A PERSPECTIVE ON REMOTE HANLDING EQUIPMENT (ARIA) DESIGN FOR FUSION MACHINE/APPLICATION

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Abstract

Remote Handling (RH) systems for maintenance and inspection of in-vessel components have been addressed in great detail for fusion machines around the world. Maintaining high availability of fusion machine and minimizing the maintenance time require robust and dependable RH systems. Such RH systems, being electro-mechanical in nature, requires research and development in various areas such as structural design, kinematic and dynamic modelling, efficient real-time control, and Virtual Reality (VR) based monitoring. Adding to the aforesaid requirements, is criticality of investment protection of the sophisticated in-vessel components and their size and weight scales. The Articulated Robotic Inspection Arm (ARIA) has been indigenously developed at IPR, India as a proof-of-concept for in-vessel maintenance.

The paper presents, in detail, the design and development of the ARIA and associated VR based monitoring and control system. ARIA is a 6-Degrees of Freedom manipulator with a cantilevered payload capacity of ~25kg at 2meters distance. ARIA is controlled using a VR based user interface that immerses the ARIA model into the working environment. The effective 1:1 scale mapping of the VR model with the manipulator hardware makes provision for task planning and executing of the control commands from a remote location. The theoretical calculations with structural analysis of components like links, shafts, couplers, lugs and bearings are elaborately discussed. Results for payload sensitivity analysis during dynamic behavior are also presented. The system is optimized and developed to incorporate efficient commercially available servo actuators, bearings and gear-boxes, to maintain a high degree of accuracy and repeatability. Experimental validation and test results on a mock-up facility show that the system can be controlled with an end-effector positional accuracy within 2mm. The design and integration methodology, presented here, lays foundation to develop efficient RH systems with greater reach and payload capacity for future fusion machines.

1. INTRODUCTION

Articulated Robotic Inspection Arm (ARIA) is a general purpose in-vessel remote handling (RH) system. The ARIA can perform various in-vessel maintenance tasks such as in-service inspections, defect identification and in-vessel diagnostics maintenance and payload handling capability up to 25 Kgs. ARIA consists of a series of linked bodies; B01 to B05 as shown in Fig. 1. When deployed, the base plate of the articulated arm can travel along the Linear Guide. Bodies B01 to B05 contain rotational joints that make up the articulated motion to perform the aforementioned tasks.

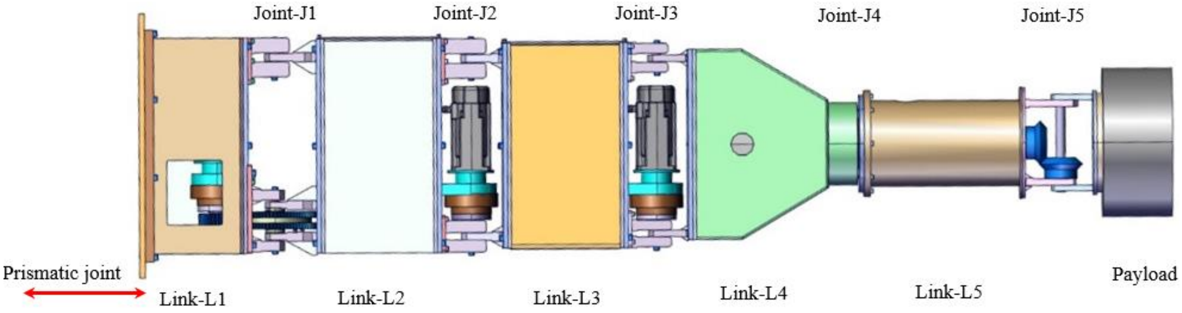

FIG. 1. ARIA: Links and Joints labelling

TABLE 1. LENGTH AND MASS OF ARIA LINKS.

Link/Body	B01	B02	B03	B04	B05
Length (mm)	293	425	402	431	410
Mass (Kg)	66.4	49.6	44.3	45.9	29.0

TABLE 2. JOINT RANGE OF ARIA ARM.

