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Fault-tolerant Mating Process of Electric Connectors in Robotic Wiring Harness Assembly Systems *

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***Abstract* - To obtain a secured mating of electric connectors is one of the most important steps in a robotic wiring harness assembly system. Although there are plentiful results about complex peg-in-hole assembly problems, little work has been done with respect to this special issue. In many cases, mating connectors can be regarded as a hole search process of a multiple hole-in-peg problem. Because various faults might occur during the search, a reliable error recovery strategy is necessary in the mating task. In this paper, we model possible faults as "trap regions" in the configure space (C-space) of the assembly. Fault isolation methods are obtained from elaborated force analyses as well. Based on these fault isolation results, error recovery strategies are proposed according to the fault models. A fault-tolerant mating of electric connectors can then be achieved. The effectiveness of the methods is finally confirmed by experiments.**

Index Terms - robotic wiring harness assembly, fault detection and isolation, error recovery, configure space.

I. INTRODUCTION

To implement a robotic wiring harness assembly system, researchers have to find a way to obtain a secured mating of electric connectors by the assembly robot. Although there are plentiful results about complex peg-in-hole assembly problems, little work has been done with respect to this special issue.

For some class of assemblies, focus shifts from the dynamics of the assembly to the problem of searching for alignment if the relative position uncertainty of the assembling parts exceed the assembly clearance. The most powerful sensor to improve the alignment might be the vision systems. Whereas, unfortunately many high precision cameras, which may be regarded as a rough approximation of human eyes, have not sufficient resolution to cope with very tiny robot move. In the case of mating electric connectors, both the assembly clearance and the size of connectors are very small. In fact the assembly clearance of connector mating is typically less than 0.5 mm, while cameras can only offer a resolution greater than 1mm. Furthermore, sometimes machine vision is not helpful because connectors are fixed in special places, e.g. the rear face of a printed circuit board. Therefore the connector mating problem involved with position uncertainty has to rely on search strategy.

Various blind search strategies are studied for peg-in-hole assemblies with position uncertainty in [1, 2]. Unfortunately, these strategies cannot be applied directly to our case because there are some differences between mating electric connectors and normal single peg-in-hole assembly problem. First, the mating process of connectors is usually a multiple peg-in-hole problem. Second, the area of the contact surface is so small that search process is prone to suffering from *deflected alignment* and *losing contact*, which result in the halt of searching because the stop condition is also satisfied. This will be further analysed in the following paragraphs. Since it is not easy to avoid such wrong ending states of the search strategy, error recovery approaches are required during mating connectors.

In a robotic assembly system, error recovery approaches are often necessary due to inevitable errors caused by unpredictable situations. The field of error recovery is often divided into three subfields, *fault detection*, *isolation* and *error recovery* [3]. The main purpose of this study is to develop a fault-tolerant assembly strategy for mating electric connectors based on some error recovery approaches. We regard all possible wrong ending states of the search strategy as faults. Both successful and faulty states are modelled as regions in the configure space (C-space) of the assembly in section II. Faults are detected and isolated by appropriate compliant motions and force analyses, which are illustrated in section III. The corresponding recovery strategies are investigated in section IV. Finally, all the methods are confirmed by the experiments. The experimental results are shown in section V.

II. MODELING FOR SUCCESSFUL AND FAULTY SEARCH ENDING

A. *Prerequisites*

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In view of the variety of electric connectors that we may meet in different tasks, it is necessary to establish a model database comprised of all possible cases. Despite the characteristics of connectors differ from each other, their underlying frictional force models are similar during a mating process. Therefore, instead of enumerating all possible cases, we investigate a special type of connectors to exemplify the whole procedure. The typical connectors studied in this paper are illustrated in Fig. 1.

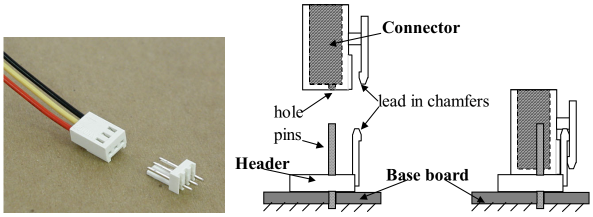


Fig. 1. A pair of typical 3-pin connectors

There are two prerequisites of the assembly task in our study. First, the tilt error between the end effector and the base board is very small. This kind of error is evaluated by the angle θ_{be} between two z-axes of frame $\{F_e\}$ and $\{F_b\}$, which is depicted by Fig. 2. A small tilt error ensures that the research focus shifts from the dynamics of the assembly to the problem of searching for alignment.

