Progress in development of the blanket remote handling system for ITER

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Abstract. Verification tests of sensor-based control using a mock-up facility of the in-vessel transporter (IVT) have been performed to clarify measurement and control specifications for the installation of ITER blankets. Test results indicate variations in positioning accuracy of approximately -3 mm, -10 mm and 10 mm in the x, y and z-axes, respectively, using sensor-based control with a camera employed in a monocular vision method. A final installation test to within 0.5 mm between the module and two keys has been demonstrated using torque control. In addition, verification tests of the major device components, rail deployment equipment and cable handling system, were performed to confirm compliance with final design specifications.

1. Introduction

Maintenance of the ITER blanket will be carried out in the vacuum vessel (VV) using remote handling equipment, including the in-vessel transporter (IVT) with vehicle type manipulators as shown in Fig.1 [1]-[3]. An estimated 440 blanket modules, each with a maximum weight of 44.1 kN, will be installed in the VV. The gamma ray dose rate is expected to be approximately 500 Gy/h during the periods of blanket maintenance. A basic demonstration was performed to verify the performance to date of the in-vessel transporter (IVT), rail deployment and various mechanical functions (such as rail support, rail establishment, etc.) using full-size mock-up of an IVT as shown in Fig. 2. This demonstration clarified the basic mechanical specifications of the IVT for ITER [4]-[7].

The current design calls for shield blocks (SB) to be installed on two keys that are part of the VV. The keys are designed to withstand the large electro-magnetic loads that occur during plasma disruptions. Therefore, blanket maintenance requires remote manipulation of the max. 4.5-ton modules and specifies that final installation accuracy be within 0.5 mm between the SB module and the two key supports in the VV. Critical issues related to these specifications include the following:

a) Positioning the modules using sensor-based control prior to key insertion; and
b) Avoiding any jamming between the blanket module and the keys as a result of excessive loading during the module installation process, a process complicated by a limited clearance of 0.5 mm between the module and the keys.

Sensor-based control for the remote installation of blanket modules was developed using a combination of distance sensors for rough positioning and contact sensors for fine positioning [8]. Because distance sensors do not have a visual function, a sensor-based control system is unable to incorporate distance sensors due to the fact that a sensor-based control system requires visual information during blanket module installation. Therefore, we have developed a sensor-based control system using a camera employed in a monocular vision method to measure relative positioning between key and blanket.

To avoid any jamming, we have developed a torque control method to reduce excessive loads which may have an impact on the end-effector. This torque method to prevent jamming is directly measured and controlled by drivers of an AC servo motor equipped to move the

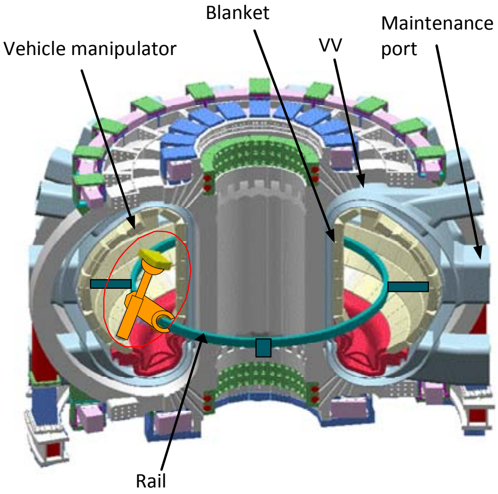


Fig.1 In-vessel transporter for ITER

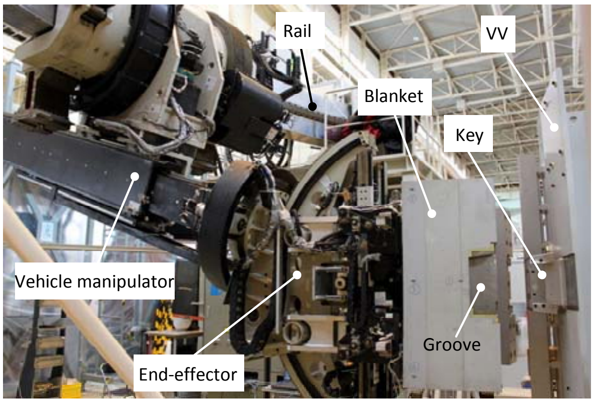


Fig.2 Mock-up facility of in-vessel transporter for blanket replacement

manipulator and end-effector during module installation.