Joint	Prismatic	J01	J02	J03	J04	J05
Joint range	0-1800 mm	±65°	±65°	±65°	±180°	±65°

D. Loesser, D. Kungl, et al. [1] presented the activities involved in TFTR manipulator development which is a six link folding boom housed in a vacuum antechamber connected to vacuum torus through a port to perform defined maintenance and inspection tasks inside vacuum torus so as to minimise personnel exposure. A.Loving P.Allan, et al. [2] presented the evolution of JET RH from a small scale maintenance capability to one of high efficiency large volume installations. Various shut down phase demanded the replacement of many thousands of components ranging from about 100 g to 130 kg in weight. The scale of this type of operation and the necessity to maximise operational availability intensified the demands for high productivity whilst maintaining the necessary high standards for precision, reliability, cleanliness, and operational security. O. David, A.B. Loving, et al. [3] presented that JET has the unique experience of creating the only operational system for tokamak maintenance which has already successfully carried out long-term maintenance campaigns under fully remote conditions. Shibanuma, K., Kondoh, M., et al. [4] presented the design progress, development and demonstration of 1/5 scale concepts of the rail mounted in-vessel maintenance system and the blanket handling system for ITER/FER to confirm its feasibility. Further detailed designs of these maintenance systems in engineering design phase can be developed on the basis of the data base of the scale models. ManoahStephen M., et al. [5] have presented the conceptual design and structural reinforcements of sub-components of ITER Multi-Purpose Deployer (MPD) to verify the structural integrity of the MPD system, and to provide reaction forces to the interfacing systems such as vacuum vessel and cask based on static structural, modal and frequency response spectrum analyses (various seismic events) performed.

This paper presents the design, fabrication and testing to confirm the conceptual design of the rail mounted maintenance and inspection system with 06-Degrees of Freedom, ~2m long system with payload capacity up to 25kg with a positional accuracy of <2mm. Further the Structural optimization and reinforcement of machine elements and results for the design of ARIA taking gravity loads due to self-weight and varying payload in to consideration. There is discussion on selection and use of commercially-off-the-shelf equipment for the machine elements like gears, shafts, couplers, bearings, gearboxes etc. based on theoretical calculations. A VR based user interface is used to control ARIA that immerses the ARIA model into the working environment. ARIA demonstration test has been carried out with a cantilevered payload of 25 kg at ~2m distance in a mock-up torus vessel.

2. DESIGN OF ARIA

ARIA is 06 Degree of Freedom (DOF) system which is capable of handling 25kg cantilevered payload at a reach of ~2m. ARIA is mounted on a linear guide which acts as prismatic joint. The joints 1 to 3 are yaw joints. Joint 4 and 5 together form a roll tilt mechanism for positioning the end-effector as shown in Figure 1. ARIA is controlled using a VR based user interface that immerses the ARIA model into the working environment.

2.1 THE YAW JOINT: Distributed motorization approach in which use of actuators which directly drive the joint axis on which they act as shown in Fig. 3. The actuators components consists of upper lug and lower lugs which are interfaced with the body through keys. Cyclo-drive FC A15 has been used for higher speed reduction and no backlash. Servo Motor AKM 42C has been used to actuate the cyclo-drive for ARIA links B01, B02 and B03.

2.2 THE ROLL JOINT: In link B04, Upper Lug and Lower lugs are interfaced with the link B04 through keys to transmit the motion. Cyclo-drive F1C A25 has been used for higher speed reduction and higher moment handling capability. Servo Motor AKM 42C has been used to actuate the cyclo-drive. The cyclo-drive and motors are mounted in horizontal position as shown in Fig. 2.

2.3 SPEED REDUCERS AND MACHINE ELEMENTS: The Spur gear in link B01 is mounted on the shaft which is designed based on the maximum joint tip velocity of 1.3 m/s and other parameters given in Table 3. In link B01 cyclo to spur gear connection is made through pinions made up of SCM 415 with a gear ratio 2.33.

TABLE 3. SPUR GEAR DESIGN.

