Structure Design of an End Effector for the Chinese Space Station Experimental Module Manipulator

*Kui Sun, Hong Liu, Zongwu Xie, Fenglei Ni

State Key Laboratory of Robotics and System, Harbin Institute of Technology, China
e-mail: sun.kui@163.com

Abstract

For the maintenance of the space station and other space servicing tasks in the future, China is developing her own Experimental Module Manipulator(EMM) which includes a seven degrees of freedom manipulator and two end effectors. Based on the functions and requirements, design scheme of the end effector and its cooperative grapple fixture were optimized. The end effector includes capture module, power transmission module and other modules. In accordance with the capture sequence, motion principle of capture & locking module of the end effector were analyzed, then engineering prototypes of the end effector, the grapple fixture and the ground testbed were built. The experiments were conducted, the results proved that the end effector can satisfy the design requirements, it can work well in the simulated space environment.

1 Introduction

The space manipulator is a very important tool for On-Orbit Servicing(OOS)[1], its servicing capability has been demonstrated[2][3]. To complement the length limitation and extend its utility, one of the methods is giving the manipulator self-relocation capability. The self-relocating manipulator is symmetric about its elbow with two identical 3 degree of freedom(DOF) shoulder and wrist clusters, including two identical end effectors which are attached to the end of each cluster. The grapple fixtures spread throughout surface of the space station and act as base points. The end effector acts as a hand to capture grapple fixture[4], then the manipulator can "walk" from one base point to another, also called inchworm-like movement[5]. With help of several connectors, the end effector at the base point provides mechanical and electrical connections to the space station for manipulator support and operation. Thus the end effector plays a key role for the self-relocation of the manipulator.

Among the ones apply to space servicing, there are two end effectors for self-relocation, they are the Latching End Effector(LEE)[6][7] and the Basic End Effector(BEE)[8].

The LEE is attached to the two ends of the Space Station Remote Manipulator System(SSRMS) which has been used for the International Space Station(ISS) assembly successfully[9]-[11]. The LEE has a three-cable snare mechanism, a rigidizing mechanism, four latching and umbilical mechanisms, an EVA drive and a force moment sensor, its dexterous tasks are realized by the Special Purpose Dexterous Manipulator (SPDM) and its ORU(Orbital Replaceable Unit) Tool Changeout Mechanism (OTCM)[12].

The BEE is attached to two ends of the European Robotic Arm(ERA) which will be used on the Russian segment of the ISS[13]. With the force moment sensor and the leading edge being carefully designed, the BEE can perform soft capture by managing the capture force and moment. The BEE has a three-hook/lever-system grapple mechanism, connector unit, an EVA drive and a force moment sensor. The BEE also can not perform dexterous tasks, which is realized by EUROBOT and its end effector and tools[14][15].

Besides the above two end effectors, those of the fixed space manipulators also include the docking system of the Orbital Express(OE)[16]-[19].The docking system of the Orbital Express(OE) is used for satellite capture. It is an enveloping capture with three fingers and the docking is a soft docking with dampers for preventing impacting. The rigidization is obtained by the motor and ball screw which applies the necessary preload to grapple fixture.

The paper is organized as follows: section 2 will introduce structure of the end effector and its grapple fixture, section 3 will expatiate capture sequence of the end effector, section 4 will give two main experiments of the end effector, section 5 is conclusion of the paper.

2 Structure Design of End Effector and Its Grapple Fixture

2.1 Basic requirements of the end effector

As shown in Fig.1, the space manipulator arm is symmetric about the elbow with two identical 3 DOF shoulder and wrist clusters. Either cluster has three mechanical joints with perpendicular rotation axes. The end effector will be installed on each end of the manipulator, one end effector will serve as the base point of the EMM through grappling its cooperative grapple fixture and the other end effector will conduct kinds of operation tasks with its operation tools. Several grapple fixtures will be installed on the experimental segments of the space station, then the EMM can walk around the space station by changing its base point.