The module is passively positioned onto two keys using a torque control method. In addition, it is necessary to measure the six forces acting on the end-effector in order to avoid any excesses in the installation forces. Commercially available force sensors would have to be very heavy and bulky to support the large load of a module weighing 4.5 tons. The load capacity of an IVT will decrease if it has to be equipped with such a heavy force sensor. To solve this problem, a new method for measuring the six-forces using grippers is proposed.

In addition, Verification test for the major devices, rail deployment equipment and cable handling system, was performed to confirm the specification for final design.

This paper describes the recent test results of blanket module installation using a full-size mock-up facility. These test results evaluate the new sensor-based control system, which includes robot vision for position measurement using a monocular vision method, torque control and force measurement, for fully remote module maintenance. Finally, the newest results in this paper are summarizes regarding the blanket remote handling system is composed of the major devices: a rail deployment equipment and a cable handling device.

2. Verification Tests for Sensor-Based Control

The directions for positioning the blanket module are for translation and orientation. The positioning of the blanket module must be controlled by the end-effector in order to install the module on two keys in the VV. The procedures for positioning the controlled end-effector are composed of the two stages of rough positioning using robot vision and fine positioning for torque control. In the second stage, the blanket module is guided along two keys to achieve final positioning accuracy for installation on the two keys. Force measurement of three translation and three rotation loads is needed to detect the reaction forces during insertion of the module on the keys.

2.1 Rough positioning

2.1.1 Measurement scheme

Three coordinates, such as a camera coordinate (Σ_C), used as a reference measurement, a key coordinate (Σ_K) for the surface of the keys (S_k) and a tool coordinate (Σ_T) used as a reference for the blanket (S_b), are defined as shown in **Fig. 3**. Each of these three coordinates consists of six axes: three for translation and three for rotation. The tool coordinate (Σ_T)

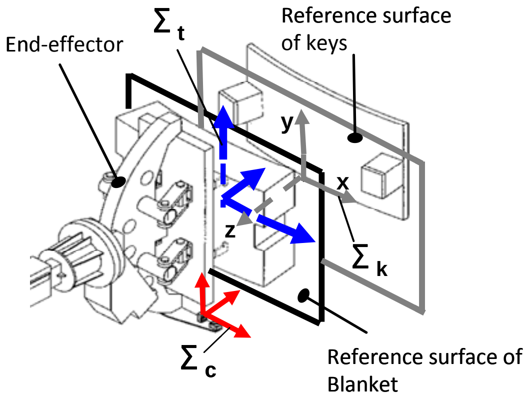


Fig.3 Coordination for robot vision

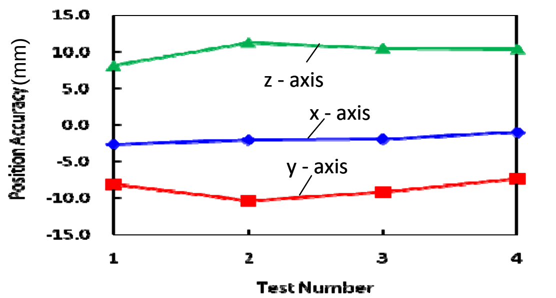


Fig.4 Test results of repeatability of the position accuracy

provides directions for moving the end-efffector. Three Matrices establishing the relationship between the positions given for each of the three coordinates are defined as follows:

$^{t}\boldsymbol{T}_{c}$: relation of position between Σ_T and Σ_C

$^{c}\boldsymbol{T}_{k}$: relation of position between Σ_C and Σ_K

$^{t}\boldsymbol{T}_{k}$: relation of position between Σ_T and Σ_K

$^{t}\boldsymbol{T}_{k}$ is given as follows:

$$^{t}\boldsymbol{T}_{k} = {}^{t}\boldsymbol{T}_{c}\,{}^{c}\boldsymbol{T}_{k} \qquad (1)$$

$^{t}\boldsymbol{T}_{c}$ is known and $^{c}\boldsymbol{T}_{k}$ is unknown. $^{c}\boldsymbol{T}_{k}$ shown in equation (1) and can be determined by measuring and calculating the $^{c}\boldsymbol{T}_{k}$. This $^{c}\boldsymbol{T}_{k}$, which describes the relationship of position between Σ_C and Σ_K, is clarified by analyzing a static image of the two keys with a monocular vision method using a single camera due to the constraints of an irradiated environment.

