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Robotized Assembly of a Wire Harness in Car Production Line

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Abstract— **This paper addresses an engineering attempt of utilizing multiple robot arms in assemblies of deformable parts. The developed robot system simulates a practically existing assembly process in an automobile plant where wrapped cables (wire harness) have to be fixed on the body of a car. This operation has been performed by skilled workers and is considered to be difficult for automatization. During the development of the system, solutions are proposed for various engineering problems confronted. The problems are all due to the deformable properties of a wire harness. Many of them are general for other operations involved with deformable objects. The proposed methods in the research are verified by a successful demonstration of wire harness assembly under a condition similar to a real plant.**

I. INTRODUCTION

In order to satisfy the requirements for inceasing efficiency and minimizing labor cost, robotized assemblies have been realized in many fields of industry. In automobile plants, multi-degree robot arms are employed in various assembly processes. With the employment of the robots, many dexterous tasks have been automatized. These tasks include painting, welding and nailing etc. They had been relied on operation of skilled workers. However, even with the advance of automation technology, there are still some processes which can not be completed without human involved. The task of assembling cables into car body is among the several difficult tasks for robotization. Thus, recently, robotization of the assembly processes involving deformable parts is regarded as the key for further improvement in manufacturing efficiency and cost reduction. This research is launched by a government funded organization of Japan. It contributes to explore the technologies necessary for robotized assembly of deformable objects necessary in industry. Robotized cable assembly in an automobile plant is considered in this paper.

There have been some research work concerned with problems in handling wire like deformable objects (linear deformable objects) using robot arms. Many of them concentrated on treatment of topological transition of linear deformable objects exhibited as knotting, loop generating.

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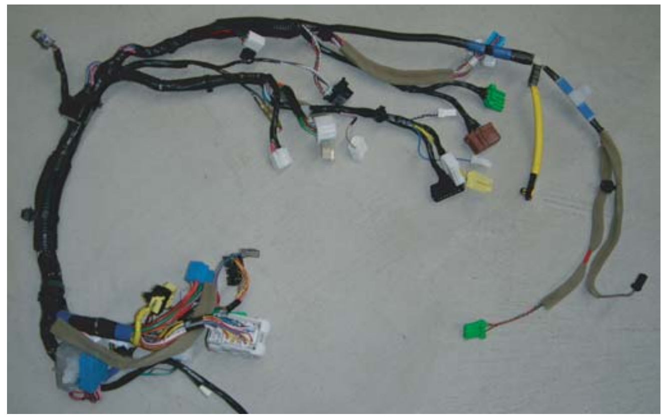

Fig. 1. A wire harness used in a car.

They apply knot theory in mathematics to describe the topological transition of the crossing state. In these approaches, a linear deformable object in three dimension is firstly projected into a two dimensional plane. The projection in the plane which is demonstrated as crossed curves can be well described and treated using knot theory. In [1], a task planning method for knotting/unknotting linear deformable objects is proposed. Four fundamental operations (among them three are equivalent to Reidemeister moves) are defined as the primitive motions for completing a transition between any two wire crossing states. It is proved in this paper that any knotting/unknotting operation which can be decomposed into a sequential topological transitions can be achieved by employing a sequential combination of the four primitive operations. The approach is verified by knotting a rope placed on a desk. In [2], the state of knot is described using invariants of knots instead of Reidemeister move. Based on this description, a similar topology based planning method is proposed. In this paper, knotting of a rope in three dimension is implemented by using two robot arms. Among the two robot arms, one holds the end segment of the rope and the other completes knotting. In this research, in order to measure the three dimensional position of the rope, stereo vision is employed.

In above two research [1], [2], knotting is achieved by using a gripper like robot hand in which only a gripping DOF is possible. While in [3], knotting is considered to

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be achieved by employing a high-speed multi-fingered hand. Following a similar approach based on topological transition model, the motion sequence necessary for knotting a rope is generated. Because of the usage of multi-fingered hand, some operations like ”rope permutation” become possible even with one robot hand. Here ”rope permutation” refers to the operation of exchanging the places of two ropes through twisting them while pinching the ropes between two fingers. The additional DOF introduces new skills for wire handling. These skills are reflected as new primitive operations for wire handling. Implementation of ”rope permutation” in [3] requires employment of force torque sensor mounted in the fingers.