Parameters	Values	
No. of Teeth	Gear (70)	Pinion (30)
Module	2.5	
Material	SCM415	
Torque on Shaft in N-m (T)	247.3	
Pitch Diameter in mm	175.0	
Shaft length in mm (L)	100	
Pressure Angle in degree (φ)	20	
Maximum Tangential load in N (Ft)	3606	
Calculated Bending stress at root in MPa	119	
Calculated Hertzian stress in MPa	906	
Allowable Bending stress at root in MPa	294	
Allowable Hertzian stress in MPa	1343	

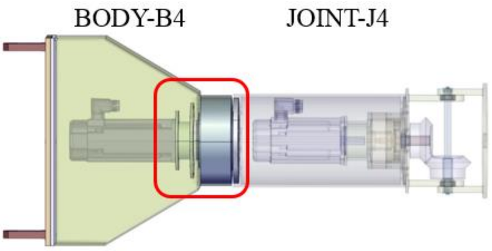

FIG. 2. Body 04 and Rolling Joint

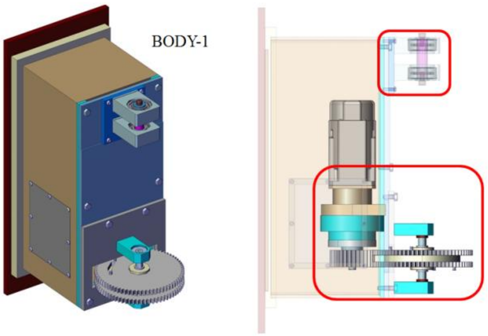

FIG. 3. Body 01 and Yaw Joint

The lugs in ARIA are integrated with the bodies of ARIA with the help of fasteners and lugs design is carried out based on followings data shown in Table 4.

TABLE 4. DESIGN OF LUGS.

Bending stress due to Axial Load	
Distance from the fixed end in mm	84
Birdth in mm	64
Height/Thickness in mm	12
Moment of Inertia in mm^4	9.22E+03
Bending Stress in MPa	3.88
Bending stress due to Radial Load	
Birdth in mm	12
Height/Thickness in mm	64
Moment of Inertia in mm^4	2.62E+05
Bending Stress in MPa	6.36
Combined Bending Stress in MPa	10.24

Upper Lug and Lower lugs are interfaced with the body 05 through keys to transmit the motion. Cyclo-drive F1C 415 has been used for higher speed reduction. Servo Motor AKM 43G has been used to actuate the Cyclo-drive. The cyclo-drive motion is transmitted to pitching/yawing joint by mitter gears as shown in Fig. 4.

As the load on the bevel gear is bidirectional and both sides of the tooth are equally loaded, the allowable bending stress at root is to be taken 2/3 of the allowable bending stress limit mentioned in Table 5. The bevel gear in body B01 is mounted on the shaft which is designed based on the maximum joint tip velocity of 0.2 m/s.

TABLE 5. BEVEL GEAR DESIGN.

Parameters	Values	
No. of Teeth	Gear01 (30)	Gear02 (30)
Module	2.5	
Material	SCM415	
Maximum Tangential load in N (Ft)	4028	
Calculated Bending stress at root in MPa	266	
Calculated Hertzian stress in MPa	904	

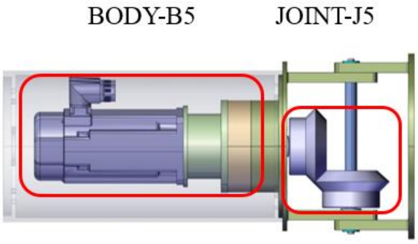

FIG.4: Body 05 and Roll/Yaw Joint

The actuators of ARIA arm consist of servo motors coupled with a high reduction fine-cyclo gearbox. ARIA has generic end-effectors interface at the tip to mount machine vision cameras or maintenance tools. Joint parameters are tabulated below in Table 6.

TABLE 6. JOINT PARAMETERS.

