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Study on the key technologies of the Transfer Equipment Cask for Tokamak Equator Port Plug

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HIGHLIGHTS

- Design on Intelligent Air Transfer System (IATS) for Transfer Equipment Cask (TECA).
- A rhombic-like parallel robot for docking with minimum misalignment.
- Design on electro-hydraulic servo system of the TECA for Tokamak Equator Port Plug (TEPP) manipulation.
- A control architecture with several algorithms and information acquired from sensors could be used by the TECA for Remote Handling (RH).

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ABSTRACT

The Transfer Equipment Cask (TECA) is a key solution for Remote Handling (RH) in Tokamak Equator Port Plug (TEPP) operations. From the perspectives of both engineering and technical designs of effective experiments on the TEPP, key technologies on these topics covering the TECA are required. According to conditions in ITER (International Thermonuclear Experimental Reactor) and features of the TEPP, this paper introduces the design of an Intelligent Air Transfer System (IATS) with an adaptive attitude and high precision positioning that transports a cask system of more than 30 tons from the Tokamak Building (TB) to the Hot Cell Building (HCB). Additionally, different actuators are discussed, and the hydraulic power drive is eventually selected and designed. A rhombic-like parallel robot is capable of being used for docking with minimum misalignment. Practical mechanisms of the cask system are presented for hostile environments. A control architecture with several algorithms and information acquired from sensors could be used by the TECA. These designs yield realistic and extended applications for the RH of ITER.

1. Introduction

The ITER (International Thermonuclear Experimental Reactor) is the most promising candidate for superconducting nuclear fusion. Tokamak could provide sustainable development in clean energy for commercial use in the next decades. This unique advantage has received increasing attention in both scientific research and government energy strategy considerations. This international collaborative project is aiming to study and search for physical feasibilities and technical design schemes for the Tokamak Complex; these are the key steps toward practical nuclear fusion.

The Tokamak Complex has numerous benefits; however, the hostile environment appears to be the biggest obstacle [1]. Components inside the Vacuum Vessel (VV) are placed into ray activation; these components are contaminated by toxic substances, such as beryllium, which could spread to the device hall. Furthermore, these components are successively deuterated or tritiated in the plasma process. Because of these extreme working conditions, the operation of the internal components cannot come into contact with personnel and must be replaced by a Remote Handling (RH) system [2].

Transfer Equipment Cask (TECA) is one type of RH system which should be considered in the operation of Tokamak; this RH system should be implemented in detail to protect operators from harmful effects of radioactivity. On the one hand, the TECA is a

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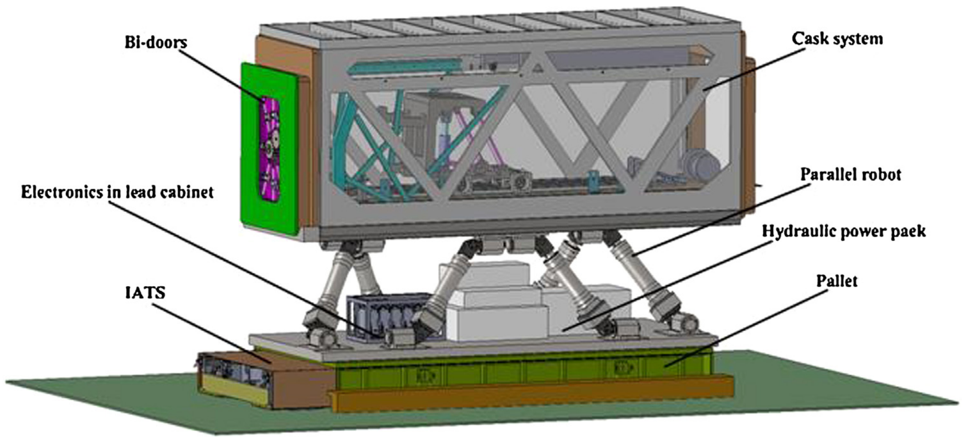

Fig. 1. The TECA.

synergistic combination and inseparable project of the RH that is used to transfer the Tokamak Equator Port Plug (TEPP) or radwaste capsules from the Tokamak Building (TB) to the Hot Cell Building (HCB) [3]. This could confine the contamination within the cask and stop the spread of radioactive dust into the TB. A few sensors with radiation shield are in the cask, such as limit switches. Additionally, plenty of controllers and sensors for driving lay inside the sealed cabinet with lead plates. Thus, the radiation hardness is confined inside the cask diminishing the effects on the electronics. On the other hand, the TECA is significantly important for other teams, including the Blanket Shield Module (BSM) and Divertor Cassettes, because their systems also require the transfer of operation components [4]. Transportation of different tools also heavily relies on the TECA. Our TECA proposes a potential feasible technique to directly enhance the cooperation opportunities.

China National Magnetic-Confinement Fusion Energy R&D Program (ITER) is a semi physical representation of all sizes and weights of all parts in the Tokamak Complex; this program is the 1:2 mock-up for the experiment, which is a balance of the finances with the research risks. The TECA, as one of the work plans in the above research program that is consulted on by the ITER Cask and Plug Remote Handling System (CPRHS), is aiming at the TEPP, which will be a solid step for the Transfer Cask System (TCS) in RH. Notably, the sizes and weight-bearing of the cask system in ITER are 8.5 m × 2.62 m × 3.68 m and 45 tons, which are scaled down to 4.25 m × 1.3 m × 1.75 m and 30 tons, respectively [2]. Additionally, the TECA could be scaled up to a surplus capacity of 48 tons according to the payload. The program will develop the full system in the subsequent research projects.

The TECA is divided into four components which are presented in Fig. 1: the Intelligent Air Transfer System (IATS), pallet, parallel robot and cask system. All facilities are 1:2 mock-ups that are aiming to justify the technical designs and implementation methods. The remainder of the paper mainly provides details of the system solution from the following aspects: the design of the IATS; the mechanism of the parallel robot, bi-directional sealing doors (bi-doors) and tractor; the electro-hydraulic servo drive system and the control architecture and sensors. These four parts are integrated into a compact system, which is designated TECA.