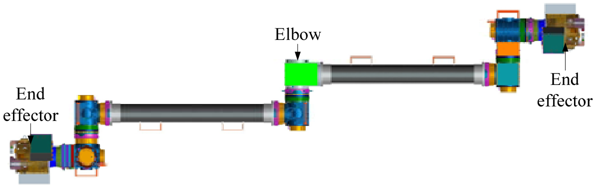

Figure 1: the Space manipulator of EMM

The functions and requirements are listed below:

1) Functions

(1) Self-relocation, the end effector is attached to the grapple fixture so that the manipulator can step over from one base point to another or perform an inchworm-like movement with the exchange between the wrist and shoulder.

(2) Payload handling, one cluster's end effector is attached to the grapple fixture stably so that the cluster acts as a shoulder base, while the other cluster's end effector acts as a hand to perform kinds of operation tasks.

(3) Power transmission, the end effector can transmit torque to drive the attached tool to accomplish certain on-orbit servicing tasks.

2) Requirements

(1) The end effector must be able to provide large capture misalignment tolerance, and mechanical and electrical connection.

(2) The end effector must be able to perform soft capture and soft docking.

(3) The end effector must be able to have high strength, stiffness, reliability and long life, whatever it acts as a shoulder or a wrist.

(4) The end effector must be interchangeable.

(5) The end effector is required to operate on orbit for 10 years and can be extended to 15 years with maintainability and refurbishment.

The performance parameters of the end effector are shown in Table 1.

According to the functions and requirements, the end effector and its grapple fixture were designed, as shown in Fig.2. As an integrated structure, The figure also displays a 6 dimensional force/torque sensor and a fast exchange interface.

Table 1. Design Requirements of the end effector

Number	Parameter	Value
1	Size	<Φ500 x 400 mm
2	End Effector Mass	<35 kg
3	Grapple Fixture Mass	<8 kg
4	Output Torque	>40 Nm
5	Axial Capture Distance(X)	0-80 mm
6	Lateral Capture Misalignment Tolerance(Y/Z)	±40 mm
7	Angular Capture Misalignment Tolerance(Yaw/ Pitch/ Roll)	≥4 °
8	Drag Force	1000 N
9	Capture and Latch Time	<240 s
10	Operating Times	1000 times

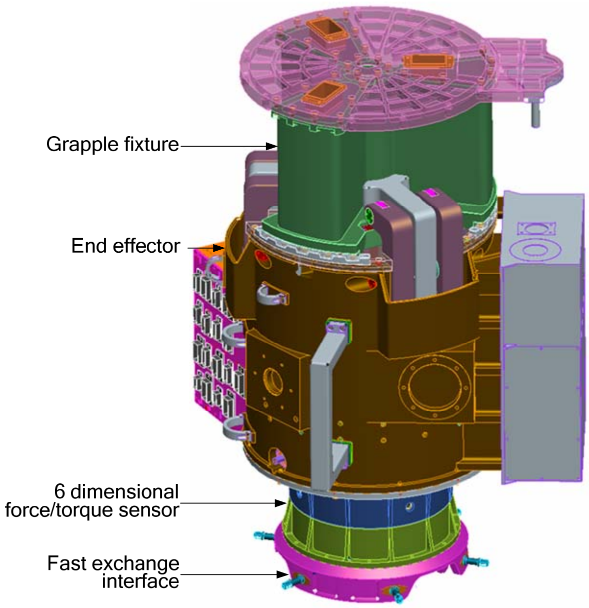

Figure 2: the end effector and its grapple fixture

2.2 Design of the end effector

Fig.3 shows detail structure of the end effector, it includes capture module, sensor module, power transmission module and electrical controller module.

1) Capture module

The capture module consists of brushless DC motor, reducing gear, ball screw, power off brake, capture fingers, latching fingers, EVA interface, etc., which are all contained in a supporting shell. A top plate assembly is attached to the supporting shell, which integrates alignment pins, electrical connectors, micro switches, engagement teeth, and so on. Fig.4 shows shape of the capture finger, latching finger and there relationship.