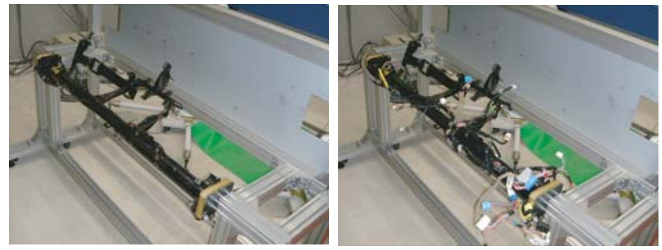
There are also some works contributing to solve the problems of deformable object handling applied in assembly line in factories. Maruyama et al propose a wire handling system used in assembly line of electric parts, where a robot arm is used to insert signal cables into clasps [4]. This work is characterized by the wire measurement system. In this system, a multi-planar laser light projector is configured with a camera in stereo vision style. Since the laser beam emitted from the projector is well positioned, the matching between projection of wires from laser beam and that in camera plane becomes easy. Axel et al. [5] work on similar problem with us. They also consider to realize robotized car cabling. In their research, they have proposed a method for detecting contact state of a cable with environment from 2-D image. With the information from the contact analysis and optical sensor, gripping of car cables is demonstrated.

This research is an engineering attempt on a robotized wire handling system which is expected to be realizable in a practical automobile assembly line. Therefore all the conditions employed in the experiments are referenced from a real automobile plant. As the first step of a research aiming to realize a reliable and realizable cabling robots for future implementation in plants, the experiment described in the paper play the role of demonstrating technical feasibility and exploring necessary technologies for further development.

This paper is organized as follows. Section I, II present the motivation of the paper and describe the task to be automatized respectively. In section III, our proposal to the problem is presented. Its effectiveness is verified by experiments described in IV. The paper ends with concluding remarks in section V.

II. Task description of a wire harness assembly

The object of this study is a practical manufacturing process in an automobile assembly line. In this process, a worker has to complete to fix a wire harness to the instrument panel frame (a parts in front of a car for hosting various meters, car air conditioner etc. Fig.2(a)). Here a wire harness refers to a string of cables wrapped by electrical tapes as shown in Fig. 1. It has a tree-like structure with each of its branches connected to a specific instrument. A wire harness exhibits complex physical properties. During assembly, both elastic deformation and plastic deformation are demonstrated. This property makes an attempt on obtaining a precise dynamics



(a) Instrument panel frame. (b) Instrument panel frame with wire harness fixed on it.

Fig. 2. Assembly of a wire harness into instrument panel frame.

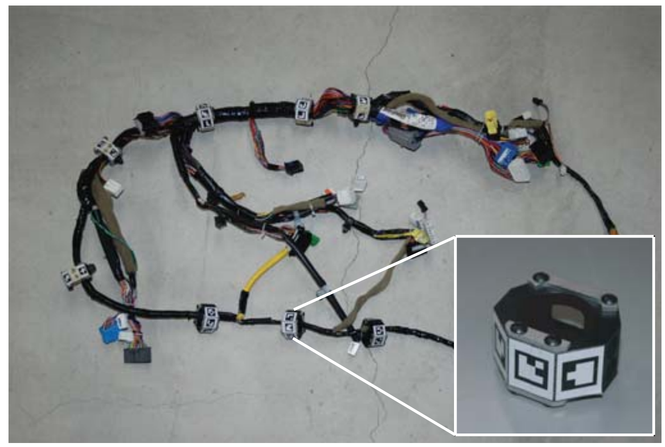


Fig. 3. Clamp cover attached with markers for recognition

model of it very difficult. As shown in Fig. 1, there is a set of plastic clamps bound on a wire harness. They are used for fixing a wire harness on the frame. Actually, on the surface of an instrument panel frame, there are a set of holes. Fixing of a wire harness is achieved by inserting the clamps bound on it into these holes. A robot system capable of completing assembly of a wire harness has to solve two basic problems: how to measure the state of a wire harness and how to handle it.