The specifications of each module in the TECA relevant to ITER requirements are as follows:

- Loading capability of the IATS: ≥30 tons.
- Navigation misalignment of the IATS: ±10 mm.
- Size of cask: 4.25 m × 1.3 m × 1.75 m ($L \times W \times H$).
- Docking misalignment: ±1 mm.
- Retractable force to the TEPP: ≥5.6 tons.
- Leakage rate in the cask: ≤1 Pa l/s.

ITER environment relevant to the TECA are presented as the following:

- Irradiance rate: 1×10^3 Gy/h.
- Operating temperature: <80 °C.

2. Intelligent Air Transfer System

The IATS, known as the air film transporter, provides advantages in flexible path planning, tight integration, large weight-bearing capacity and high precision of positioning. Because of the confined footprint from the HCB to the TB, the IATS is the preferred transporter compared with wheeled, rail and crawler transporters such as trucks, trams, and tractors. These other transporters may result in unbearable sophisticated problems including vibration, noise, friction and abrasion in a fusion nuclear environment. Additionally, designs of the IATS for the TECA are discussed because their intelligent characteristics meet the requirement of the RH and precision in ±10 mm of navigation and adaptive attitude for loading 30 tons.

2.1. Modular design on IATS

The modular design of the IATS is illustrated in Fig. 2. Several distinctive features of the IATS include the highly rigid frame for

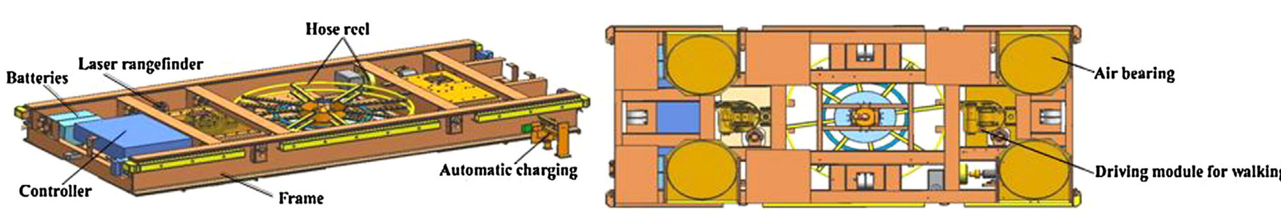

Fig. 2. Intelligent Air Transfer System.

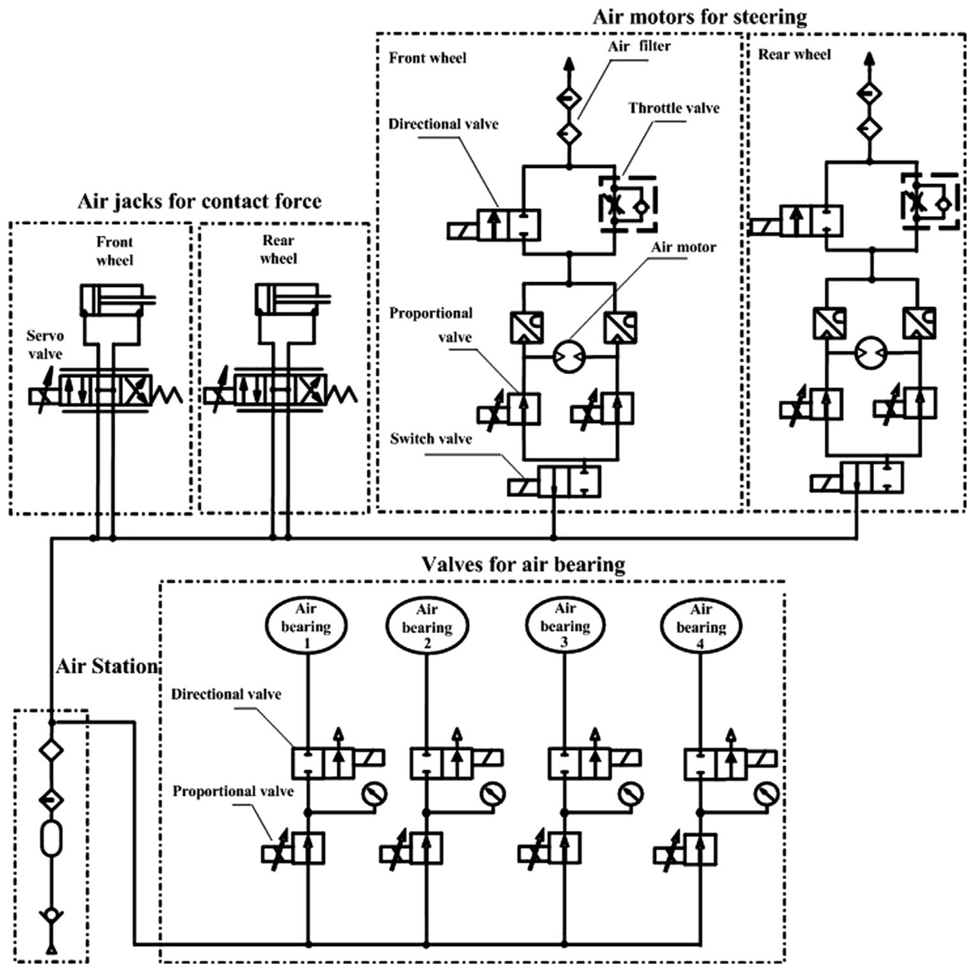

Fig. 3. Pneumatic design of the IATS.

heavy loading, effective air bearings for a loading film, and the driving module for precise walking. The trussed frame could provide mechanical properties for the weight-bearing margin and compact space for integration of other modules.

2.2. Pneumatic drive for loading and attitude control

The pneumatic designs for the loading and attitude control are illustrated in Fig. 3. Adaptive attitudes for matching the pressure with loads are important characteristics of the pneumatic drive. Thus, the pneumatic drive combined with laser rangefinders on each corner of the IATS have regulation functions on the deflated thickness that could be controlled by height adjustments of each air bearing to the floor. In addition, the contact force of the driving wheels with the ground and walking angles could be regulated.