Joints	Tip Speed	Cyclo-drive (Sumitomo make)	Motor continuous torque (N-m)
Joint 01	0.2 -1.3 m/s	FC A15	3.35
Joint 02	0.2 - 1.1 m/s	FC A15	3.35
Joint 03	0.2 - 1.4 m/s	FC A15	3.35
Joint 04	16 - 35 rpm	F1C A25	4.8
Joint 05	0.2 - 1.4 m/s	FC A15	3.35

2.4 CONTROL AND FEEDBACK: ARIA is controlled using a VR based user interface that immerses the ARIA model into the working environment. The VR based control and monitoring of ARIA through remote location inside the mock-up torus vessel is shown in Fig. 5. The kinematics based on the D-H parameters given in Table 7 has been used. A control application is executed to communicate the joint pose and orientation along with the velocities from the VR simulations to the servo control system of ARIA. For the continuous tracking of ARIA, the VR model is periodically updated with the values read from the encoders mounted at the joint locations. In the event of the failure of equipment controller drives, it is important to recover the joint positions.

FIG. 5: Block diagram of VR based control system (A) VR based controlling of ARIA arm (B)

The VR based monitoring and control system has been tested and demonstrated. The initial performance tests show a low latency with precise and accurate control over the RH equipment.

3. KINEMATICS OF ARIA

The DH parameter kinematic model and coordinates is as shown below in Fig. 6. The DH parameters of the ARIA manipulator is given in Table 7.

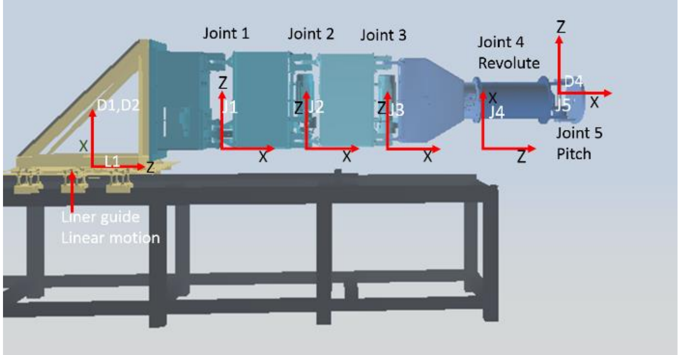

FIG. 6: ARIA Articulated Arm Coordinate Systems for DH Parameter

TABLE 7. DH PARAMETERS OF ARIA ARM.

Joint type	α_i (Deg.)	a_i (m)	d_i(m)	θ_i (Deg.)
Prismatic	90	0	$variable$	0
Revolute	0	0.6	0	$variable$
Revolute	0	0.425	0	$variable$
Revolute	0	0.402	0	$variable$
Revolute	90	0	0	$variable$
Revolute	90	0	0.2	$variable$

The above D-H parameters for the ARIA robotic arm are used to develop a C++ class. This class is used to define the robot and initiate it for simulation. The class can be further used to implement with the actual hardware setup.

4. STRUCTURAL ANALYSES

The software used for CAD design was CATIA V5. Moreover, a parametric approach using ANSYS Workbench has been adopted for payload sensitivity analyses (varying from 20 Kg to 100 Kg). In other words, just the profiles of the structure were modelled, while the actual thickness of bodies and links were defined at the time of FEM analyses.

The 3D CAD geometry was imported to ANSYS workbench. All the bodies are considered as SS 304L. The joints are modelled as rigid connections connecting the bearing contacting surfaces in each body. Along with the mass of the links, actuator masses were defined as point mass on the link geometry and dead weight analysis with varying payload was carried out to check the structural integrity.

Inertial load of ARIA, its components and payload: The analysis has shown that the maximum stress intensity of 101 MPa appears near the connecting area between lugs and link bodies. The maximum displacement at the distal end of the structure of mm appears. The distribution of the stress intensity and deformation of ARIA structure is shown in Fig. 7. The yield strength of SS304L at 20°C is See = 140 MPa.

