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Structural synthesis and motion analysis of hyper-redundant remote maintenance robot for small openings

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1. Introduction

Remote handling operation for monitoring and maintenance is critical for most fusion facilities [1-5]. Such devices usually have common characteristics: 1) small openings, 2) larger interior space, 3) complex internal structure, etc.

Traditional industrial robots cannot satisfy the unique maintenance demands mentioned above and these existing methods aren't suitable of structural synthesis of redundant robot [6-8].

Therefore, we should explore a novel structural configuration synthesis approach and motion analysis process for hyper-redundant robot, which can be used to remote maintenance of small opening devices.

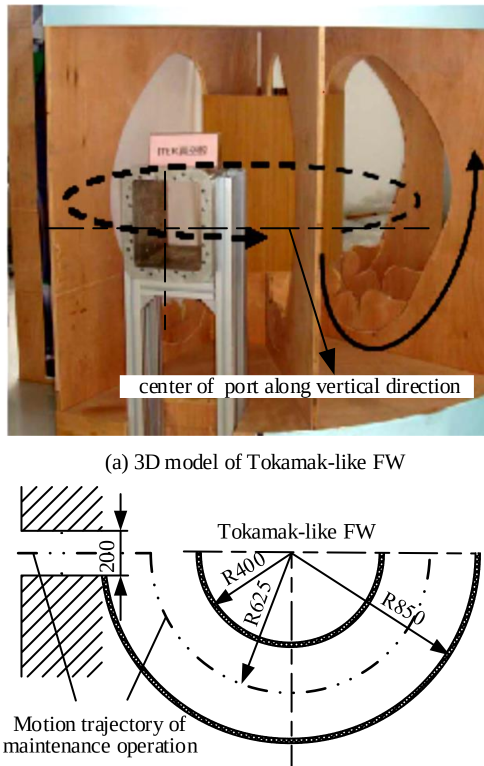
In this paper, we aim to address a maintenance task based structural synthesis methodology that can be seen as a simple and practicable tool for redundant robot structural synthesis based on particular task. Then, taking the remote handling maintenance robot of Tokamak-like First Wall (FW) for example, the proposed structural configuration methodology can help the correlation designers to consider task description and spatial geometrical constraints, acquires robot structural configuration, and robot prototype for the special maintenance task of Tokamak-like FW.

2. Description of maintenance task

A Tokamak-like FW prototype is constructed according to 1:10 scale of ITER Tokamak, which is used to explore a remote maintenance manipulator (RMM-Robot) for Tokamak maintenance, as shown in Figure 3a.

Figure 3b represents the key dimensions of Tokamak-like FW, in which the motion trajectory of maintenance operation includes the dash arrow in Figure 3a. Its port is 250mm height and 200mm width (Figure 3b). And its maintenance space is a circumferential environment with multistage arc-shaped cross section, as shown in Figure 3b.

Therefore, how to go through the small port and do maintenance operation in the Tokamak-like FW is one of the main basis for the development of maintenance robot.



(a) 3D model of Tokamak-like FW

(b) topview of Tokamak-like FW from the center of port along vertical direction (unit : mm)

Fig.1 Maintenance principle for the RMM-Robot

3. Type synthesis for the RMM-Robot

The spatial geometric constraint equation of each joint length for the RMM-Robot is be constructed:

$$\begin{cases} L_T + H_J \le L_J \le 2R_M \bullet \sin\dfrac{\pi}{2(N_J - 1)} \\ L_J \le R_E - R_I - H_J \end{cases} \quad (1)$$

Where L_T is the transmission mechanism length for every joint; R_M is the radius of maintaining trajectory for Tokamak-like FW ; N_J is the joints number required for maintaining half a circle of Tokamak-like FW; R_E and R_I respectively represent the radius of external and internal circle for Tokamak-like FW.

Based on the equation (1), the RMM-Robot should meet some conditions [9-12]:

(1) The maintenance of multistage arc-shaped area need a 6 DoFs robot, as shown in Figure 3a solid arrow. The 6 DoFs robot is called Teleopration Robot (TO-Robot).

(2) The TO-Robot should be carried access to the Tokamak-like FW. Therefore, a load-carrying and transit robot (LCT-Robot) must be a part of RMM-Robot. And the number of DoFs for the LCT-Robot should satisfy the spatial geometric constraints of Tokamak-like FW. The LCT-Robot plays a role for horizontal toroidal maintenance, as shown in Figure 3a dash arrow.