2.3. Path planning

One specified trajectory is predetermined for the galleries from the TB to the HCB. Both the velocity and acceleration of the IATS along the selected trajectory are also predefined. The risk of collision is also carefully analysed when the IATS moves in the galleries or other confined environments. Additionally, trajectories of the IATS should maximize for the number of obstacles and motion smoothness, whereas minimize the path length [5].

3. Pallet

3.1. Pallet as interface

The pallet, as the bearing framework, plays three important roles as shown in Fig. 4:

1. Location and lock on limit guides for the cask system after the IATS departs.
2. Interface for the IATS and the parallel robot.
3. Load-bearing for the cask system.

3.2. Automatic charger on the pallet

Many components, such as batteries and the hydraulic drive, require a power supply. The TECA will draw power after arriving at designated locations; current intensity could reach 150 A, and the peak value is above 200 A. An electromotive handspike is used to implement the contact displacement, and then facilities on the pallet will be charged automatically. Furthermore, the power of the IATS also charges automatically in the parking area.

4. Mechanisms of the cask system

Mechanisms of the cask system are cornerstones for job performance and special manipulations. The cask system mainly consists of a parallel robot, bi-doors and a tractor. In view of the previous

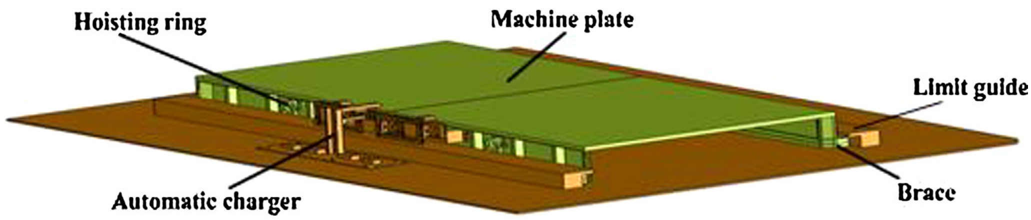

Fig. 4. The pallet.

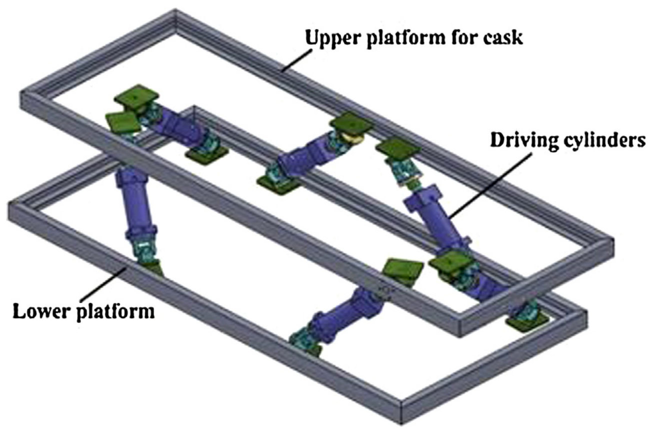

Fig. 5. Parallel robot for docking.

designs and analysis in the ITER [6–8], this paragraph will discuss the primary designs of the cask system.

4.1. Parallel robot for docking

The parallel robot is suitable for docking between the bi-doors on the cask and equator port [9]. This allows for more flexibility and generality for cask system docking to VV ports with 6 degrees of freedom (DOFs) when compared with the jacking system in the CPRHS [3,11]. Docking misalignments depend both on static heavy loads and dynamic loads caused by the manipulations of the TEPP. The parallel robot should be a better choice because of the high stiffness and precision. Additionally, the parallel robot, which has been widely used in various technological fields, is mature and reliable. The mechanism of the parallel robot with a rhombic-like structure is presented in Fig. 5. The parameters for the manipulation of the TEPP are listed in Table 1. The initial height is 995 mm and the maximum restrained angle in a single DOF could reach 18.75°.

4.2. Mechanisms in the cask

Manipulators and tools in the cask, i.e., the bi-doors and tractor, are engaged in teleoperation in hostile contaminations [10]. Mechanisms in the cask are presented in Fig. 6.

4.2.1. Bi-directional sealing doors

The purpose of using bi-doors with specified open/close procedures is to confine the contamination of radioactive doses in the cask. The bi-doors contain a cask door and maintenance door which are located on the cask and port of the VV, respectively. Several interfaces on each door are used in guidance during docking [11]. After docking has been accomplished, the cask door and maintenance door are locked together and draw back to the roof of the cask following the programming path along the tramroads.

4.2.2. Tractor

The tractor is divided into a manipulator and drag mechanism. The frame of the manipulator is supported by a pair of hydraulic cylinders which are servo actuated to jack-up into the holes of the interfaces on the TEPP. The drag mechanism consists of a driving motor, a reducer, pulleys, riggings and guideways. Notably, two groups of guideways are used for bearing loads and preventing tilting of the manipulator with the TEPP.

5. Electro-hydraulic servo drive for the TECA

Considering the heavy loads, dynamic loads, a high stiffness for the articulation and precision on actuators at lower velocities, a hydraulic drive should be selected. After comparing the drive with electromagnetic actuators, a hydraulic drive will provide strong supports to the RH for casks weighing more than 30 tons.

The main advantages of the hydraulic drive are listed as follows:

(1) High rigidity. The drive easily gains much more control force that is more applicable to heavy loads handling.
(2) More security. The drive is able to hold pressure for self-locking and provide protection against overloads.
(3) Higher integration. Lighter and smaller actuators at the identical level of power enhance the abilities of the mechanical assembly and enlarge the available space.
(4) Electro-hydraulic servo drive has a better performance for dynamic responses and precision to 2 μm under heavy loads.

Along with the benefits of the hydraulic drive system, the system maintains the challenge of docking a bulky cask into the port of the VV with a $\pm$1 mm misalignment, large loads of the TEPP manipulation with close tolerance [6], and limited space for bi-doors operations. We propose a hydraulic design to address with those problems. Furthermore, the drive is the foundation of water hydraulic power drive for the TECA.