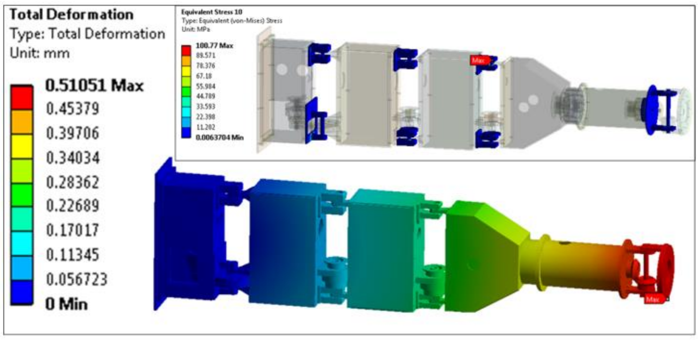

FIG. 7. The overall deformation of ARIA (A) and peak Von Mises stress (B)

5. FABRICATION AND DEMONSTRATION OF ARIA

The Articulated Robotic Inspection Arm (ARIA) has been indigenously developed at IPR, India as a proof-of-concept for in-vessel maintenance. The fabricated ARIA arm mounted on a linear guide is shown Fig. 8. ARIA demonstration test has been carried out with a cantilevered payload of 25 kg at ~2m distance in a mock-up torus vessel. Further a demonstration of viewing tool with self-illumination mounted at Joint 05 to detect the defect on a dummy tile is achieved.

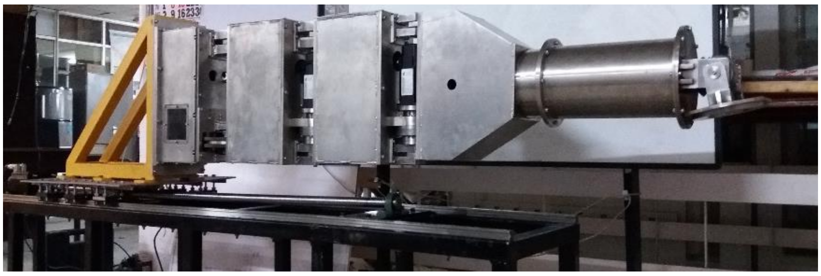

FIG. 8. Fabricated ARIA

5.1 PAYLOAD DEMONSTRATION: ARIA needs to execute pick-and-place operations, handling multiple objects with unknown payload dynamic characteristics. Hence, having a good and quick estimation of the dynamic parameters of the payload would allow a more accurate execution of the task, without wasting too much time. Keeping in mind restricted motions allowed in a cluttered workspace, we have evaluated the payload dynamic characteristics by performing just a few small movements in the neighbourhood of the pick and manipulation position. Demonstration test for manipulation for full joint range yawing and pitching joint with payload of 25 kg was carried at JOINT -05 as shown in Fig. 9.

FIG. 9. ARIA Payload demonstration (A) J5 Yaw Full range test (B) J5 Pitch Full range test

5.2 TILE DETECTION: A pan-tilt-zoom (PTZ) IP camera mounted as payload at the end-flange serves as the eye-in-hand camera for visual servo mechanism [6]. The centre of a tile position in the toroidal mock-up vessel is defined by the simple toroidal coordinates (R, φ, θ). A particular location with the tokamak is defined by the toroidal angle of deployment (θ) from the port at which the arm enters. Once the system has reached the desired toroidal location at a macro level, visual Servoing will correctly align the end effector along a tile or in-vessel component. The wall-to-wall distance inside the tokamak is very limited thus only joint-3, 4 & 5 are used for the visual Servoing. At any given arbitrary position of the end-effector camera as shown in Fig. 10A, the operator initiates a blob-tracking algorithm by selecting points on the tile. The gain of the control law is set to constant 0.3. An adaptive gain control is implemented as a part of future work. The end-effector tracking trajectory is as shown in Fig. 10A. The corresponding feature error, instantaneous joint angular velocities for joints 3, 4, 5 which follow a very smooth profile and camera velocities are shown in Fig. 10B using the VISP curve plotter.

