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Design and Implementation of Remote Control System for Reactor Vessel Weld Inspection Manipulator

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Professional paper

In this paper a design and implementation of a remote control system of a manipulator for weld inspection of nuclear reactor vessels are described. Based on the client-server TCP/IP software architecture, the presented control system enables an operator to perform the entire inspection procedure remotely over a network, avoiding exposure to dangerous radiation normally present in nuclear reactor environments. The developed graphical user interface provides tools for planning weld scan trajectories, their verification on a robot and reactor vessel 3D model, and finally, execution of planned trajectories on a remote robot. In addition, the weld inspection process can be monitored in parallel on a virtual robot and reactor vessel model and by watching live video streams captured by two cameras mounted on the robot.

Key words: Reactor vessel inspection, Remote control, 3D visualization

Projektiranje i implementacija sustava upravljanja robotskim manipulatorom za udaljeno ispitivanje zavara na reaktorskim posudama. U ovom radu opisan je postupak projektiranja i implementacije sustava za udaljeno upravljanje robotskim manipulatorom koji služi za ispitivanje zavara na posudama nuklearnih reaktora. Opisani sustav temelji se na komunikacijskoj arhitekturi tipa TCP/IP klijent-poslužitelj, te omogućuje provedbu cjelokupnog postupka ispitivanja na daljinu, bez potrebe izlaganja opasnoj radijaciji koja je uobičajeno prisutna u okruženju nuklearnog reaktora. Postupak ispitivanja provodi se korištenjem razvijene programske aplikacije, koja putem grafičkog korisničkog sučelja operateru nudi alate za planiranje potrebnih trajektorija, njihovu provjeru na virtualnom 3D modelu posude i manipulatora, te izvršavanje na udaljenom manipulatoru. Operateru je također omogućen uvid u trenutno zbivanje u posudi tijekom cijelog postupka ispitivanja, paralelnim praćenjem virtualne 3D scene, te video slika s dvije specijalne kamere ugrađene na manipulatoru.

Ključne riječi: ispitivanje reaktorske posude, udaljeno upravljanje, 3D vizualizacija

1 INTRODUCTION

The use of robots for inspection and maintenance of nuclear power plants is primarily determined by economical reasons, as shorter inspection and maintenance periods increase plants availability. Some estimations have been made that one non-productive day of a 1000-MW nuclear power plant can cause financial losses up to 500 000 USD based only on non-produced electrical power [1]. Introduction of remotely operated robots into nuclear power plants has been also determined by medical reasons. Many inspection and maintenance tasks can only be done when a reactor is shut down, due to the presence of radiation that is too high even for workers fully equipped with protective clothing. The total occupational radiation exposure (ORE) of plant personnel is strictly limited to allowed annual values. This means that for many routine inspection and maintenance jobs a large number of workers are assigned to do just a small portion of the work in order not to reach the ORE limit. By replacing people with robots, these problems are overcome. The most challenging task in the nuclear power plant inspection is inspection of a nuclear reactor vessel.

The safety of a nuclear reactor vessel - a steel container enclosing a reactor core and systems controlling the reaction, is one of main concerns in nuclear power plants. A pressurized water reactor vessel comprises cylindrical shell with two hemispherical heads and nozzles around the upper shell. The vessels are constructed by welding large rolled plates, lower head and nozzles together. To ensure the highest integrity and continuous serviceability of the reactor vessel over a nuclear power plant lifetime, its cylindrical and bottom parts must be inspected periodically. A goal is to identify the status of the reactor vessel by ultrasonic and visual inspection of vessel base metals and all welds. However, the reactor vessel inspection is one of the most challenging non-destructive examinations performed at any nuclear facility. The entire inspection procedure is conducted underwater, which requires the use of special waterproof equipment. Furthermore, there are many different types of vessel parts and welds that have to be examined, thus making the inspection procedure even more complex. The exposure of inspection personnel to the radioactively contaminated vessel walls is another important issue.

In order to minimize exposure of inspection personnel to high radiation in hostile nuclear environments, a lot of effort has been invested to design remotely controllable (teleoperated) inspection systems. The most frequently used is a conventional central mast manipulator [2] with a three-leg base, which is mounted onto the top flange of the reactor vessel before the inspection starts. Ultrasonic or visual inspection sensors used for acquisition of measurement data are installed at the manipulator's end effector. The size of a specific robot construction allows for inspection tool to reach any part of the vessel. During inspection, the robot executes a scanning trajectory, moving the sensors over the inspected vessel area. Recently, Areva developed a remotely operated inspection robot Trans-World System (TWS) [3]. Unlike the central mast manipulator, the TWS uses a three-leg base which spans the reactor vessel diameter to provide a solid anchor for the 6DOF robotic arm. Using the TWS, an inspection can be performed with two manipulators in the vessel at the same time, reducing vessel occupation time (VOT) in that way.