The hydraulic drive system contains four components: the hydraulic power pack for the fluid with variable pressures and flow, valve units for the servo control, actuators for 14 joints and sensors for real-time detection. The operational parameters for the cask system are summarized in Table 2.

5.1. Drive for the parallel robot

Docking of the cask is remotely handled by the parallel robot that is conducted to the force/position hybrid control by the hydraulic channels and feedback sensors.

The hydraulic channels for the parallel robot provide positioning with high accuracy and holding pressure for self-locking. In detail, the valves and hydraulic power pack are combined to execute four control modes. In brief, the solenoid valve could be used to select the control function. The stroke of the hydraulic cylinders is controlled by the servovalve. The force and velocity of the actuators are regulated by the reduce valves and proportional throttle valve.

Table 1
Parameters for a parallel robot.

Orientation	Working space	Acceleration	Velocity	Acceleration (deceleration) time	Even time	Repeatability
T_x	±0.155 m	0.008 m/s^2	0.023 m/s	2.929 s	14.142 s	0.3 mm
T_y	±0.21 m	0.016 m/s^2	0.023 m/s	1.464 s	7.701 s	0.3 mm
T_z	±0.09 m	0.024 m/s^2	0.035 m/s	1.464 s	7.071 s	0.3 mm
Pitch	±4.2°	0.014 rad/s^2	0.020 rad/s	1.459 s	7.082 s	0.05°
Yaw	±11°	0.014 rad/s^2	0.020 rad/s	1.459 s	7.082 s	0.05°
Roll	±8°	0.014 rad/s^2	0.020 rad/s	1.459 s	7.082 s	0.05°

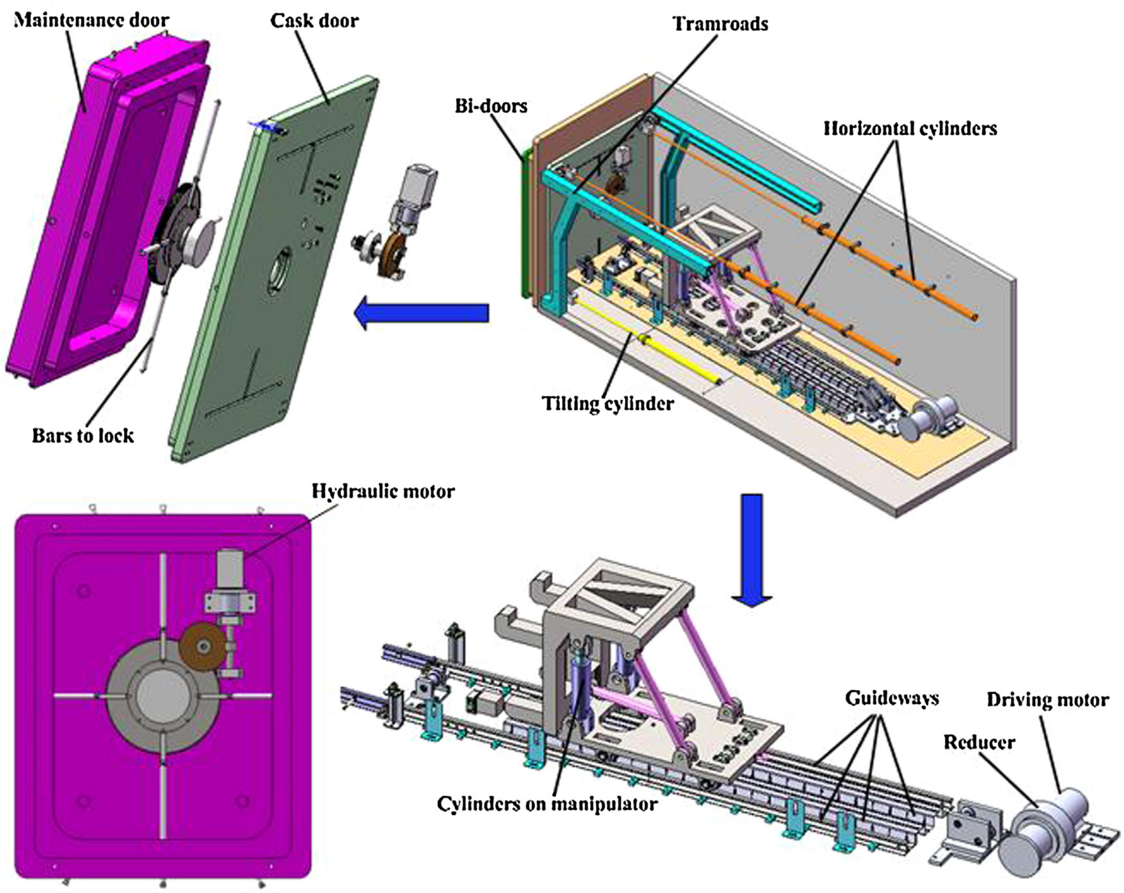

Fig. 6. Mechanisms of the cask system.

1. Quick return/extension function.
   Fluid in the cylinders returns to the tank directly whereas the left coil of the solenoid valve is energized.
2. Self-locking function.
   Cylinders maintain balance with loads by hydraulic locks, and the servovalve and solenoid valve are in the neutral position simultaneously. Thus, the two stages of self-locking improve the security and reliability. Simultaneously, the pump will be in standstill and the accumulators begin to work and sustain the work pressure.
3. Servo functions on the position control.
   The pressure and flux in the inlets of each cylinder are controlled by a servovalve. The flow which returns to the tank is regulated solely by a proportional throttle valve when the right

Table 2
Requirements of operation for mechanisms in the cask.

Module	Parameters	Comments	Value (max)
Tractor	F_{t1}, F_{t2}	Operating force of manipulator	80 kN
	T_t	Torque of rigging	1500 N m
	n_{tmax}	Speed of rigging	0.05 m/s
Bi-doors	T_s	Torque for bi-doors	86 N m
	n_{smax}	Rev of motor in cask's door	200 r min^{-1}
	F_h	Force of horizontal cylinders	6 kN
	F_a	Force of tilting cylinders	6 kN
Parallel robot	F_p	Force of driving cylinders	196.35 kN

coil of the solenoid valve is energized. Therefore, that position in the servo control is enabled, and the flow coupling of each cylinder is eliminated.