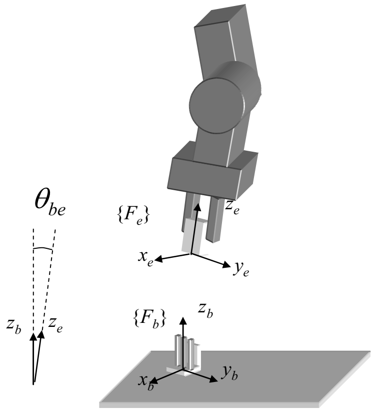


Fig. 2. The tilt error between the end effector and the base board

In this case, the mating process of electric connectors is actually a multiple hole-in-peg assembly problem because the end effector is a female connector. From the point of view of the hole search strategy, this kind of assembly is similar to a rectangular hole-in-peg problem.

The second prerequisite of this study is that the initial translational and rotational errors on the contact surface are small and bounded. This assumption guarantees that there is a secure contact between two connectors just before the search strategy starts. It can also exclude the occurrence of some extreme faulty cases, which are analysed detailedly in the following. The equivalent multiple hole-in-peg problem and the two sorts of initial position errors are given in Fig. 3.

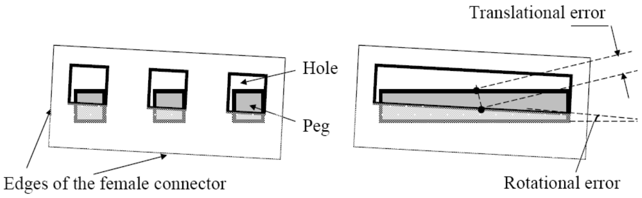


Fig. 3. The equivalent multiple hole-in-peg problem and two sorts of initial position errors

B. Success region in the C-space

To facilitate the further analysis, we model both successful and faulty search ending states in the C-space of the assembly. Here we are concerned about the similar rectangular hole-in-peg problem. C-space is referred to as the 3D space given by the position of the rectangular hole center $P:(\Delta X, \Delta Y)$ and the orientation of the female connector $\Delta\theta$, which is shown by Fig. 4. Note that the original point O is the center of the rectangular peg.

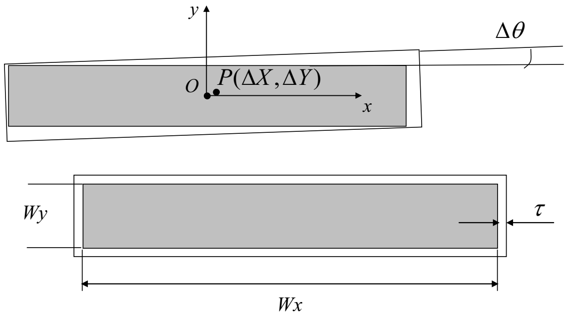


Fig. 4. The representation of C-space of the similar rectangular hole-in-peg assembly and the clearance of assembly

As Miura did in [4], we define the success region as flows.

Definition 1. The success *region is referred to as the free area of the female connector in the C-space of the assembly.*

Obviously this region is determined by the clearance τ. Comparing to the size of connectors, the volume of success region is very small. If a search process ends with point P locating in the success region, then it is said to be a successful search ending state. According to our assumptions, a successful mating of connectors will be obtained after the search strategy ends successfully. The shape of a success region is shown in Fig. 5. It should be pointed out that the shape and volume of success region may be used to determine parameters of the search strategy. Chhatpar shows the procedure of how to determine the pitch of a spiral search with the assembly clearance [1]. Whereas he only investigated the case of single circular peg-in-hole assembly. In this study, a spiral search algorithm together with some rotation about the tool axis is assumed to implement the hole search for the rectangular hole-in-peg assembly. This method is extensively applied in the 'puzzle' assembly [5]. We don't give the detail of how to determine the parameters of the search strategy because it is not our research focus. In addition, it is just a simple extension to 3D C-space of the work in [1].