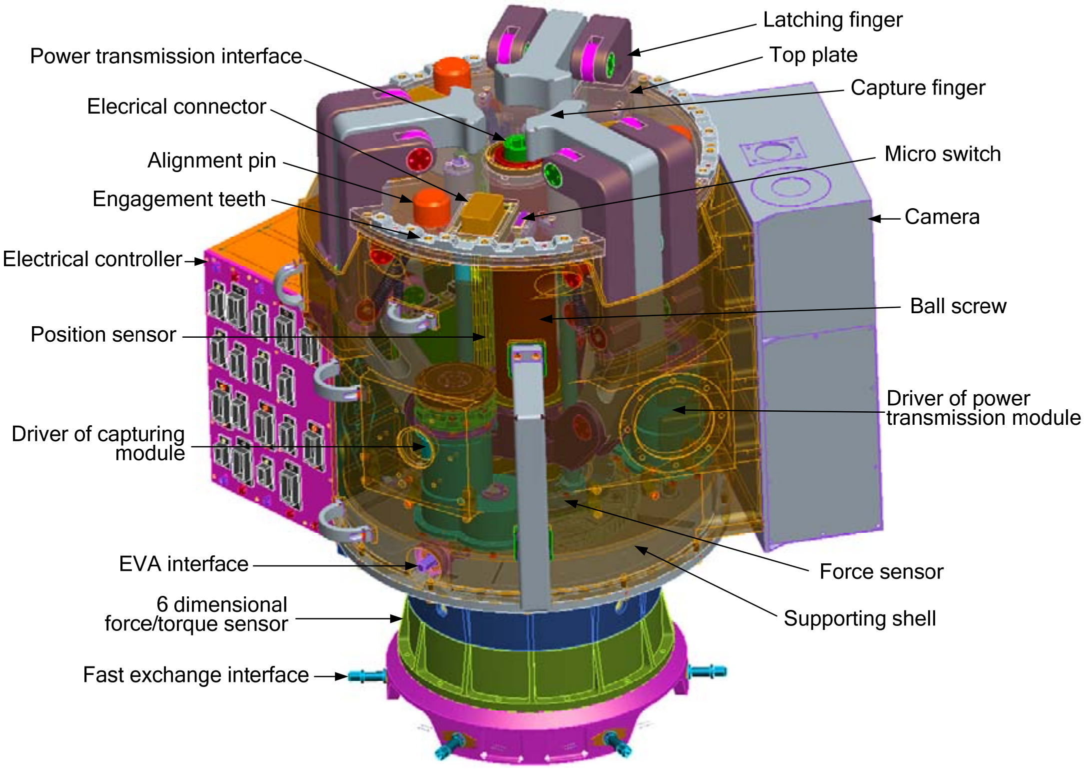

Figure 3: end effector major components and its layout

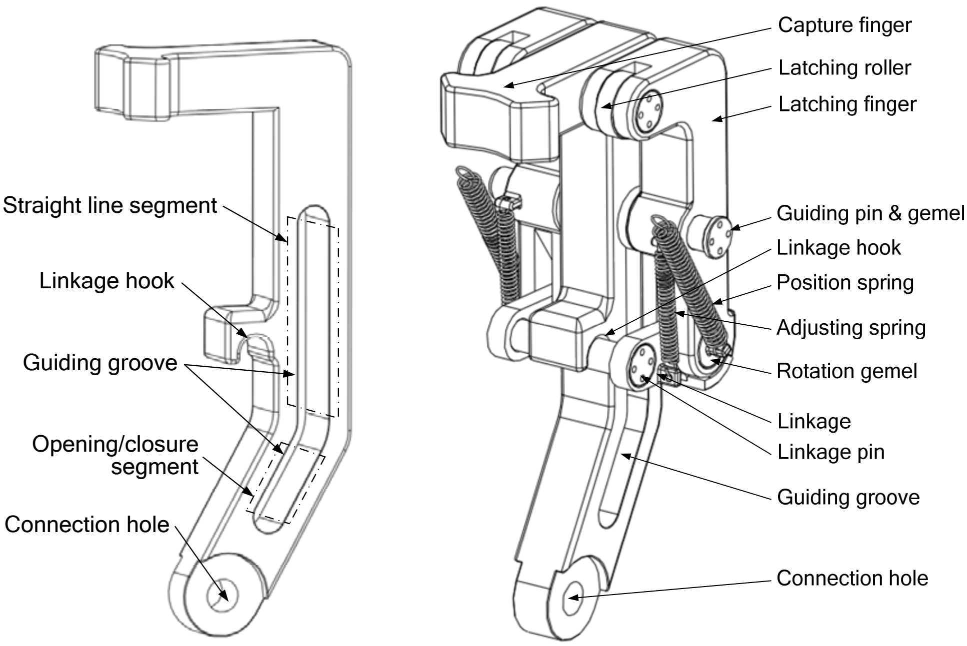

Figure 4: schematic of capture finger and latching finger

Three capture fingers are symmetrically attached to the screw nut and simultaneously restricted on the guiding pin & gemel via guiding groove which is composed of straight line segment and opening/closure segment. The latching mechanism is installed on the guiding pin and symmetric about the capture finger. It is driven by the capture finger and can rotate around the guiding pin.

There is a guiding groove on capture finger which can contact with the guiding pin & gemel which mounted in the supporting shell, when moves along the guiding pin upward from its closure position, the guiding groove can make the capture finger move and open/close respectively with its straight line segment and opening/closure segment.

The latching finger is a linkage structure, when the capture finger move downward, its linkage hook can contact with the linkage pin of the latching finger, thus can make the latching finger rotated around the guiding pin & gemel. The adjusting spring connects the linkage and the latching finger, the position spring connects the latching finger and the top plate, then position of latching finger can be adjusted by the adjusting spring and position spring automatically.

Upon receipt of command, the brushless DC motor begins to drive the ball screw which translates an axial movement through the three stage reducing gears. Three capture fingers connect with the screw nut through connection holes, when move upward together with screw nut, the capture finger will open at the same time because of its guiding groove, thus get ready for capture the grapple fixture.

The position sensor based on potentiometer is designed to demonstrate current position of the capture fingers. For the safety consideration, mechanical and electrical position limitation is settled.

In order to monitor the capture status of the end effector, a force sensor is installed between the screw nut and the supporting shell. The force sensor is designed based on shear strain theory. Eight strain gauges are used to construct two full-bridges, which can compensate the effects of temperature. Mechanical limitation is settled to prevent the force sensor from over load.

When working in the space, perhaps the electrical unit will out of work, for the safety of the system, an EVA interface based on a pair of straight bevel gear is designed between the second stage and the third stage reducing gear, astronaut can open or close the capture module through the EVA interface by an electrical tool in emergency condition.