III. A robotized wire harness assembly solution

A. The prototype robot system

A prototype robot system has been developed for verifying the technologies required for realizing automatic assembly of a wire-harness. It is specially designed for this process. As shown in Fig. 4, it has three robot arms (Mitsubishi PA10) configured in front of an instrument panel frame. In this research, employment of three robot arms is designed to enlarge the workspace and the additional robot arm is expected to assist operations like wire permutation, re-grasping. On the end-effector, an one DOF gripper is mounted (Fig. 5). This gripper is designed for two kinds of operations. With the toe at the tip of it, parts mating by inserting the toe into holes is enabled. On the other hand, the middle segment of gripper is also used for possible grasping of wire segments. In this case, the target wire segment is clipped between two arms of the gripper. The end-effector is also equipped with

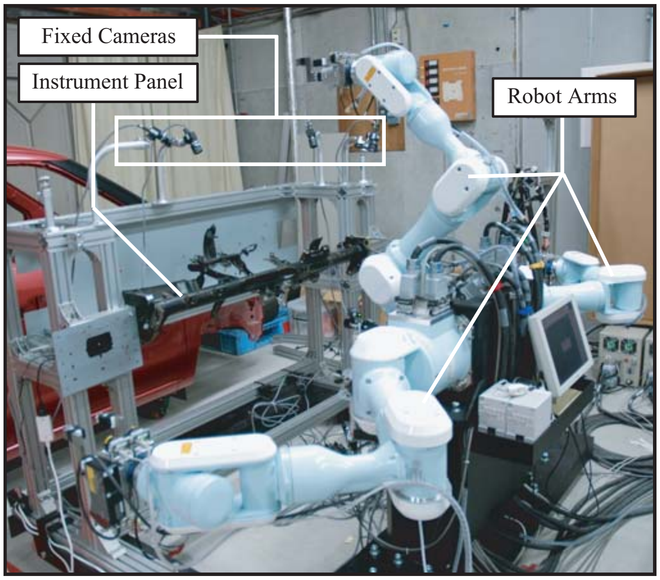


Fig. 4. Overview of the developed prototype robot system.

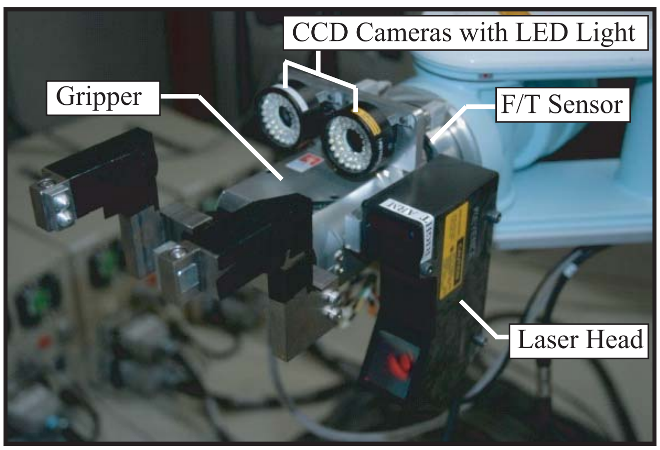


Fig. 5. Closeup view of the end-effector.

two CCD cameras and a laser range sensor. The two cameras have different focus length. The employment of the cameras are switched according to the distance to the target. Thus recognition of the target is ensured within a large range. The laser range sensor is used in situations when precise measurement to a wire segment is necessary. Surrounding the work cell, there are ten cameras fixed facing to system from various directions. Taking into account the cameras mounted on the end-effectors, the prototype system totally employs 16 cameras for recognition.

B. Measurement of a wire harness

In the prototype system, recognition of the wire harness is implemented by utilizing vision based approach. As shown in Fig. 3, a specially designed plastic cover is attached to every harness clamp. In addition, markers for recognition are attached on the surfaces of the clamp covers. Recognition of the markers is realized by applying open source soft