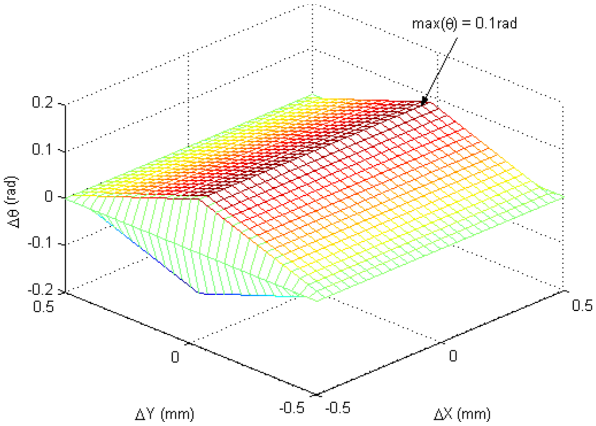


Fig. 5. Success region in the C-space when $\tau = 0.5, W_x = 10, W_y = 1$

C. *Trap regions in the C-space*

The stop condition of the search strategy is the significant decrease of the force in the direction perpendicular to the base board. Due to the characteristics of connector mating, search strategy might stop at many possible positions, where the stop condition could be satisfied. Then we can give the definition of trap regions as follows.

Definition 2. Trap regions are referred to as those regions where the search stop condition is satisfied in the C-space of the assembly, except the success region.

If the search strategy ends in some trap region, a mating error must occur as the results. To realize error recovery approaches in the assembly, all possible trap regions should be considered. As we mentioned above, the search strategy is prone to suffering from some misalignments because the mating process is actually a multiple hole-in-peg assembly problem with a small search area. We divide these misalignments into two classes, '*deflected alignments*' and '*losing contact*', which are depicted by Fig. 6 and Fig. 7.

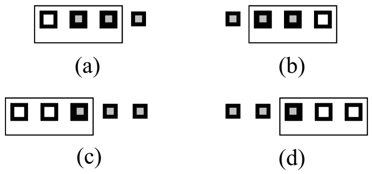


Fig. 6. Class 1: Deflected alignments

In terms of the second prerequisite, the initial position errors are small so that extreme misalignments, such as case (c), (d) in Fig. 6 and case (b), (c) in Fig. 7, won't occur in this study. In reality, the small initial position errors can be achieved by using a rough vision system easily. Therefore, it is adequate to only investigate part of the faulty cases list above. All the concerned trap regions can also be represented in the C-space, which are illustrated in Fig. 8.

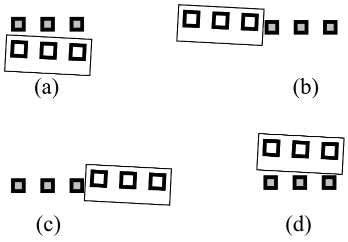


Fig. 7. Class 2: Losing contact

As we can see from Fig. 8, distances between success region and trap regions are not large enough to guarantee the initial search position locates near the success region, if there are position uncertainties. Thus, it has every possibility that a search process might end in a certain trap region. As a result, mating error would happen. Hence the key problem is how to recover from the undesired search ending states.

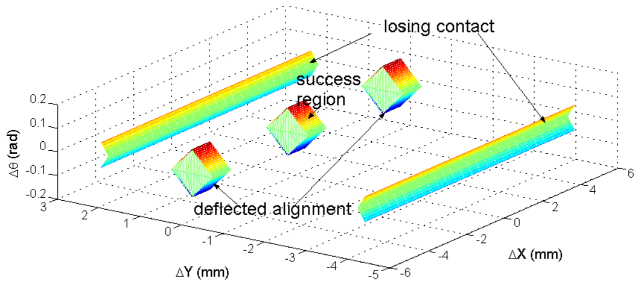


Fig. 8. Success region and trap regions in the C-space for the typical 3-pin connectors

III. FAULT DETECTION AND ISOLATION

The first step of implementing a recovery approach is the fault detection and isolation. The previous section provides models for both successful and faulty hole search. It is apparent that we cannot immediately identify in which region the search process has entered. A trial of mating will help us isolate the current fault effectively. In our former research, an online robust fault detection algorithm has been proposed for the mating process of electric connectors [6]. The isolation methods are discussed as follows.

First, the two classes of trap regions can be separated easily by some compliant motions of end effector. In the view of motion DOFs [7], if we insert the connector a little after the search process entered a trap region belonging to 'deflected alignment' class, the motion DOF of the manipulator will be transformed into a constraining DOF. On the other hand, if we insert the connector a little after the search process entered a trap region belonging to 'losing contact' class, the motion DOF will be a detaching DOF. Usually, manipulator has more freedoms when its motion DOF is a detaching DOF. Thus, these two classes of trap regions can be separated by trials of compliant motions in the detaching directions easily.

