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Analysis and optimization on in-vessel inspection robotic system for EAST

Weijun Zhang*, Zeyu Zhou, Jianjun Yuan, Liang Du, Ziming Mao

Robotics Institute, Shanghai Jiao Tong University, Shanghai, PR China

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ABSTRACT

Since China has successfully built her first Experimental Advanced Superconducting TOKAMAK (EAST) several years ago, great interest and demand have been increasing in robotic in-vessel inspection/operation systems, by which an observation of in-vessel physical phenomenon, collection of visual information, 3D mapping and localization, even maintenance are to be possible. However, it has been raising many challenges to implement a practical and robust robotic system, due to a lot of complex constraints and expectations, e.g., high remanent working temperature (100 °C) and vacuum (10^{-3} pa) environment even in the rest interval between plasma discharge experiments, close-up and precise inspection, operation efficiency, besides a general kinematic requirement of D shape irregular vessel. In this paper we propose an upgraded robotic system with redundant degrees of freedom (DOF) manipulator combined with a binocular vision system at the tip and a virtual reality system. A comprehensive comparison and discussion are given on the necessity and main function of the binocular vision system, path planning for inspection, fast localization, inspection efficiency and success rate in time, optimization of kinematic configuration, and the possibility of underactuated mechanism. A detailed design, implementation, and experiments of the binocular vision system together with the recent development progress of the whole robotic system are reported in the later part of the paper, while, future work and expectation are described in the end.

1. Introduction

The first Experimental Advanced Superconducting TOKAMAK (EAST) was built in Hefei city of China in 2006 [1], and has been keeping in experimental operation for years. It was reported that the plasma facing components (PFCs) [2], namely, the main parts of first wall in vessel, were partially damaged in some local areas due to the high energy particles and electromagnetic force, and had been optimized and upgraded to full graphite tiles bolted to copper alloy heat sinks from 2008 [1]. The maintenance was a long term and hard task, nevertheless, has to be carried out cyclically in future. Robotics and remote handling technologies therefore have been considered as great challenges for such routine maintenance [3], or for an observation of in-vessel physical phenomenon after the experiments, or for a collection of visual information, etc., since their robust automated/tele-operated features are capable of doing multiple in-vessel operation/inspection tasks without converting or breaking so much the initial environment.

We have proposed a conceptual robotic system composed of base, big arm, and small arm with 10 degrees of freedom in total for EAST inspection, as shown in Fig. 1. The base has one translation and two rotation joints, the big arm takes three sliding DOFs and is responsible to move along toroidal direction in an equatorial plane of the TOKAMAK, and the small arm is for the motion in each vertical section. More detailed description of the structure could be found in literature [4]. So far the situation and requirements for robots have been changing a lot under a long term investigation. An updated discussion on the in-vessel inspection features is given in order to make the later optimization and development easy to be understood.

1.1. A fast setup

The main body of robot is stored in an extended equatorial port ($W \times H$, 528 mm × 970 mm) directly connected to the TOKAMAK with an identical vacuum pressure of 10^{-4}–10^{-5} pa during plasma discharge, and is driven in/out through the port between the experimental intervals. A thermal shield may be placed to protect the robot.

* Corresponding author.
E-mail address: zhangweijun@sjtu.edu.cn (W. Zhang).

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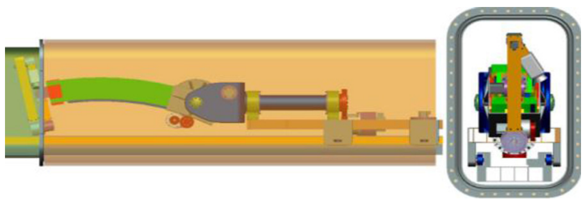

Fig. 1. The inspection robot system.

A fast setup means that the robot is capable to be used in the first couple of days of experiment intervals while the in-vessel temperature is still high (100 °C level). It helps people to understand early and well on: (1) what have happened in-vessel, especially for physical phenomenon, (2) whether to perform maintenance or to continue scheduled experiments directly, and (3) precise location of the place needs to repair/replace. It enhances an efficient way to fusion research; the intervals could also be shortened consequently.

The Articulated Inspection Arm robot (AIA) [3] was designed for ITER under similar considerations. Recent experimental reports [5] show good function under high vacuum and high temperature conditions.