Other inspection robots frequently used are wall climbing mobile inspection robots presented in [4-7]. The climbing robots are defined as robots able to move on vertical surfaces of upside down. They are generally distinguished by locomotion abilities and the way they adhere to the wall [8]. An inspection method employing an underwater wall climbing robot, guided by a laser positioning unit with precise resolution of 0.01 degrees has been described in [9]. The robot moves on the reactor vessel wall by four magnetic wheels, and performs inspection using 4DOF manipulator with ultrasonic probes attached to its end effector. In [10], two walking-climbing robots, NERO (Nuclear Electric Robot Operator) and SADIE (Sizewell A Duct Inspection Equipment), which have been applied successfully to inspect two Magnox reactors in the UK, are described.

The third group consists of small underwater inspection vehicles. From the control engineering point of view, trajectory control of the underwater robot is a difficult task due to robot nonlinear dynamics, which includes various hydraulic forces such as buoyancy and hydrodynamic damping, the difference between the centre of gravity and buoyancy, and disturbance from a tether cable. The paper [11] presents trajectory-tracking control of the underwater inspection robot to solve such problems. In [12] the AIRIS 21 underwater inspection robot is presented. The robot swims in the water toward an area to be inspected and sticks to the vessel wall using two propellers. The underwater robotic inspection system URSULA is presented in [13]. The 6DOF manipulator locks on the reactor vessel using three suction cups and uses special harmonic-drive submersible joints to provide high-torque and low-speed motion. A remotely operated miniature inspection submarine and a real-time system for creation of animated synthetic images of the underwater environment being inspected are given in [14].

Compared to the central mast manipulator, mobile inspection robots have some advantages like smaller dimensions, easier maintenance and a possibility to perform simultaneous inspections with several robots. The main advantage of a central mast manipulator is the time invariant relation between the robot and the vessel coordinate systems, which allows the usage of simpler control algorithms and provides faster tool positioning.

The paper is organized as follows. An insight into the concept of the remotely controllable system for reactor vessel inspection robot is given in Section 2. The high-performance servo amplifiers used for driving robot joint motors, as well as the server side software architecture, are presented in Section 3. Description of the developed graphical operator interface for scan trajectory planning, remote scan execution and online 3D visualization of inspection robot operation is described in Section 4. In Section 5 we give details of the implemented information exchange protocol between the server and client applications, including reference data, sensor data and servo amplifiers configuration data. We conclude the paper with some ideas and directions for future work.

2 DESCRIPTION OF REMOTE INSPECTION ROBOT CONTROL SYSTEM

In the presented system, the vessel inspection is performed by a 4DOF central mast manipulator having cylindrical configuration which is mounted onto the top of the vessel before starting the inspection, as shown in Fig. 1. The manipulator comprises two linear and two rotational axes (marked in Fig. 1):

1. HOIST EXTEND - vertical extension,
2. BOOM ROTATE - the rotation of the vertical axis,
3. BOOM EXTEND - tool extension,
4. HEAD ROTATE - tool rotation.

The concept of the system for remote reactor vessel inspections is shown in Fig. 2. Remote inspection strategy is based on a client - server TCP/IP architecture. For that purpose, a control system comprising two separate Windows