Furthermore, different cases in the same class of trap regions should be identified because the corresponding recovery approaches are different. For example, recovery of a left-side deflected alignment is obviously different from that of a right-side deflected alignment. Both of the two classes of trap regions are investigated in the following.

A. 'Deflected alignment' trap regions

So far, plentiful methods have been reported about identifying contact state from force sensor signals. These methods include model-based technologies [8], intelligent pattern recognition skills [9] and so on. Whereas it is still an open problem to identify contact state of objects with complex structures. In our case, contact states are difficult to be analyzed because there are too many possible contact points during mating. These possibilities are brought by special shapes of connectors and multiple pegs and holes. On the other hand, only a simple two-classes pattern recognition is required to classify different cases in a same class of trap regions.

We realize our identification method from careful force analysis. It should be pointed out that this analysis method can be easily extended to other connectors with more pins although only a typical 3-pin connectors are investigated here. An example of the force analysis is shown by Fig. 9.

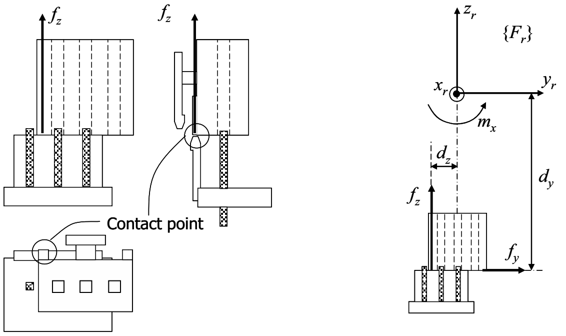


Fig. 9. Force/moment analysis of mating when the search strategy ends in a right-side 'deflected alignment' trap region

After the search strategy ends in a right-side 'deflected alignment' trap region, a trial of mating will result in a contact state, whose full view is given by Fig. 9. Owing to the special structure of the female connector, there is a contact point between the convex part of the female connector and the rear part of the header. From the experimental observations, the z-axial contact force mainly comes from this contact point, which is denoted by f_z. $\{F_r\}$ denotes the frame of the wrist of the robot arm where the force sensor is mounted. In the analysis, we are concerned about the moment m_x, which exhibits distinct characteristics in the two different subclasses of deflected alignments. The moment m_x is consisted of two main components, which are caused by the y-axial force f_y and the z-axial force f_z respectively. The moment m_x can be computed by

$$m_x = f_y \cdot d_y - f_z \cdot d_z \,. \tag{1}$$

Note that even there is no certain contact point shown in Fig. 9, the arm of force d_z of the resultant z-axial force f_z will be located in the negative direction of the y_r axis. Similarly, in the case of left-side deflected alignment, the equation of moment m_x can be given by

$$m_x = f_y \cdot d_y + f_z \cdot d_z \,. \tag{2}$$

Because all the forces and moments can be measured online, the relation among f_y, f_z and m_x can be formulized by

$$\hat{m}_x = d_y \cdot f_y + d_z \cdot f_z \tag{3}$$

where $\hat{m}_x$ denotes the estimated moment m_x. Given a set of n training samples $T = \{f_y(k), f_z(k), m_x(k)\}$, coefficients d_y and d_z are typically determined by the least square estimation (LSE) method through minimizing the performance

$$J = \sum_{k=1}^{n} \left(m_x(k) - \hat{m}_x(k)\right)^2 \,. \tag{4}$$

Note that we don't need to control f_y to a small value, because this information is required in the LSE method. Some experimental results are given in section V.

B. 'Losing contact' trap regions

In this case, the isolation task is fairly simple because different classes of trap regions produce different detachable directions after a trial of mating. Thus the two subclasses of 'losing contact' trap regions, which are illustrated by Fig. 7 (a) and (d), can be easily identified through some trials of compliant motions.

IV. ERROR RECOVERY APPROACHES

After the faulty case is isolated, the corresponding error recovery approach will be applied. These approaches are also discussed in two cases as aforementioned.

A. Recovery from 'deflected alignment'

A simple recovery approach is implemented by employing the known size information of connectors. Apparently, the most useful size information is the distance between the centers of two neighbouring holes. The main idea is given by Fig. 10.