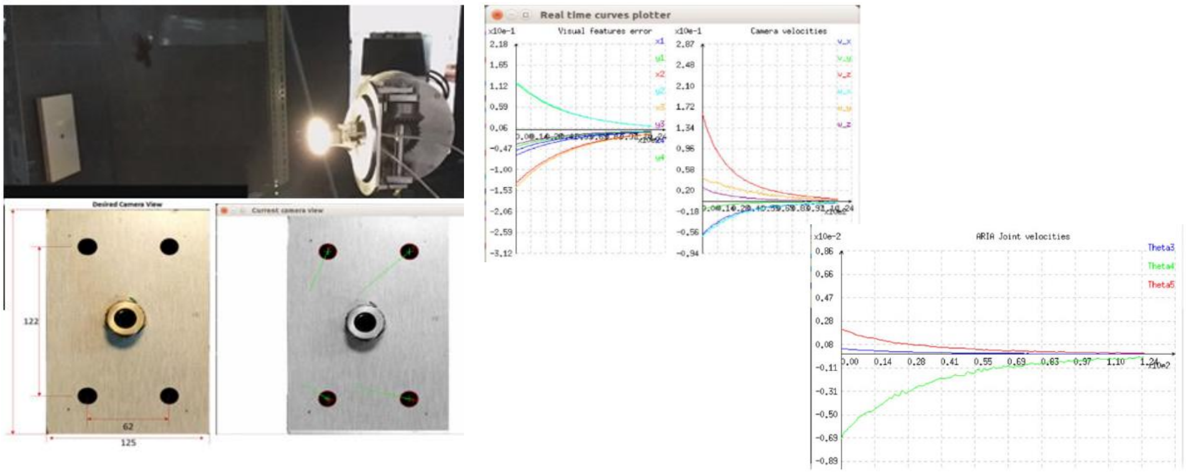

FIG. 10. ARIA Tile detection (A) Viewing tool on ARIA, desired and current pose (tracking trajectories) of tile (B) Feature Error, End-Effector Velocity and ARIA Joint Velocity Plot

5.3 VR MOVE SIMULATOR: In the VR MOVE simulator [7], the physical ARIA arm is replaced by a virtual model of the arm which mitigate the risks on the hardware. All the ‘man in the loop’ RH operation can be planned virtually using this system. When the operator gives the next motion commands, a new instance of the virtual model is created and moved with the given inputs. If the operator is satisfied with the motion, then with a click of a button the motion commands are passed to the physical ARIA arm. In the event of the failure of equipment controller drives, it is important to recover the joint positions. The rescue of the arm can be planned using the VR MOVE platform.

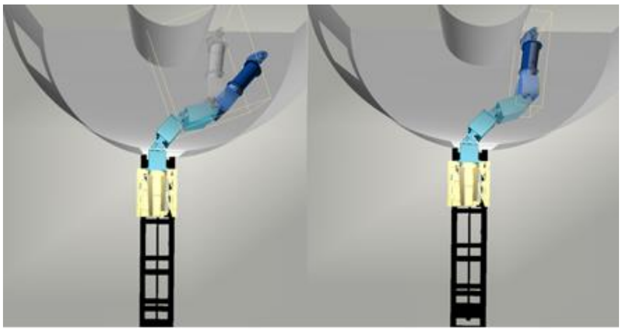

FIG. 11. VR Move as simulator for operator training

6. SUMMARY

In this paper, the detailed design and development of the ARIA and associated VR based monitoring and control system has been tested and demonstrated for maximum payload handling and inspection of tiles in mock-up facility.

The theoretical calculations with structural analysis of components like links, gears, shafts, lugs and bearings are elaborately discussed. The system is optimized and developed to incorporate efficient commercially available servo actuators, bearings and gear-boxes, to maintain a high degree of accuracy and repeatability.

Experimental validation and test results on a mock-up facility show that the system can be controlled with an end-effector positional accuracy within 2mm. The design and integration methodology, presented here, lays foundation to develop efficient RH systems with greater reach and payload capacity for future fusion machines.

The effective 1:1 scale mapping of the VR model with the manipulator hardware makes provision for task planning and executing of the control commands from a remote location. The initial performance tests show a low latency with precise and accurate control over the RH equipment. The system can also be used as a training platform for the RH operators.

As a part of the future work of the paper, the developed code will be integrated to the general ROS based control platform for ARIA. This will enable to use the visual Servoing mechanism inherently with the controller platform. A Virtual reality technique has been used to develop the RH equipment control system for monitoring and control of the in-vessel RH operations planned inside a tokamak.

ACKNOWLEDGEMENTS

This work was supported by Institute for Plasma Research, India. We deeply thank all the members of ARIA design team, project students, project engineers, contractual engineers and support staff in RHRTD, IPR for their support in this project.

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