2.1.2 Test results

Figure 4 shows the results of four measurements to verify the above scheme for measuring the position relationship between Σ_C and Σ_K. The results regarding position accuracy were -3 mm, -10 mm and 10 mm for rough positioning for the x, y and z-axes, respectively, before insertion of the blanket module on the keys. These results indicate that two keys must be equipped with a chamfer of more than $\pm$10 mm for module insertion on the keys. On the other hand, variation in positioning accuracy was low, i.e, 1.2 mm, 2 mm and 3mm for the x, y and z-axes, respectively.

2.2 Fine positioning

2.2.1 Scheme for torque control

It is necessary to reduce excessive loads acting on the end-effector during module insertion to achieve final positioning to within a 0.5 mm margin needed to fit the key and groove shown in Fig. 2. If the key insertion is carried out by position control, the torque upon the AC servo motor increases due to excessive loads such that the torque can’t be controlled in response to changes in the torque.

To solve these technical issues, torque control was applied to defer the forces acting on the groove of the blanket. **Figure 5** shows the principle of torque control from T = t2 at the start of contact to the final position at T = t3. In the case in which the blanket has contact with the key in T =t1, the torque increases up to the target torque in T = t2. The torque is deferred so as not to go beyond the target torque. The position is modified in order to defer the torque. Finally, the blanket module is positioned on the two keys as shown in T = t3 of Fig.5.

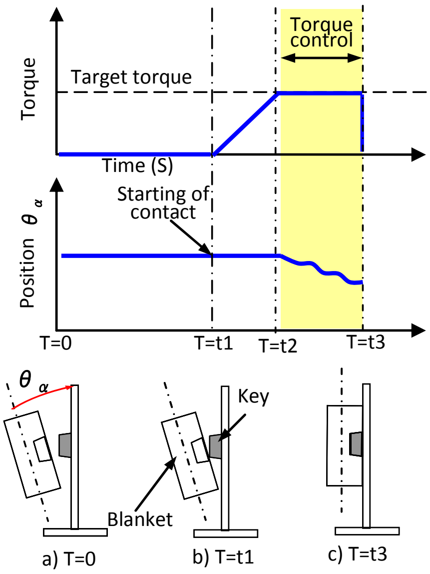


Fig.5 Torque control scheme

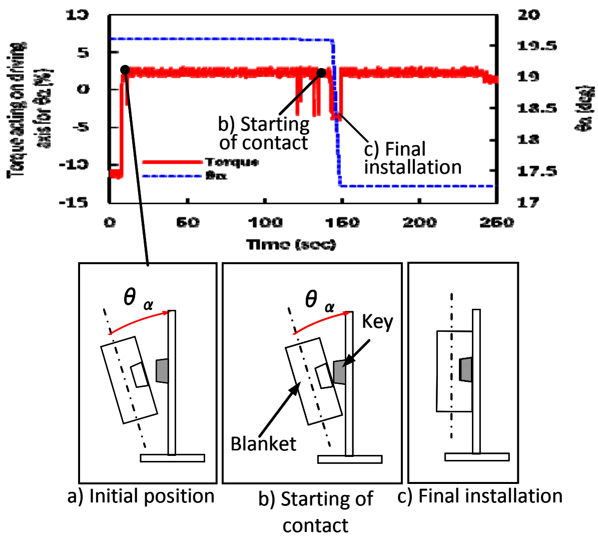


Fig.6 Test results of torque control during the key insertion

2.2.2 Test results

A verification test was carried out to confirm the torque control scheme. Test conditions were the following:

- Target torque: 5 % (a proportion of the output torque to the max. rated torque)
- Initial position: x = -3 mm, y=-10 mm, z = 10 mm (θ_α of the relative angle: 1.2 degrees)
- Velocity: 25 % (a proportion of the output velocity to the max. rated velocity)

As shown in Fig. 6, the position of θ_α was modified from 19.7 deg. to 17.25 deg. based on the torque of the AC servo motor with a driving axis of θ_α so as not to increase beyond the target torque of 5 % established in the test conditions. The vertical load acting on the keys is about 5.4 kN in this test case.