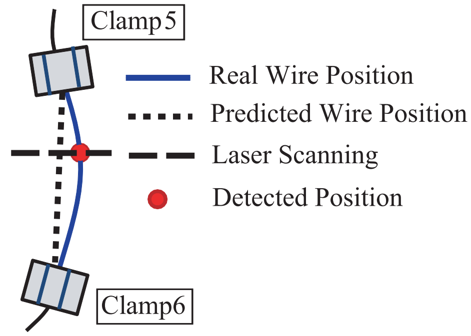


Fig. 6. Measurement to the deformable segment of a wire harness

package **ARToolKit** [6]. This software toolkit is originally designed for applications of Augmented Reality. It provides a set of easy-to-use libraries for detecting and recognizing the markers. When the markers are projected on the camera, the relative pose between camera and planar marker can be obtained from the library. This research makes use of this property. In the system, different markers are attached on the surfaces of each clamp cover. Using the library, not only the relative pose, pre-specified ID information corresponding to the markers can also be obtained. The cameras employed in the system function in different ranges. The ones fixed around the works cell are used for roughly recognizing the information like where is the target harness clamp. The position of a wire segment is estimated by interpolating the position of its adjacent harness clamps. The end-effector is guided to approach to the target clamp with the position information obtained from the surrounding fixed camera until the wrist camera also find the target. From that moment, the guiding control is switched to relying only on the wrist cameras. The precision provided by the wrist camera in that distance can ensure reliable grasping of clamps. Estimation to the deformable segments also rely on the artificial markers. As shown in Fig. 6, position of the target deformable segment is estimated firstly by interpolating the pose of its adjacent clamps. Since the interpolated curve as shown in Fig. 6 is not precise enough, the estimated area is then scanned again by the laser scanner. The scanner emits a planar beam with a particular width. The position of the scanned wire can be estimated from the distance profile obtained from laser sensor.

The employment of the markers greatly simplifies the measurement to a wire harness. Since under this scheme, measurement to a linear deformable object is realized by recognition to the markers. Though the employment of the specially designed clamp covers increases the cost of the system, it provides real-time performance and reliability necessary for subsequent experiments.

C. Handling of a wire harness

In this research, handling of a wire harness refers to both gripping the clamp covers and to directly manipulating deformable wire segments. As described in previous sections, a set of specially designed clamp cover are employed in

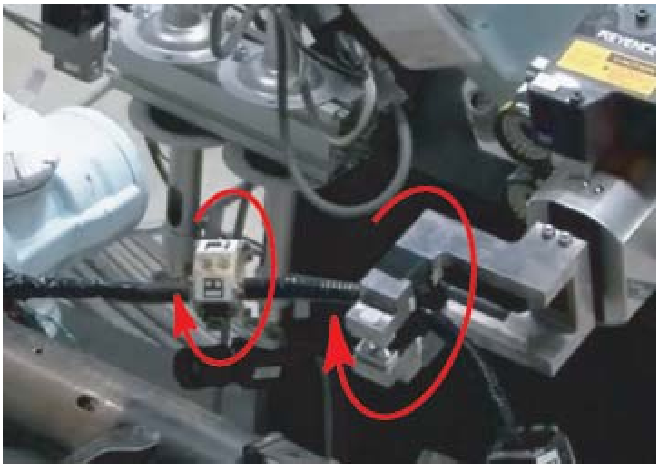


Fig. 7. Twisting a wire segment.

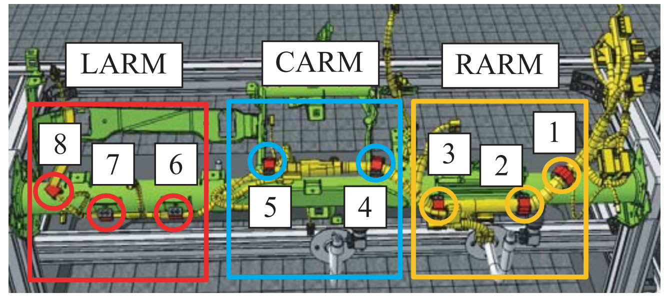


Fig. 8. Sequence of the assembly.

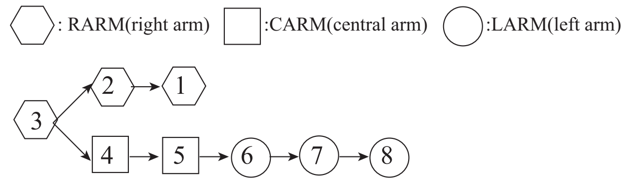


Fig. 9. The order of assembly.

the research. It enables fast and reliable measurement of a wire harness. The clamp covers are designed with holes for parts mating. Thus they are grasped by inserting the toe in the gripper into the holes. Besides this, there are also some occasions where an assembly operation makes it necessary to directly handling a wire segment. For instance, in many processes, a ”shaping” operation of a wire harness is required before the corresponding robot arm can execute the scheduled task. Fig. 7 demonstrates one of such operations. In this figure, one robot hand is trying to regulate the orientation of a clamp in order to position it where it can be reached by another robot arm. Currently, in this case, the only way to achieve this is to twist the nearby wire segment. Actually, we have attempted to shape the wire by twisting its adjacent clamp. However, due to the low torsional stiffness of the wire segment, it is proved that it is impossible for this way to twist the wire segment to the desired orientation state. In the subsequent experiments, the torsional state of the wire is regulated by twisting the nearby wire segment of the target clamp as shown in Fig. 7. During the regulation, pose of the target clamp is monitored by the surrounding cameras. Twisting will continue until the orientation of the target clamp coincides with the reference value.