4. Servo functions on force control.

   The relief coefficients on the back pressure in the return port are regulated by a proportional throttle valve according to the loads whereas the solenoid valve is in a neutral position. The driving force could be controlled and the pressure coupling could be removed among each cylinder.

Finally, the positions of these six cylinders are controlled by a servovalve and proportional throttle valves when the flux of the fluid in the hydraulic cylinders returns to the tank. Conversely, the force servo function is performed by reduce valves according to the back pressure on the return port in each cylinder.

A description of the hydraulic channels for the parallel robot that control procedures for the docking is presented in Fig. 7. The PLC in the cask regulates the parameters of pressure and flux through the servovalves, whereas the solenoid valve and proportional throttle valve are energized to realize the function switch. Combining this process with the displacement sensors and the attitude measurement module, the host computer performs the control process for the parallel robot with several algorithms such as impedance algorithms.

5.2. Drive for the internal cask

The abilities to open/close the bi-doors and manipulate the TEPP are the main power driving objectives inside the cask.

5.2.1. Motion control of the bi-doors

The bi-doors are locked together by a hydraulic motor on the cask door with a locking mechanism. The horizontal cylinders and two tilting cylinders are servo driven with 16:7 matching speed to open/close the bi-doors along the predetermined trajectory with movement on the tramroads in the cask. Each hydraulic cylinder is able to self-lock and synchronize for the identical pair of cylinders. Simulations for the opening process of the bi-doors in Adams are illustrated in Figs. 8 and 9.

5.2.2. Drive for the tractor

The tractor consists of a manipulator and a drag mechanism. Two hydraulic cylinders in the manipulator cooperate to jack-up the TEPP, and the hydraulic motor coupled to a 1:20 reducer in the drag mechanism will draw back the manipulator with the TEPP. The buffer bridge could reduce the pressure surfing caused by the substantial inertia of the retracting process.

5.3. Hydraulic power pack

The hydraulic power pack has two functions which transfer power into the hydraulic flowrate and pressure to the actuators.

5.3.1. Power fluid supply

The hydraulic power pack supplies the fluid with a variable flowrate and pressure, and the pressure will be 12–16 MPa and 21–25 MPa for the high and low flow cases, respectively. The parallel robot can use high pressures with low flowrate, whereas the motion of the bi-doors and tractor are also achievable with a high flowrate and lower pressure. The power pack contains valves, pumps and accumulators. The flowrate and pressure are controlled by a sequence of logical operations.

5.3.2. Cooperation for the servo drive

The power pack has four elements. The first piston pump is the major supply of power in the fluid. The second piston pump

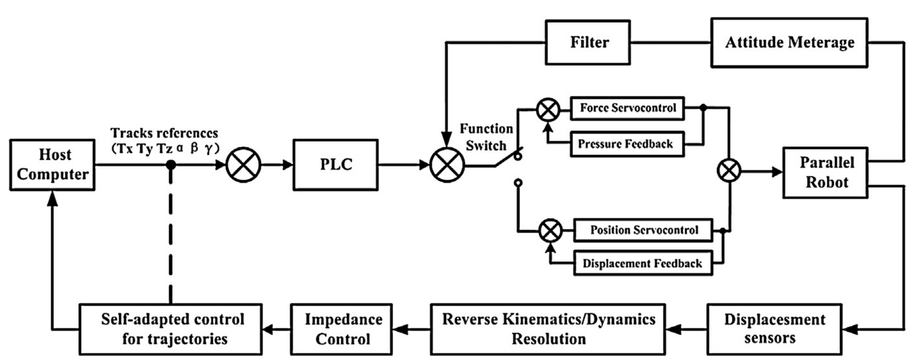

Fig. 7. Force/position hybrid control for the parallel robot.

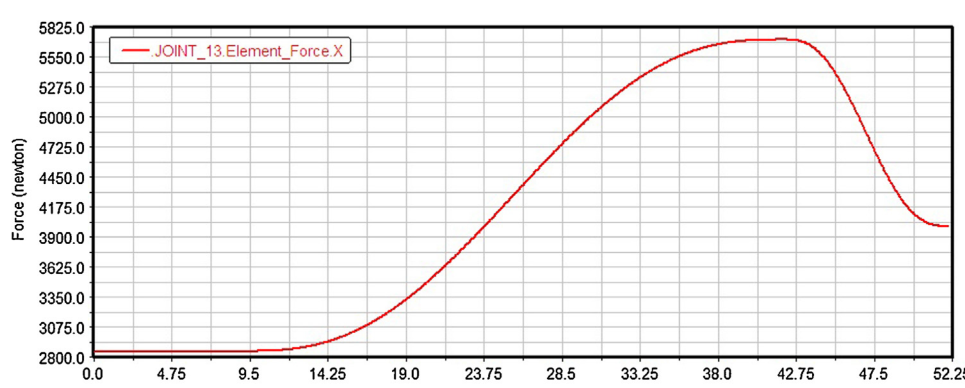

Fig. 8. Simulation for tilting cylinders.

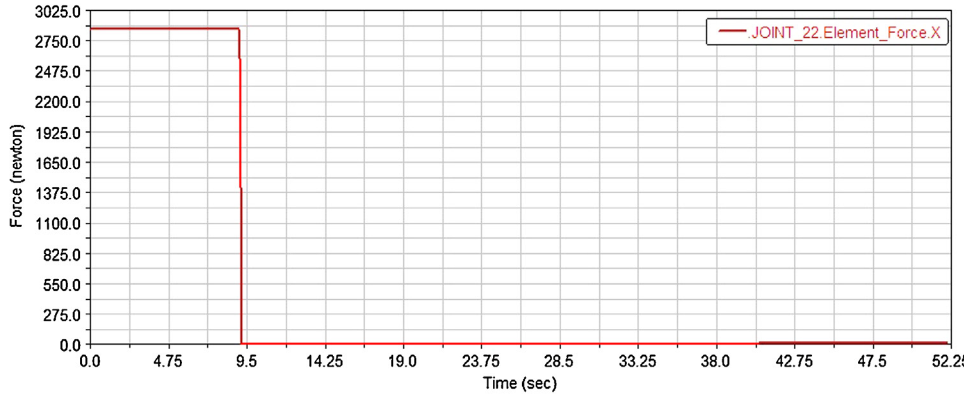

Fig. 9. Simulation for horizontal cylinders.

