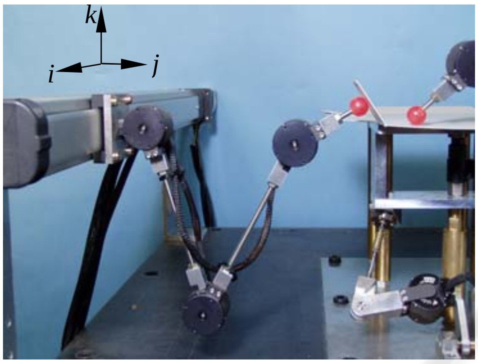
6 VERIFICATION USING THE PROTOTYPE ROBOT SYSTEM

The rectangular carton box as shown in Figure 1 has been assembled to verify the usefulness for proposed motion planning approach and robot motion. It is proved that the folding procedures for carton flaps can be quantified. And the robot fingers, the translational mechanisms and the rotating mechanism can move simultaneously, which are based on the proposed approach. Also, it is proved that the carton box can be assembled.

In case of the rectangular carton box has twelve folding operations, the mean Cycle time for carton folding is 10.5 seconds. It is because that maximum speed of a robot finger actuator is limited to 22.5rpm. When it is required that robot finger moves more quickly, the actuator of that robot finger should be improved to adapt to higher rotation. Figure 8(a) shows the relations of each robot finger joint angle with the sample motion for the carton flap folding at



(a) Relation between the folding angle and each robot finger joint angle to 135degrees



(b) Robot finger motion at the folding angle 60 degrees

(c) Folding motion for “Boy-scouts tent” type carton box

Figure 8: The test motion of a carton flap folding

60 degrees. Each joint angle of a robot finger for folding operation is shown in Figure 8(b). Considering the "Spring-back" characteristic, that carton paper is folded to 135 degrees. Also this proposed motion planning approach using robot system doesn’t need a force control of a carton folding. It is similar to the conventional special assembling machine.

Then, this robot system based on proposed approach, can deal with the complex shape of the carton box like “Boy-scouts tent” in which the conventional special assembling machine cannot be adapted as shown in Figure 8(c). And using proposed approach, the robot motion can be taught by off-line. It isn't necessary to move each robot finger to teach like a conventional robot system. It is very useful to reducing the set-up time.

In future work, to realize the other operation for carton packaging, we will investigate the grasping procedure of papers or products with force control.

7 CONCLUSIONS

For carton box assembling, the carton flap folding procedure which is quantified to simplify the motion planning approach has been newly proposed. This procedure considers the loci of the center of gravity of carton flaps and the robot motion. Using the multi-fingered prototype robot system, we have verified the proposed approach; it is proved that the folding procedures of the carton flaps can be quantified. Also the carton box can be assembled. For the sample assembling rectangular carton box, the mean "Tact-time" for a carton flap folding is the 10.5 seconds.

In future work, to realize the work-handling of the carton packaging that is different from the carton flap folding, we will develop the approach of grasping with a force control.

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