IV. Verification experiments

With the developed prototype robot system, cabling experiments have been carried out. The detail about the experiment is described in the following section. This experiment is designed to implement a practically existing assembly process in an automobile plant. The whole process starts from picking up a wire harness from a hunger. Then inserting of eight wire harness clamps is completed. The process finally ends by returning to the initial standby position. Fig. 8 shows the assembly places of the clamps and the responsible robot arms respectively. They are determined based on the analysis to the reachable ranges of the respective robot arms. The assembling order is demonstrated in Fig. 9. Motion sequence of the robot arms during the process is generated by using a graphical simulator as shown in Fig. 10. Potential collisions between the robots and the surrounding environment, collisions within the robots are monitored by implemented collision detection algorithm in real-time. In motion generation, some of the operations in the motion sequence is generated by taking reference from human worker. For this purpose, motions of a human worker during the assembly have been captured. The captured data comprise the motion of the worker and the corresponding behavior of the wire harness. The data indicates the skills of a human worker when he performs the same task. In many operations, the strategy taken by a human worker is proved to be more effective. In the subsequent part of the section, some characteristic operations embedded in the process are presented in detail.

A. Twisting control of a wire segment

In the experiment, difficulties preventing the whole process from ending with the final clamp assembly is mainly due to infeasible handling position for a robot hand. Take the assembly of the clamp 5 as an example, it should be fixed after its adjacent clamp 4 has been fixed on the frame as indicated in Fig. 8. In this situation, the segment left to clamp 4 is not yet assembled and it droops down besides clamp 4. In this condition, it is very likely for the clamp 5 to be in a position that can not be reached by the responsible robot arm (center arm). The embedded approach in the situation is to pre-shape the target wire segment in order to ensure a successful grasping. Firstly clamp 5 is raised up by the left arm by gripping the wire segment near clamp 5. Then the orientation of clamp 5 is regulated by controlling the torsional state of the wire segment as described in Fig. 7. This pre-shaping operation ensure that the subsequent gripping of clamp 5 is always executed in the most appropriate condition.

B. A human like cooperation between two robot arms

In some situations, assembly of a wire harness also needs a human like cooperation between multiple robot arms. To

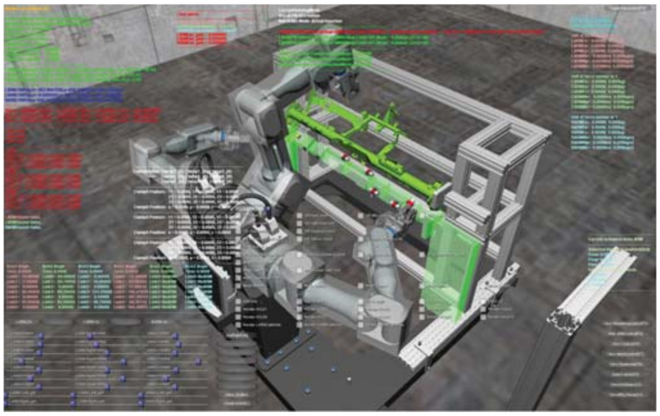


Fig. 10. Overview of simulator

(a) (b) (c)

Fig. 11. Assembly procedure of clamp 1.

describe this issue, the assembly of clamp 1 is taken as an example. Fig. 11(a) demonstrates the finished state of this assembly. Fig. 11(b) demonstrates the initial state of the assembly where the adjacent clamp 2 has been inserted into the instrument panel frame while clamp 1 droops down. As indicated in the figures, the working space available for this operation is very limited. Thus it is very likely that the robot hand can not find an appropriate position for gripping because of the potential collision with the surrounding environment. Moreover, practical experiences recommend to avoid starting this operation with the right part of the wire drooping down since that may lead the wire segments to be caught by the surrounding frame in the subsequent operations. The planned motion in this situation takes reference from the behavior of human workers. The strategy demonstrated by human that complete

A human worker is good at cooperatively taking use of his two arms to complete a task. For the current operation, a human worker is apt to complete inserting with one hand while adjusting the pose of the wire simultaneously by twisting the wire segment with the other hand. We implement the same strategy in the experiment as shown in Fig. 12.