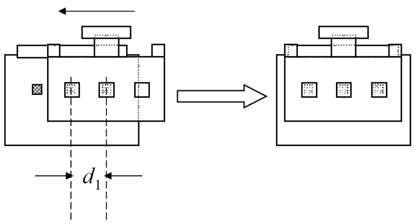


Fig. 10. Recovery from a right-side 'deflected alignment' trap region

As we can see, if the distance d_1 is accurately known, the recovery will be achieved within finite steps, as long as the number of holes is finite. The recovery procedure can be also explained in the C-space. d_1 is actually the distance of the centers of neighbouring regions (except the regions of 'losing contact'). Therefore, the position before mating can be easily adjusted only if we know the location (left or right) of the success region.

B. *Recovery from 'losing contact'*

The recovery in this case is more complicated than deflected alignments because the size information is more difficult to be exploited. We propose a series of motions to realize the recovery, which are depicted by Fig. 11.

As shown in Fig. 11, after a slight compliant rotating motion, the size information d_2 is used to guide an adjustment of the insertion position just before mating. The advance rotating motion reduces the rotation error to zero, which makes it possible to use d_2 in the recovery. This can also be explained in the C-space. The function of the rotating motion is to let the center coordinates of the female connector locate at the edge of the 'losing contact' trap region where $\Delta\theta = 0$. The distance between the edge and the center of the success region is d_2 .

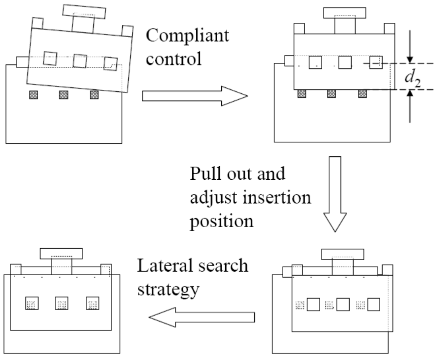


Fig. 11. Recovery from a trap region belonging to the class of 'losing contact '

Some comments should be given about this recovery procedure. First, the compliant rotating motion suffers from the unknown correct rotation direction (clockwise or counter-clockwise). This shortcoming can be overcome by a trial of rotation with a small angle in both directions. If a contact state transition is detected in a trial, then the corresponding direction must be the right one. Second, the final step is a lateral search, which may leads to a wrong search ending state in a 'deflected alignment' trap region. If so, the recovery method proposed in the previous subsection should be applied to guarantee a successful mating.

C. *Summary of the whole recovery approach*

As the main result of this study, we depicted the flowchart of the whole fault-tolerant mating strategy by Fig. 12.

At the beginning of the mating strategy, the female connector held by grippers locates at an initial position above the header. Once the mating process starts, the robot arm moves close to the header until a secure contact occurs with a constant upward force. Note that the contact between the connector and header is guaranteed by the basic assumptions given in the subsection II.A.

After the connector and header come into contact, the hole search strategy discussed in subsection II.B is performed. It should be indicated that no timeout scheme is needed during the search strategy. It is because that the search process will eventually enter either the success region or some trap region within finite time, owing to the small area of the contact surface.

Once the search process stops, a trial of insertion is performed. The insertion is monitored by an online robust fault detection module presented in [6]. If there are no faults until the stop condition of mating is satisfied, then a successful mating is obtained. Otherwise, the program enters the fault isolation module.

Fault isolation methods given in section III are applied to distinguish which trap region the previous search process has entered. Next, corresponding recovery approach is employed to make an adjustment to the initial position. A new trial of mating process is then ready. Timeout scheme is added into the loop in order to avoid the deadlock caused by unexpected faults.