A top plate assembly is attached to supporting shell, the top plate assembly is used for alignment, engagement and electrical connection during engaging phase of the end effector and its grapple fixture. It contains a top plate, electrical connectors, engagement teeth, micro switches and alignment pins. The alignment pins and engagement teeth can guide the capture process, two redundant micro switches can give a signal to confirm the successfully capture of the end effector and its grapple fixture. After the end effector grappling a grapple fixture, the electrical connectors between the two parts can transfer power and data communication.

2) Power transmission module

With the development of space robot technology, more and more work are expected to be accomplished by the space robot instead of the human astronauts. NASA and Canadian Space Agency (CSA) have conducted the Robotic Refueling Mission (RRM) in the International Space Station(ISS)[20]-[22], which have demonstrated the ability of the space robot with different tools to refuel and repair satellites in space, especially satellites that were not designed to be serviced. Among these tools, there is a common point that most of them are rotary tools that can be driven by a mechanical input interface.

Based on this background, the end effector also supplies a power transmission module, it set a rotary input interface for different tools, similarly to RRM's wire cutter tool, safety cap tool, and so on. The power transmission module consists of brushless DC motor, reducing gear and transmission shaft, output interface of the power transmission is a hexagon socket head, the output torque can be 40Nm. Different tools can be mounted on a little grapple fixture, after the end effector captured the little grapple fixture, the rotary torque can transmit to the tools through the hexagon socket head.

3) Other module

The end effector also contains electrical controller unit and hand-eye camera unit. The electrical controller unit is integrated design with the end effector which mounted on the supporting shell. The hand-eye camera unit mounted on the supporting shell, too, it can provide vision information for the operator.

2.3 Design of the grapple fixture

The grapple fixture is shown in Fig.5, it have a trefoil main body which is an integration of a cylinder, an interface plate and three wedges. The faces of each wedge intersect with the cylindrical surface. The interface plate integrates electrical connectors, engagement teeth and alignment holes, during capture process, they will engagement with the other side that mounted on the top plate of the end effector.