Table 3
Actuators in the hydraulic drive.

Mechanism	Elements		No.	Force (16 MP)		Flux (100 mm/s)		Speed		Stroke
				Push	Pull	Out	In	Normal	Peak	
				(kN)		L min^{-1}				
Tractor	Cylinders		2	80.42	41.01	30.2	15.4	5–10 mm/s	10 mm/s	280 mm
	Motor for drag		1	15–47 N m		10.6		100 r/min	200 r/min	120 r
Bi-doors	Locking	Motor	1	74–86 N m		12		0.1 rad/s	200 r/min	40 r
	Open/close	Horizontal cylinders	2	20.1	10.24	7.5	3.8	20 mm/s	45 mm/s	1600 mm
		Tilting cylinders	2	20.1	10.24	7.5	3.8	13 mm/s	25 mm/s	700 mm
Parallel robot	Driving cylinders		4	196.4	94.56	73.6	35.5	0–28 mm/s	35 mm/s	400 mm

is redundant for power storage and oil filtration. The accumulators are used for pressure holding, and the gear pumps are used as a supplement to the accumulators and control for pilot valves.

In summary, the electro-hydraulic servo drive is the hardware for the hybrid force/position control to provide high-quality performances on the parallel robot and the actuators in the cask. The abilities of actuators are illustrated in Table 3, and the hydraulic design for the TECA is presented in Fig. 10.

6. Control architecture and sensors for the RH

The control architecture consists of one host and two slave controllers which execute operations in each system. The host

Table 4
Sensors in the TECA.

Mechanism		Elements		No.	Location	Specification
Cask	Bi-doors	Approach switches		2	Tramroads	Limited stroke of actuators
		Displacement transducer		2	Bars on the lock	Locking detection of bi-doors
	Tractor	Manipulator	Limit switches	1	Articulate joint	Limit positions of actuators
				2	Frame	Tilting angle of manipulator
	Inside Cask	Vision sensors		2	Cask's corners	Scenes of internal cask
		Limit switches		2	Doorway/rear of cask	Limit position for tractor
Parallel robot		Laser sensors		4	Top platform	Attitude of cask to floor
				8	Cask	Attitude of bi-doors relative to TEPP
IATS		Laser sensors		4	Front/rear of frame	Navigation
		Electromagnetic sensors		2	Front/rear of frame	Redundancy
		Infrared sensors		2	Front/rear of frame	Obstacle avoidance
		Vision sensors		2	Front/rear of frame	Scenes of environment
Hydraulic system		Pressure sensors		1	Pump	Variable pressure
				24	Actuators	Force control
				2	Key points	Monitor
		Flow sensors		1	Pump	Flowrate detection
				4	Key points	Monitor
		Displacement/angle transducers		14	Actuators	Position/speed servo control