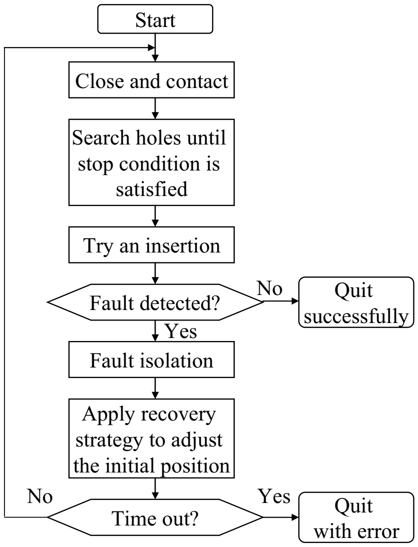


Fig. 12. Flowchart of the fault-tolerant connector mating strategy

V. EXPERIMENTAL RESULTS

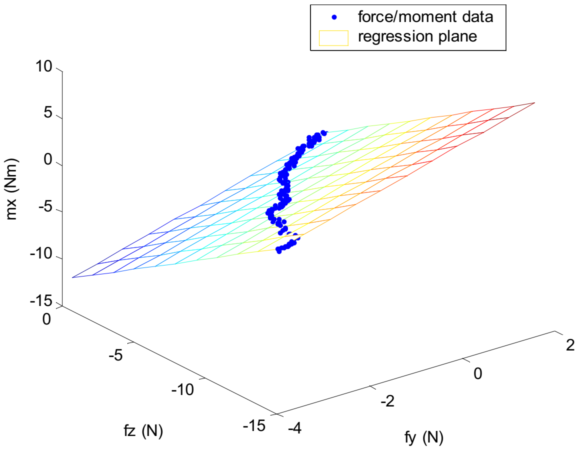
A. *Experimental condition*

The mating process of a type of 3-pin connectors was investigated by experiments. A 6-DOF RV-1A industrial robot from Mitsubishi was employed to assemble connectors. Data were acquired from the force sensor and the position sensors built in the wrist and joints of the robot. A base board installed with some headers was fixed in front of the robot.

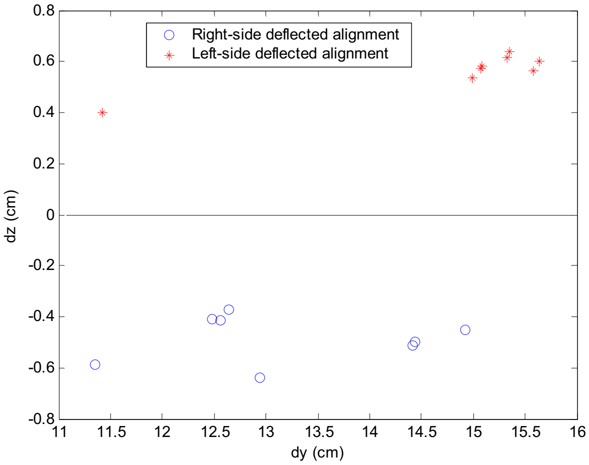
B. *Evaluation of the Fault Isolation Method*

As pointed out in section III, the identification task of 'deflected alignment' trap region is nontrivial. To evaluate the effectiveness of proposed isolation method, 10 trials were performed for two subclasses of deflected alignment separately. Displacement and force value were recorded after the upward impedance crossed a lower limit. Once a fault was detected by the online fault detection module, the arm of force d_z was then estimated by applying LSE method to Eq. (3).

A sample of the result of LSE is shown in Fig. 13, as well as the distribution of estimated d_z of all experiment trials. Obviously, the sign of d_z is a significant feature to distinguish the two subclasses of 'deflected alignment' faults, which proves the conclusion of force analysis in section III.



(a) A sample of LSE result



(b) Distribution of estimated arms of force

Fig. 13. Fault isolation for 'deflected alignment' trap regions

C. *Evaluation of the Fault-Tolerant Mating Strategy*

We simulated all possible faulty cases by preset various initial position errors before the mating process. The initial rotation error is supposed to be less than 5° and position error less than 5mm. Considering there are chamfers on both pegs (pins) and holes, the assembly clearance is about 0.5mm.

In over 10 trials for every faulty case, we had 100% success of recovery in a short time. The experimental results show satisfied performance of the proposed recovery strategies.

VI. CONCLUSION

Unlike common peg-in-hole assembly problems, mating electric connectors is prone to suffering from misalignments if there is initial position uncertainty. In this study, a fault-tolerant assembly strategy is proposed to guarantee a secured mating for connectors even faults occurred. There are two main contributions in this paper:

1. Both successful and possible faulty search ending states are clarified and modeled in the C-space of assembly as different regions. Mating faults comprises all these faulty ending states.

2. Error recovery strategies are obtained for different faults by using a-prior known size information of connectors and appropriate compliant motions.

To realize a practical robotic wiring harness assembly system, our future efforts would be made to develop error recovery strategies in handling deformable flexible objects (DLOs) by the robot.

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