Capture interface feature surface of the grapple fixture are shown in Fig.5 which marked with A, B and C.

The capture feature space is in accordance with tip of the capture finger, they will interact with the corresponding surface of capture finger during capture process, through which the gesture misalignment can be amended.

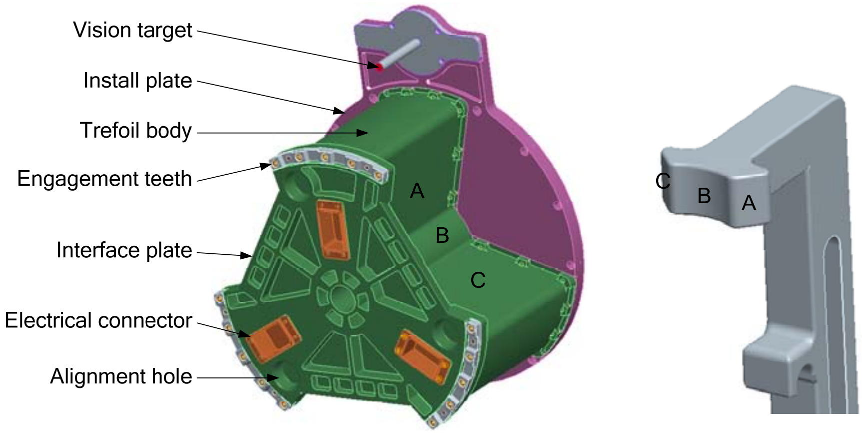

Figure 5: the end effector and its grapple fixture

3 Capture Sequence Analysis

According to their working principle, the capture operation process of the end effector and its grapple fixture is subdivided into five steps, they are deployment and preparing, envelope and constraint, close and positioning, drag and engagement, latching and rigidization respectively, as shown in Fig.6.

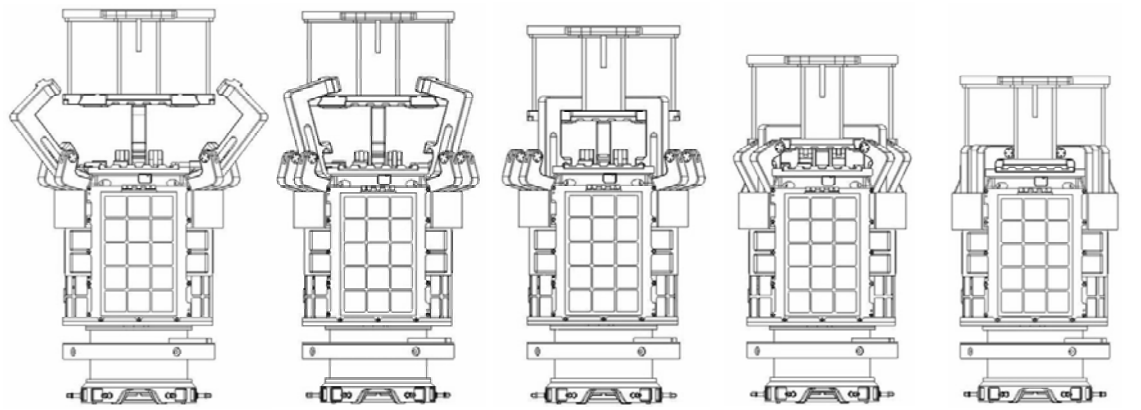

Figure 6: Capture sequence of the end effector and its grapple fixture

Each step is described as follows.

(1) Deployment and preparing

The end effector is positioned, the capture fingers begin in the maximal deployed state, the latching fingers begin in its initial opened position, the grapple fixture is fixed within the capture capability of the end effector.

(2) Envelope and constraint

Upon receipt of command, the ball screw is actuated and translates the screw nut along the length of the supporting shell. The screw nut moves with the capture fingers. With the constraint of guiding groove of its opening/closure segment, the capture fingers begin to close to a proper position and make their tips into the capture feature space. The capture is achieved as the grapple fixture is constrained within the tips of the capture fingers.