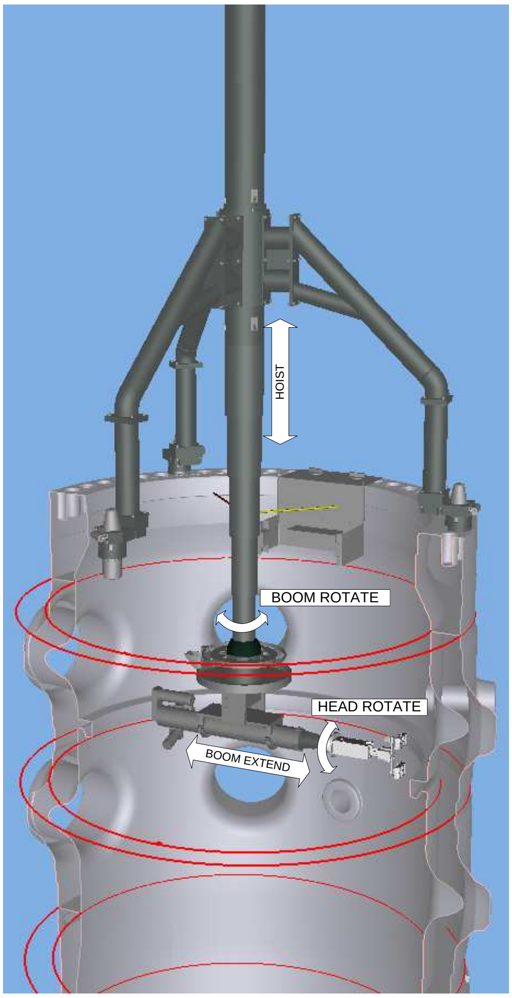


Fig. 1. Central mast manipulator mounted onto the reactor vessel

based applications has been developed - a server application, named Fiona Server and a client application, named Fiona GUI. At the client side of the system there is an operator performing reactor vessel inspection from a remote place, for example, from a control trailer located near the containment building. Since the client-server communication has been carried out through simple string command exchange using TCP sockets, as described in Section 5, there are no high requirements on the connection bandwidth. Therefore, an inspection process can be monitored from any working place with Internet connection.

Fiona server is an interface between the servo drives actuating robot joints and Fiona GUI used for scan planning and visualization (see Section 4). Fiona server runs a TCP socket server within a Windows service application on the PC located in the robot control station. The PC is directly connected to the Internet via local Ethernet network. Once the scan trajectory has been planned and verified in virtual environment containing virtual robot and vessel models, it can be executed on the real manipulator. The developed system allows the operator to view the trajectory execution both on the virtual robot model and by watching live video stream from two special video cameras installed on the robot. When the remote client-server connection has been successfully established, the server application executes incoming commands and controls robot motion.

The system allows simultaneous connection of multiple clients, but for security reasons, only one operator is allowed to control the system, while others can just monitor current system states, operator actions, and observe the progress of inspection in the provided virtual environment.

3 ELEMENTS OF ROBOT MOTION AND POSITIONING CONTROL

3.1 Ndrive HP servo drive

The high-performance motion and positioning control of the robot's end effector is crucial for acquisition of meaningful inspection data. For this purpose, the state-of-the-art Aerotech Ndrive HP digital servo amplifiers with PWM outputs were used (Fig. 3) [15]. These drives have fully digital current, velocity and servo loops. The cascade of digital current, velocity and position PID controllers provides conditions for achieving desired motion quality and positioning accuracy. Position and velocity sensors of each robot axis have been connected to the drives using special waterproof cables and connectors. All axes except the HEAD ROTATE are equipped with a tachometer and a dual resolver system for absolute position measurement. Because of a specific mechanical realization of the BOOM ROTATE axis, a single incremental encoder is used both for axis position and velocity measurement.

The servo drives being used have on-board brake relays which have been used for automatic activation of robot joint safety brakes. In addition, they contain an emergency stop sensing input, which is activated by an external failsafe emergency stop circuit installed on the robot control station. Accordingly, the servo drives have separate power connections for motor bus power and logic power, which allows the motor power to be interrupted without losing communication with the drive module. Since a 4DOF robot manipulator is controlled, four Ndrive HP servo drives are driving robot axes. Using the industry standard IEEE-1394 (FireWire) communication bus, servo drives have been interconnected and linked to the server PC through a standard PCI FireWire card. Each drive on the FireWire network has a unique communication channel, easily accessible from the software. The tuning of digital current, velocity and position controllers parameters have been made by using the accompanying Automation 3200 software running on the server PC.