The basic function of torque control, which is to defer excessive loads, was confirmed through this verification test.

3. Rail assembly Test

3.1 Strategy and design of the rail assembly

Feasibility of the rail deployment procedure into the vacuum vessel had been confirmed using a full-scale, 180-degree mock-up during the EDA period [4]. Among the remaining concerns, rail assembly in the transfer cask remained as the major technical issue related to rail installation. In particular, rail assembly of two hinge joints using a connection pin is the most critical issue due to the precision of the required positioning to within 0.05 mm. To solve the technical issues regarding the precise positioning, a procedure for rail assembly as shown in Fig. 7 and for the assembly device, which is composed of a positioning arm and connecting mechanism, is proposed as follows:

Step 1: Start rough positioning by forming a circular arc between rail-1 and rail-2 using the positioning arms;

Step 2-1: Initiate rough positioning using the positioning key attached to the connecting part. In this positioning, the positioning arm is equipped with an Oldham's coupling on the end to accommodate any disparity in the position of the arm and the rail. The coupling can move along two directions on the horizontal plane and causes a position error at the end of the rail.

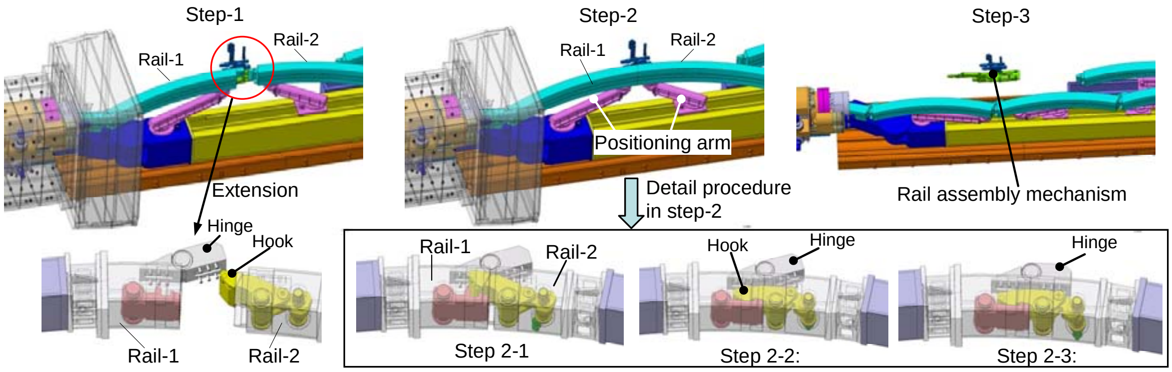


Fig.7 Procedure of the rail assembly

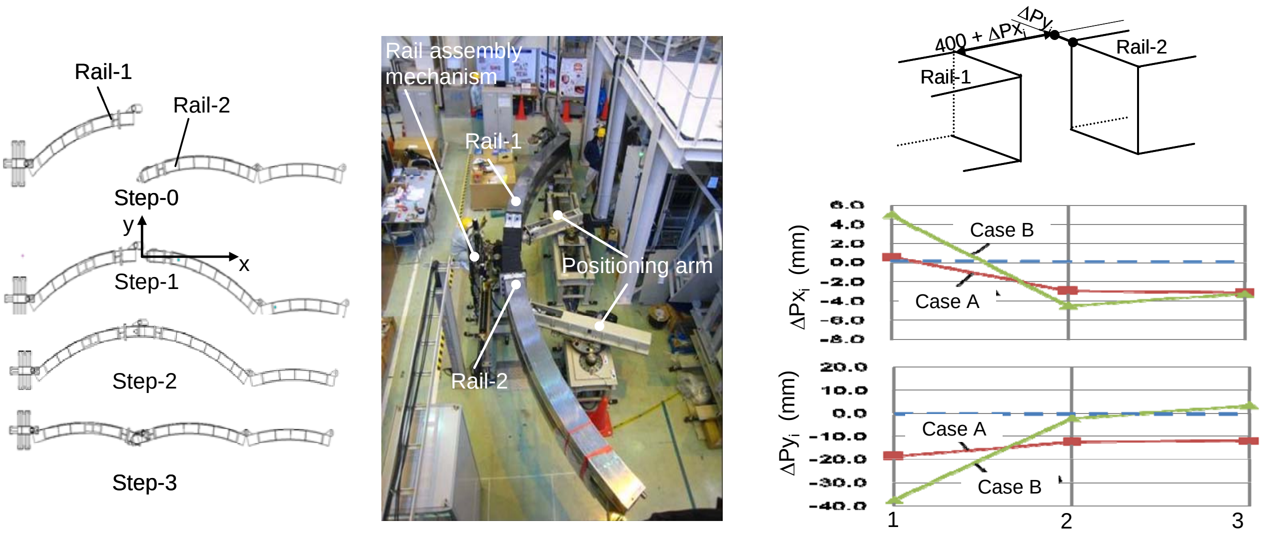
Step 2-2: Rotate the hook of rail-2 using the screwing rod, and adjust the gap between rail -1 and rail-2 to less than 1 mm.

Step 2-3: After achieving the above accurate positioning of rail-1 and rail-2, attach the rail joint hinge using the bolt screwing mechanism.

Step 3: Deploy the rail into the vacuum vessel.

3.2 Test results