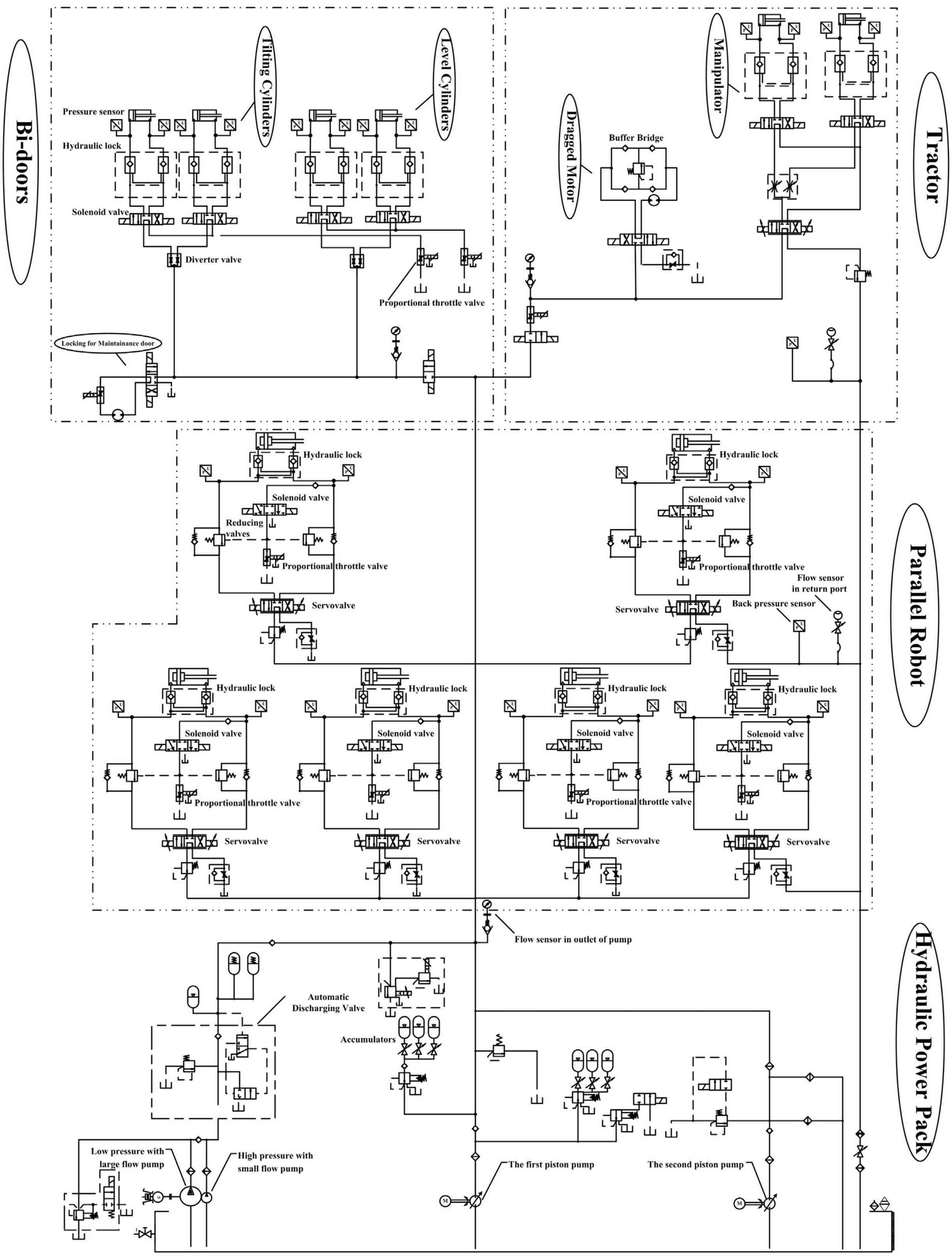

Fig. 10. Hydraulic design for the TECA.

computer in the centre control room is responsible for implementing algorithms, managing the safety, allocating tasks and exchanging instructions with the slave controller to supervise the actual operation sites [12]. The PLC in the IATS ensures automatic tracking and obstacle avoidance when moving in the galleries. The PLC on the cask is the master for docking the cask and the TEPP are remotely handled successively. The control architecture is illustrated in Fig. 11.

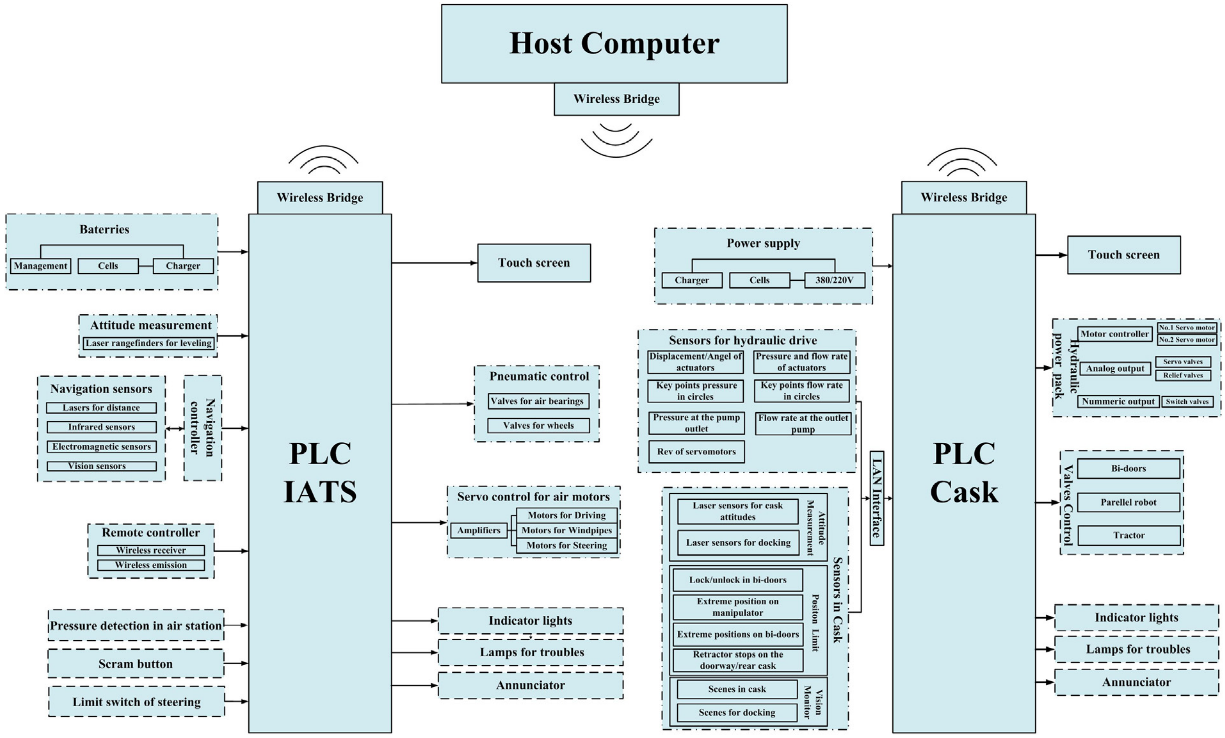

Fig. 11. Control architecture for the Remote Handling.

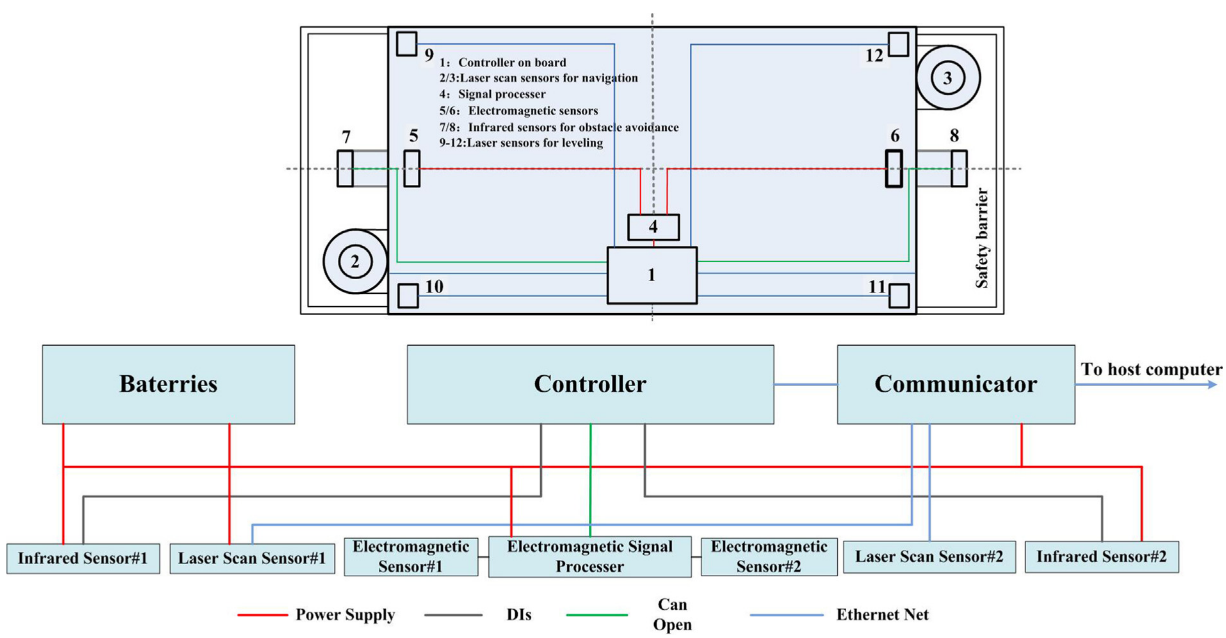

Fig. 12. Schematic diagram of the sensors on the IATS.