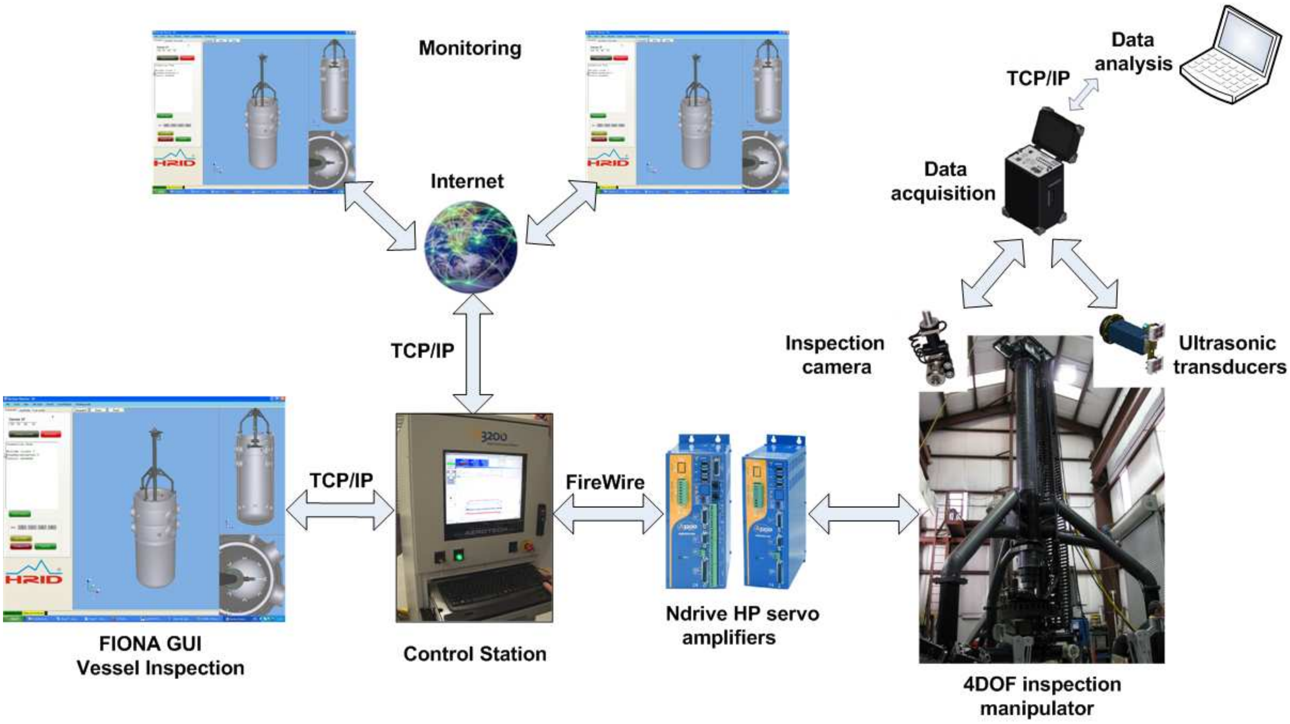


Fig. 2. The concept of remote robot control system for reactor vessel inspection

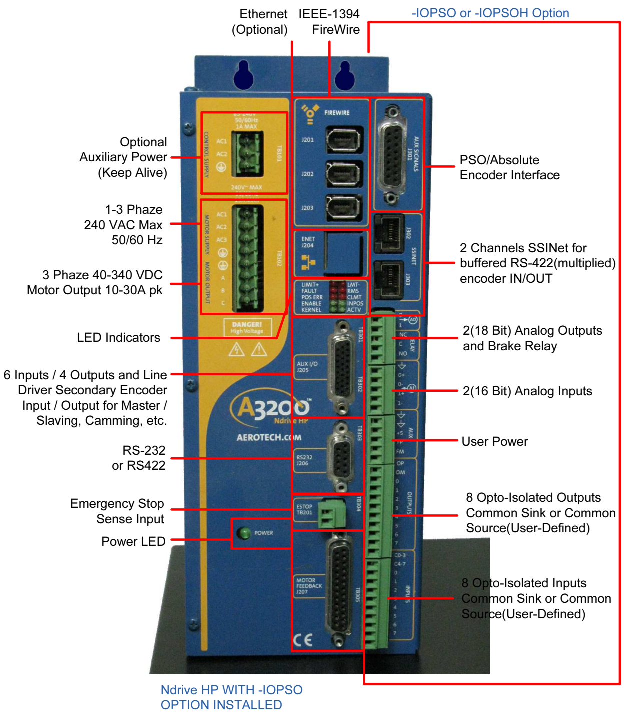


Fig. 3. Ndrive HP servo amplifier

3.2 Server side software architecture

The block diagram of the software architecture at the server side is shown in Fig. 4. The server PC runs the Automation 3200 layered software, where each layer takes instructions from the next layer up and, after processing, sends commands down to the first layer below. As can be noticed, real time activities such as the servo control are handled at lower levels, while less time-critical activities like feedback value acquisition are handled at higher levels. Fiona Server stands at the top level as a custom application, developed in C# programming language using .NET *A3200 Class* library. Fiona Server listens for client connections on the predefined IP address and port number. Before the remote vessel inspection process can start, a connection between the client application and the robot motion controller must be established by using a connection dialog in Fiona GUI. Once the connection has been established, the Fiona Server accepts, parses and executes incoming client commands by sending them to the motor servo drives using real-time Nmotion SMC controller engine. This engine executes under Windows-based operating systems in a real time kernel that runs independently of and is unaffected by other programs running on the PC. The Nmotion SMC controller is a software based motion controller that uses the IEEE-1394 Fire Wire bus to provide coordinated motion of up to 32 axes, networked with Ndrive HP drives.