Trials of the remote rail joint connection procedure were carried out to verify the design for positioning and connecting the rails using the steps shown in Fig.8-(a). Teaching points for the operation from step-1 to step-4 were generated during real operation by applying torque control to synchronize the maximum drive of the four driving axes shown in Fig.8-(b). A test of positioning repeatability was carried out using the mock-up facility to confirm the starting position accuracy in step-0. In this test, two types of couplings were used: one can move 4 mm (case A) and the other 15 mm (case B). The ΔPx_i and ΔPy_i (where i indicates the number of tests) represent the positioning errors in the x and y direction from rail-1. The results are shown in Fig. 8-(c). For case A, the maximum value of positioning error for the x and y axes were -3 mm and -19 mm, respectively. For case B, the values were 5 mm and -37 mm, respectively. In the current design, the repeatability, or positioning error, must be absorbed by a tapered key which guides the position of the rail during the connection procedure. In other words, the taper must be 19 mm and 37 mm for cases A and B,



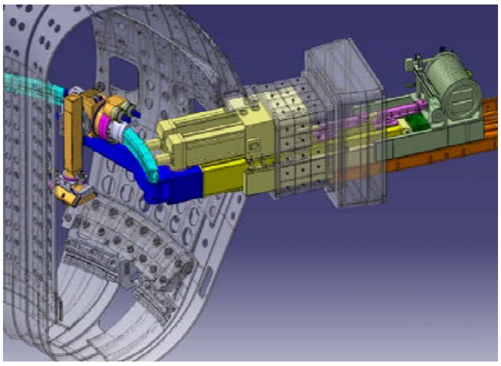
(a) Procedure of rail assembly for demonstration test (b) Mock-up facility for rail assembly (c) Test result for repeatability in step-1

Fig.8 Test results for the rail connection procedure respectively. However, the latter is too large for the current structure. Therefore, only case A is acceptable as the reference design. There are other measures than the tapered key to absorb positioning error: passive and active ones. Passive measures use position-fixing rollers to minimize error in the y+ direction. Active measures correct the position actively by measuring the position of the rail through image processing. The pros and cons of these methods will be investigated in a future design step.