The LCT-Robot must include a P pair for providing translation movement. So we can propose a novel configuration (see Figure 2):

$$\mathrm{SOC}\{-\underline{\mathrm{P}_0 \perp \mathrm{R}_1 \parallel \mathrm{R}_2 \parallel \mathrm{R}_3 \parallel \mathrm{R}_4 \parallel \mathrm{R}_5 \parallel \mathrm{R}_6} \\ \underline{\underline{\parallel \mathrm{R}_7 \perp \mathrm{R}_8 \parallel \mathrm{R}_9 \perp \overbrace{\mathrm{R} \perp \mathrm{R} \perp \mathrm{R}}}}-\} \tag{2}$$

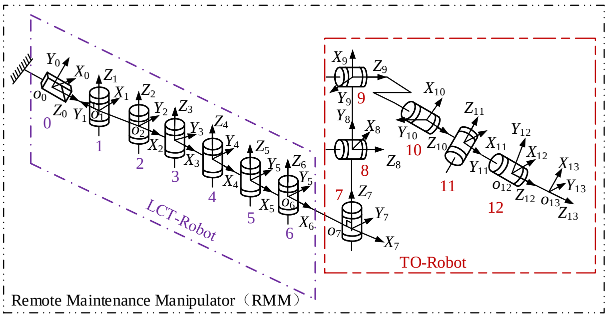


Fig.2 Coordinate frame of RMM-Robot

4. The judge condition of collision avoidance

Based on the geometric constraint Equation (1), the distance between point N to line PQ (see figure 3) is described:

$$\mathrm{d} = |[\sqrt{4R_N^{\,2} \bullet x_P^{\,2} - \left(\mathrm{R}_N^{\,2} + x_P^{\,2} - L_J^{\,2}\right)^2} \bullet \left(\mathrm{R}_E + x_P\right) - \frac{\mathrm{W}_E}{2} \bullet (\mathrm{R}_N^{\,2} - x_P^{\,2} - L_J^{\,2})] \bullet \frac{1}{2x_P \bullet L_J}| \tag{3}$$

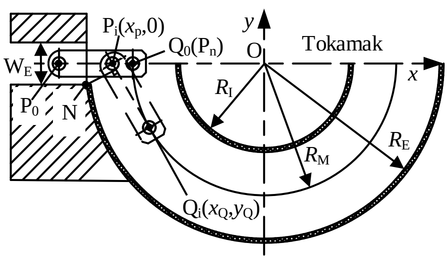


Fig.3 The judge condition of collision avoidance during entering into tokamak FW

Substitute the 1:10 FW parameter into equation (3), a series of curves represent the variable selection trend, as shown in figure 4.

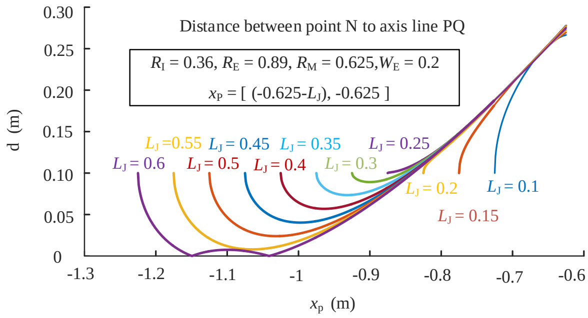


Fig.4 A series of curves between L_J and the distance collision avoidance in 1:10 Tokamak

5. Experiment and conclusion

Figure 5 shows the RMM-Robot, which is stored on a designated multipurpose transport cask(MTC).

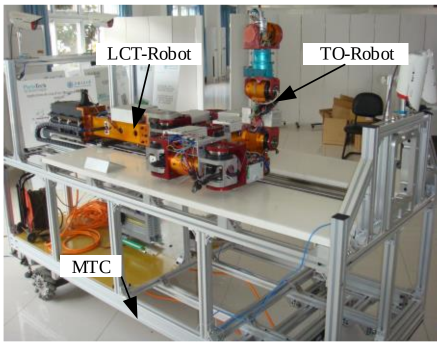


Fig.5 RMM-Robot in line with initial configuration

For verifying the correctness of the method, by means of experiment of Screwing / unscrewing some socket head cap screws located at the Tokamak-like FW, the correctness of motion planning of the 13 DOFs RMM-Robot is verified. Meanwhile, whether RMM-Robot can run access to Tokamak-like FW smoothly depends on the motion stability of the LCT-Robot.

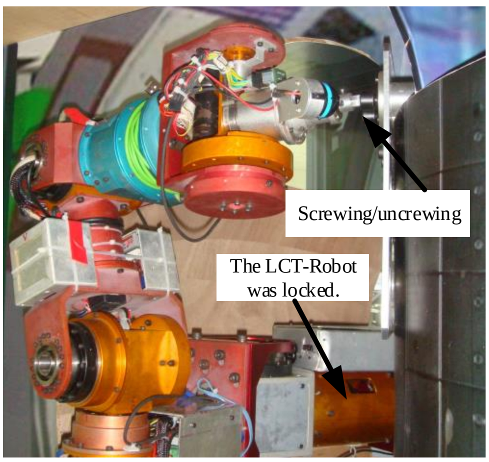


Fig.6 The screwing/unscrewing operation

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