(3) Close and positioning

The capture fingers continually close along the guiding grooves till the beginning position of the straight line segment. The capture finger tips are guided by the wedge faces to mate with the corresponding surfaces A, B and C. During the engagement, the grapple fixture is centered and positioned, which eliminates the position error and angle error between the end effector and grapple fixture.

(4) Drag and engagement

As the capture fingers continually move down along the straight line segment, the capture finger tips move down along cylinder surface, then engage the interface plate and draw it together. When the linkage hooks of the capture fingers contact with the linkage pins of the latching fingers, the downward movement of capture fingers simultaneously actuate the latching fingers. After the latching rollers contact with the interface plate, they begin to actuate it to depart from the capture fingers and continuously move down. When the alignment pins enter into the corresponding alignment holes, the end effector and the grapple fixture align each other. When the micro switches contact the interface plate, they will send out signals that confirm the engagement.

(5) Latching and rigidization

The capture fingers continuously move downward along the last stage of the closure segment. The latching rollers begin to press the elastic elements to produce deformation preload. When all the latching fingers move to their final positions, the deformations of the elastic elements will be maximum. The corresponding deformation load makes the end effector and the grapple fixture rigidize as an integration.

4 Experiments

Engineering prototype of the end effector and grapple fixture were developed and the ground experiment supporting system which based on an air bearing table were built, which were shown in Fig.7.

Ground experiments were conducted to verify validity of the design scheme, included conventional performance parameters test, sine vibration test, random vibration test and thermal vacuum test.

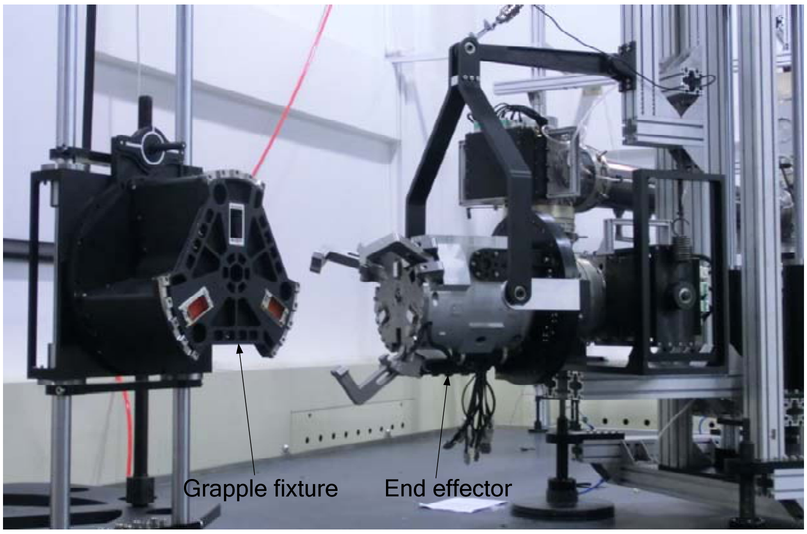

Figure 7: the end effector and its grapple fixture

4.1 Capture misalignment tolerance test

The most important performance parameters test was capture misalignment tolerance test that represents working ability of the end effector. The experiment system that based on two industrial robots was set up which is shown in Fig.8.

The end effector was mounted on robot E, and the grapple fixture was mounted on robot T through a six dimension force/torque sensor. Initial position and gesture misalignments between the end effector and its grapple fixture were measured and adjusted by a laser tracker. During the experiment process, robot E was fixed, the end effector was deployed to capture the grapple fixture, robot T was working at compliance control mode, which was very similar to whole the on orbit working process, the force and torque between the end effector and the grapple fixture could be measured by the six dimension force/torque sensor which could monitor the experiments process.

The experiment result has demonstrated that the end effector can achieve the capture task successfully, part of experiment data is shown in Table 2. It can be confirmed that the end effector has satisfied the requirements of position and gesture misalignment tolerance.