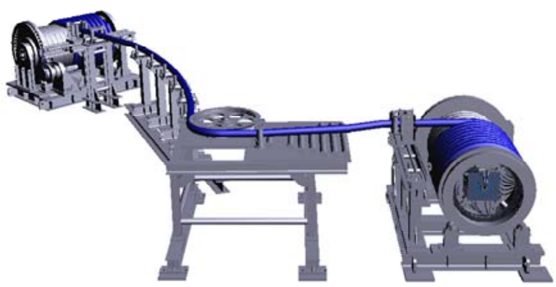
4. Cable handling

4.1 Design for cable handling

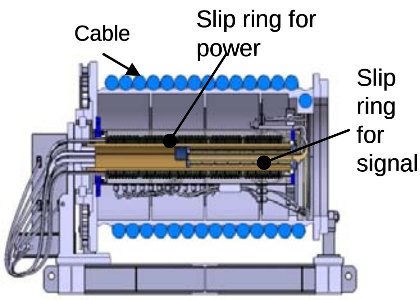
Cable handling technology is also a critical issue for a movable robot. The length of cable is estimated to be about 40 m, and over-tension of the cable should be avoided for stable movement of the vehicle manipulator along the rail. A new idea for a cable handling system using a drum-type cable winding mechanism was designed for compact storage of the long cable in the cask as shown in Fig.9-(a). The test facility for cable handling consists of two drums (one for vehicle simulations), a multi-cable system for handling both power and signal cables, a guide mechanism for cable winding with traverse motion, and a simulated cable route with a guide mechanism at the front corner of a maintenance port, as shown in **Fig. 9-(b)**. New features in the test facility include a drum diameter of 750 mm and a slip ring to maintain electrical power and signal connections during drum rotation as shown in Fig.9-(c). The design of a drum-type cable winding mechanism includes the possibility of storing both power and signal cables in a single co-axial cable as shown in Fig.9-(d). The number of lines included in a mock-up, composite cable was similar to that estimated for a real machine: 80 lines for power and 220 lines for signals. A thicker cable requires a larger spool and therefore, the cable diameter must be reduced for compact design of the cable handling system. Optimization of the cable shielding reduced cable diameter to 75 mm but made the cable sensitive to noise. The effect of noise on this system was investigated through a mock-up test.



(a) Design of cable handling

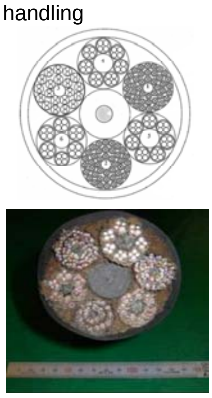


(b) Test facility of cable handling



Vertical cross section

(c) Cable winding mechanism



(d) Co-axial cable

Fig. 9 Cable handling system

4.2 Test Plan

A test stand for cable handling consists of two drums (one for vehicle simulation), a multi-cable, guide mechanism for cable winding, a simulated cable route with a guide mechanism at the front corner of a maintenance port. The feasibility of the new idea for a cable handling system with a drum-type cable winding mechanism includes compact storage of a long cable in the cask.

The following test items were included:

- Tension and torque during cable handling, including cable feeding operations along a curved route;
- Feasibility of the cable guide mechanism to feed the cable along a curved route;
- Feasibility of the cable guide mechanism to successfully wind the cable around the drum;
- Feasibility of stable cable handling with tension or torque control, according to the simulated speed of the vehicle; and
- Impact of the noise-to-sensor signal via the slip-ring and a long, multi-cable which supplies power to the AC servo motors.

3. Conclusion

The recent test results of blanket module installation using a full-size mock-up facility were presented in order to demonstrate the feasibility of the new sensor-based control system, which includes robot vision for position measurement using a monocular vision method, torque control and force measurement to achieve fully remote module maintenance. The major results of the verification tests include:

- A measurement scheme applying a monocular vision method using a camera adapted for use in an irradiated environment, was verified for achieving rough positioning prior to key insertion. Position accuracy was -3 mm, -10 mm and 10 mm for rough positioning on the x, y and z-axes, respectively.
-, Confirmation of the basic function of a torque control scheme which defers excessive loads on the AC servo motor during key insertion in order to avoid jamming between the blanket module and keys due to overloading during module installation.
- Evaluation and proposal of a method for measuring the six forces acting on the end-effector in order to achieve accurate key insertion.
- Positioning repeatability to start rough positioning of the rail assembly was verified to determine the final design of the positioning arm equipped with an Oldham's coupling on the end to absorb any disparity in the position of the arm and rail.
- A new idea for the cable handling system with a drum-type cable winding mechanism was designed. Major test items to verify the design will be examined.

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