Sensors, which are configured on the TECA, are used for feedback information of the operations and environment. The details are listed in Table 4.

6.1. Controls for the IATS

The controller is selected for the PLC to exchange instructions with a remote master controller using wireless communication. The motion of the IATS is dominated by the predetermined path from the TB to the HCB. Thus, the IATS can be directly manipulated and monitored by the host computer. Additionally, the autonomous positioning with obstacle avoidance and man-in-the-loop modes are complementary methods despite of preassigned trajectories. Man-in-the-loop is an important method that could introduce human intervention, including commissioning and real-time control. The purpose of these three modes is specialized for complex operations and preserves promotion opportunities to generalize more flexible paths.

The sensors on the IATS for navigation and attitude measurement are separable for realization of these three control modes. A set of laser sensors, including electromagnetic sensors and infrared sensors, are used for the dynamic perception of the deflated

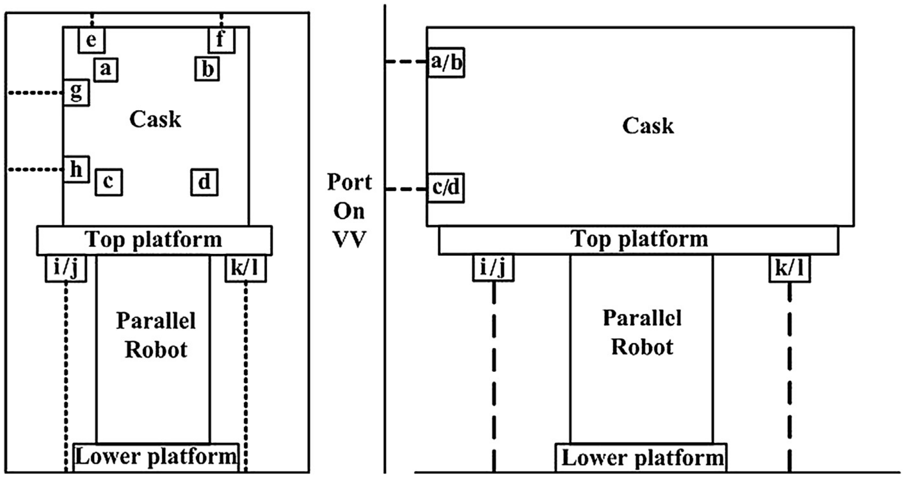

Fig. 13. Sensors for docking to the port of the VV.

thickness and angles to attitudes. These values are fed back to allow for steering along the predefined routing or autonomous navigation. The use of these laser sensors is a primary means of navigation whereas the electromagnetic sensors are redundant. Several reflective labels are present in the work environment for the laser sensors which could generate a full range of position and attitude information. The electromagnetic sensors, associated with the predetermined electric wires under the floor, provide auxiliary navigation information during a specific operation. Infrared sensors are used for obstacle avoidance in the running direction. In the corners of the IATS, four laser sensors (laser rangefinders) for levelling are equipped for attitude control. The physical joints of these sensors on the IATS are illustrated in Fig. 12. Based on these sensors, autonomous navigation is also feasible to allow for flexible path planning dependent on the on-board PLC.

The performance of each sensor is specified:

navigation error of the laser sensor: $\leq$10 mm,
navigation error of the electromagnetic sensor: $\leq$30 mm,
positioning error of the charger: $\leq$20 mm,
update frequency of the electromagnetic signal: 10 Hz, and
update frequency of the laser signal: 8 Hz.

6.2. Feedback for docking

Position and attitude information is integrated for docking. The information has been determined by the laser sensors which are located on the top of the platform of the parallel robot and cask door. Sensors on the TECA for docking are presented in Fig. 13.

The laser sensors of a, b, c, d (e, f, g, h and i, j, k, l) are configured on the cask and measure transversely the relative distance X (Y and Z) and the attitude angle of deflection α (β and γ) with respect to the X (Y and Z)-axis.

6.3. Sensors for operations

The sensors for operations mainly provide information on the displacement/angle of actuators, pressure/flowrate in the hydraulic drive, limit positions of mechanisms and vision information for operational scenes.

7. Conclusions

As discussed above, the RH for the TEPP by the TECA has been successfully implemented on the 1:2 mock-ups.

To summarize the TECA and compare the TECA with the current ITER CPRHS, the system displays the following aspects:

(1) The IATS for the cask system has been designed to assure flexible path planning with $\pm$10 mm positioning error and provide the weight-bearing capacity of more than 30 tons during transportation.
(2) Mechanisms of the cask system have been shown to operate in the hostile environments and features of the TEPP.
(3) A rhombic-like parallel robot could display 6 DOFs which enhances the flexibility and generality of the docking to the VV ports with minimum misalignments compared with the jacking system in the CPRHS.
(4) The hydraulic power drive will provide more integration and better performances to the cask system. For the next research plan, the drive provides the foundation of water hydraulic power drive system for the TECA which could display higher adaptability to radiation hardness.
(5) Controllers and many sensors could be used for the real-time control and information feedback that strengthen the abilities to the RH for the TEPP.

More integration on mechanisms, smarter on air transfer systems, better performances on hydraulic manipulation, and intelligent on information feedback and control have been embodied in the TECA. All these components will play an important role in the RH for ITER in future.

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