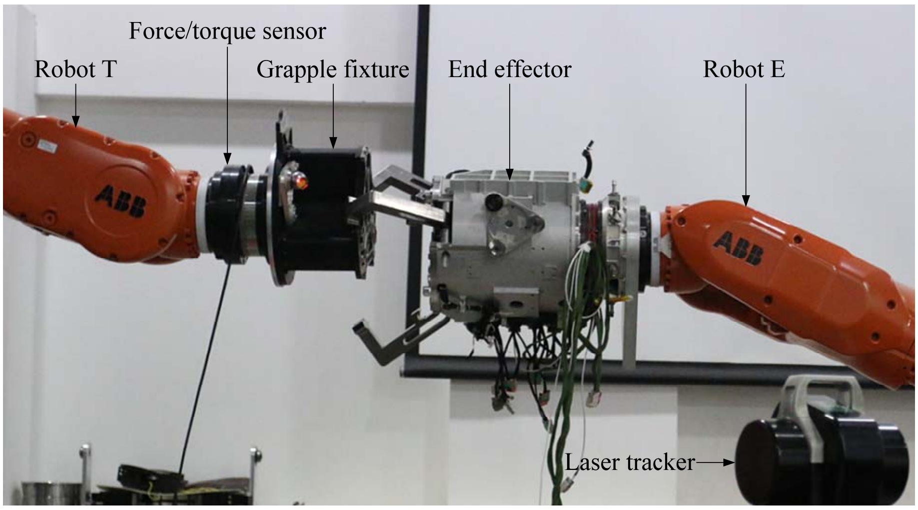

Figure 8: Misalignment testing

Table 2 Data of capture misalignment tolerance test

	Position Misalignment Tolerance（mm）			Angular Misalignment Tolerance(°)		
	X	Y	Z	Rx	Ry	Rz
1	121.0	-71.7	49.9	7. 9	8.5	7.0
2	104.7	-40.7	-59.6	12.5	-4.7	-12.4
3	104.8	47.7	-66.2	-12.0	-9.2	-9.2
4	107.4	-62.5	-65.6	-12.0	-9.2	-9.2
5	101.8	41.6	42.9	5.9	4.0	7.5
6	100.9	59.0	-44.4	4.4	4.2	7.4
7	108.9	-48.5	-73.7	4.3	4.2	7.4
8	110.6	-87.1	65.9	4.4	4.2	7.4
9	123.2	55.4	-56.3	-4.4	5.5	-4.6
10	125.3	52.3	41.8	-4.6	-5.8	-5.4

4.2 Thermal vacuum test

In order to verify the performance of the end effector working in space environment, the thermal vacuum experiments was conducted after sine and random vibration experiment. Fig.9 shows test layout in the thermal vacuum equipment.

The end effector is fixed on a supporting base and the grapple fixture is hung by three springs, the rated bending torque was executed outside the thermal vacuum equipment through a steel rope during the experiment. Their relative position is fixed and dx(along the axial direction) is the main misalignment between the end effector and the grapple fixture.

Motor current was one of the most important variables during the test. Motor currents of the end effector working in ambient environment and high-low temperature in thermal vacuum equipment were analyzed and compared, no abnormal phenomenon was found. That represents the end effector can work in the space successfully.

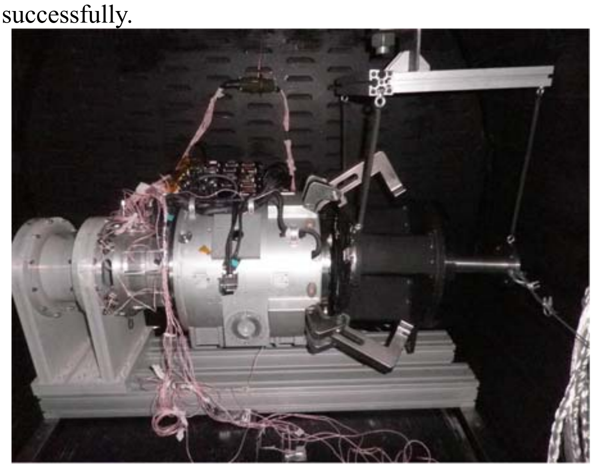

Figure 9: Thermal vacuum testing

5 Conclusions

The end effector and its cooperative grapple fixture for Chinese Experimental Module Manipulator were developed, a ground testbed based on an air bearing table were built, the capture sequence was analyzed and simulated. The experiments in both ambient and thermal vacuum environments were conducted to verify their working ability of the end effector. The experiments results have demonstrated that the end effector can meet all the required parameters and it can be used in the space environment in the future.

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