C. Wire orientation regulation making use of plastic deformation.

In the whole process, there are some situations where it is difficult to implement a ”pre-shaping” of the wire segment cooperatively employing two robot arms as described in the previous sections. Fig. 13 demonstrates an example. It indicates the process of assembling clamp 6. For this operation, it is expected that the left robot arm completes fixing it to the frame since it is the only robot arm that can reach to the target. Fig. 13(a) demonstrates the moment when the left robot arm approaches to clamp 6. When it is determined that gripping of clamp is not achievable as demonstrated in Fig. 13(b), the left robot arm will try to grip the wire segment near the clamp instead of gripping the target clamp as shown Fig. 13(c). Then the robot revises the torsional state of the wire segment by twisting it. The figure Fig. 13(d) indicates how the robot arm tries to make the clamp to face to left side more. Due to the plastic property of the wire, torsional state of the wire will eventually change after repeating twisting the wire segment for several times. Until the orientation of the target wire segment is appropriate for gripping, one more attempt to grip the target clamp will be executed again.

With the implemented strategies, the whole assembly process composed of fixing eight clamps on the instrument panel frame is achieved within 3 minutes averagely (see the attached video file). Though the average speed is still far from the requirement of practical application, it demonstrates the technical feasibility of robotized wire assembly.

The experiments reveal the problems needed to be solved for improving the system to be reliable and fast enough for practical industry application. As indicated in previous sections, the assemblies involved with wire segments in plants often have to implement pre-shaping of the wire segment during the process. Compared with knotting/unknotting operations, torsional state of wire segments according to the process is more important for the success of these tasks, since many assemblies are characterized by handling parts bound on the wire. Therefore a gripper equipped with twisting DOF similar to one demonstrated in [3] is proved to be very effective. When considering improving the speed of the task execution, the dynamic behavior of the wire should be considered. Actually, in the captured motion of skilled worker, motions of dynamically swinging the wire in order to avoid the surrounding obstacles are confirmed. When implementing assembly with similar speed, special approaches are necessary for suppressing the dynamical behavior of the wire.

V. CONCLUSIONS

This paper addresses an engineering attempt on realizing robotized assembly of a wire harness employed in automobile plant. Different from the previous research concerned with linear deformable object handling, this research is characterized by its application background. Though many of the approaches employed in the research are straightforward, the proposed solution successfully realized automatic assembly with the prototype robot system. It demonstrates the potential of automation for this kind of tasks. In addition, as the first step to ultimately achieve a robotized assembly which satisfies industry requirements, the experiments of this research reveal the necessary technologies for further developments.