1.2. A close-up observation

In order to collect sufficient information of the first wall from scheduled inspection, both accurate motion and precise images are indispensable. The former is ensured by high quality sensors and components mounted into the robot; but the latter must be realized by high definition CCD cameras, and a close-up, preferably, normal observation to the main surfaces of the PFCs.

However, performing a very close-up observation takes long time for a whole in-vessel scanning, which not only is inefficient but also enlarges risks of unexpected collision, for instance. Therefore, a switch function of control software is superior to make a optimal effects for a fast scanning routine and a necessary close-up observation.

1.3. Toward a practical and robust implementation

As described before, first of all, an automated in-vessel inspection is highly expected for EAST to speed up the research and development of fusion technologies. Meanwhile the scientific research has to meet the requirement toward a practical and robust implementation as close as possible. A combination of high quality commercial components and highly developed techniques may make sense.

2. An upgraded proposal of robotic system

2.1. A binocular vision system

We propose a binocular vision system attached to the tip of the robot manipulator, and basically is comprised of two different spec CCD cameras. One camera is in charge of routine but fast scanning task with auto focusing spec, keeping a close distance (250 mm level) from the camera front to main surface of the PFCs. The other camera is with manually adjustable focus lens but higher resolution spec, and is particularly used for more close-up inspection, the distance from the lens front to PFCs is 100 mm level.

In order to enhance the inspection efficiency, we install the two cameras very closed to each other but vertically distributed up and down, as shown in Fig. 2. When any suspect image is found during a routine vertical scanning, the system is able to response directly, by interrupting the scanning task and giving an instant close-up inspection at the spot. The high resolution camera then sends back high quality images for further diagnosis. An example is given in the right side of Fig. 2.

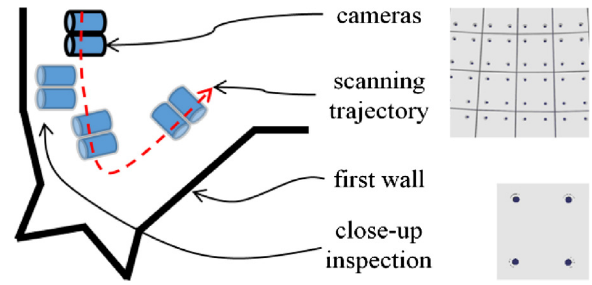

Fig. 2. The objective of binocular vision system.

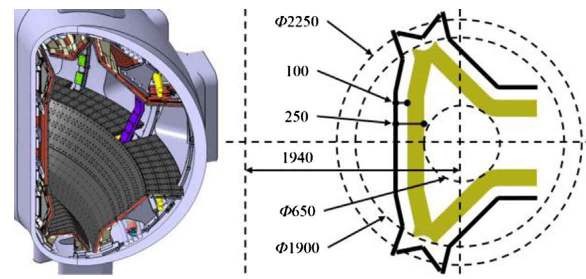

Fig. 3. In-vessel dimension unit of mm.

2.2. Structural optimization

Fig. 3 shows a schematic in-vessel dimension of vertical section of EAST. A highlighted workspace of the camera/lens fronts is plotted between fast scanning (250 mm) and precise close-up inspection (100 mm). The robot, particularly, the small arm for vertical section motion must be capable of carrying the vision system to traverse the whole workspace, and contracting its pose into the equatorial port.

It is easy to find a maximum and a minimum concentric radiuses (namely, r_{max} and r_{min}) from the workspace. While, the distance from polar-axis to the common center is defined as *equatorial radius* R_e, which is 1940 mm in EAST. With a detailed examination in Fig. 4, we consider a serially linked configuration with three revolute joints for the small arm, and set the first joint *S*-I locate at the common center.

Define a and b as joint to joint lengths for each arm frame, while, c as joint to camera front distance and partially determined by dimension of the vision system. The three parameters basically keep following geometric/kinematic constraints.

- Maximum reachable constraint:

$$a + b + c \geq r_{max}$$

- Minimum reachable constraint:

$$c + (a - b) \leq r_{min},\ \text{or},\ c - (a - b) \leq r_{min}$$

- Safety constraint:

$$\max(a, b, c) \leq r_s$$

- Normal observation constraint.

Computational optimal solutions of a, b, and c are derivable by dividing the linearized vertical section boundaries into