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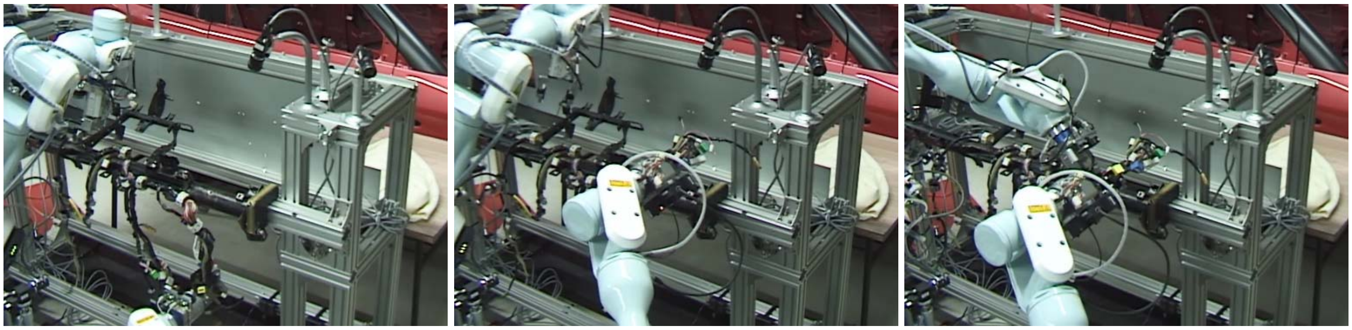
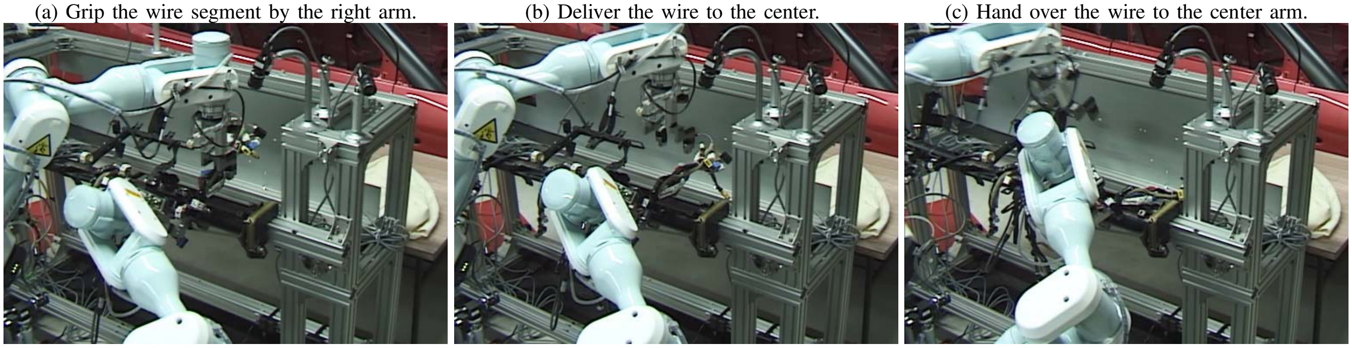
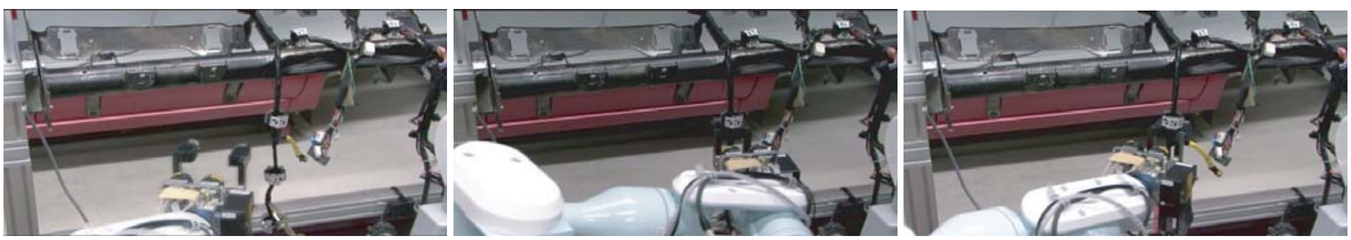


(a) Grip the wire segment by the right arm. (b) Deliver the wire to the center. (c) Hand over the wire to the center arm.

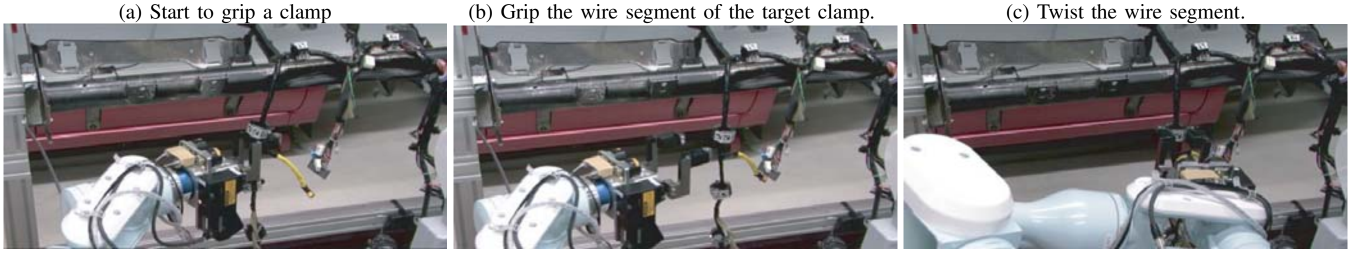


(d) Adjust the orientation of clamp 1 (the center arm) until it is proper for gripping by the right arm. (e) Grip clamp 1 by the right arm. (f) Insert clamp 1.

Fig. 12. A human like cooperation between two robot arms



(a) Start to grip a clamp (b) Grip the wire segment of the target clamp. (c) Twist the wire segment.



(d) Twist the wire segment iteratively to change the orientation of the wire. (e) Release the wire. (f) Grip the target clamp gain.

Fig. 13. Adjustment of torsional state of a wire utilizing plastic deformation.

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