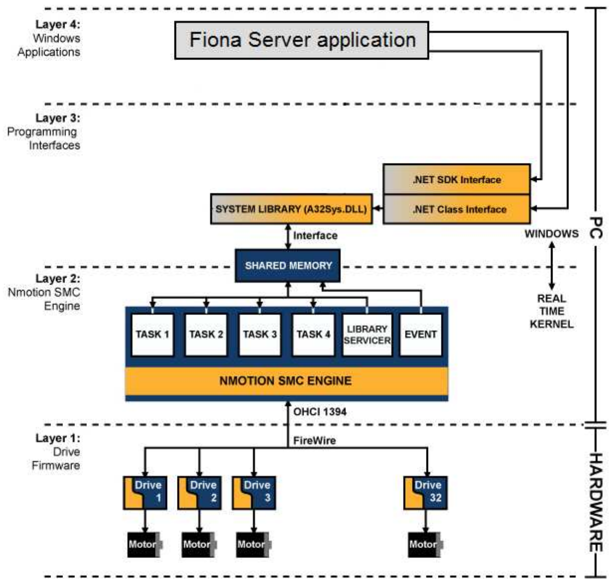


Fig. 4. The server side software architecture

3.3 Control permission

When the operator has decided to start vessel inspection using Fiona GUI, a control request is sent to Fiona Server. Fiona Server handles requests from all connected clients, and assigns the control permission to only one client at the time. The operator who wants to take the control of the robot will get the permission by the server only if no other operator is currently controlling the robot. Otherwise, the operator in charge will be asked by the server to handover the control permission to a new requester. Depending on the operator's decision, the server will permit or deny the takeover. In case there is no response from the currently active operator's application within next 15 seconds, and if the robot is idle at the moment, the server will automatically grant system control to a new robot operator.

4 FIONA GUI APPLICATION

Using the developed Fiona GUI application, the operator is provided with tools for weld scan trajectory planning, their verification on a virtual robot and vessel model, and for execution on a remote robot. As can be seen in Fig. 5, Fiona GUI contains three visualization screens; main screen that allows the operator to move, rotate and zoom the virtual scene model, and two additional scene views that provide sideways and top views of the scene. These additional views provide better insight into the robot's tool position and orientation with respect to the vessel.

4.1 3D Visualization

Fiona GUI provides a 3D virtual scene model in order to enhance the control performance of the remotely controlled manipulator. The scene is comprised of a dynamic robot model attached to the static vessel model (Fig. 5). Since the virtual robot model is driven by real process values continuously received from the server, it accurately reflects the real robot states. Furthermore, using real robot and vessel 3D models, advanced algorithms for collision detection have been developed, providing a means for collision-free scan trajectory planning. Collision detection represents very important feature of the developed application, as it prevents potential destruction of very sophisticated and costly inspection equipment being used. Moreover, it is inadmissible for any robot part to fall into the reactor vessel, since it would cause great damage in the power plant primary loop system.

Fiona GUI visualization engine is based on the open source software VTK (Visualization ToolKit) that supports 3D computer graphics, image processing, and visualization [16]. Fiona GUI is customized for 3D visualization of reactor vessel inspection systems, using virtual models of robot and vessel in 3D Studio MAX format (.3ds) format. Before an on-site inspection procedure can start, a virtual scene model must be adjusted to conditions found on site. Virtual .3ds models integrated into a virtual scene are described with corresponding Denavit and Hartenberg (DH) parameters [17]. DH parameters provide standard robot representation needed for solving direct and inverse kinematics problems. They can be defined in the Robot Constructor dialog within Fiona GUI. When the virtual robot model has been adjusted to the exact on-site situation, it has to be attached onto the vessel model by defining relations between the robot and vessel coordinate systems. The result is a new compact scene model, which can be loaded or saved for further use.

4.2 Scan trajectory planning

As already mentioned, the main goal of each vessel inspection is to identify the quality of vessel base metals and all welds. The weld inspection implies the inspection of the entire weld volume, which consists of the weld volume and an extra volume, as indicated in Fig. 6.

The figure shows the cross section of the vessel shell and ultrasonic tool in process of weld inspection. The weld volume is colored green, and an extra volume red. As can be seen, the tool consists of two sleds, each of them comprising four transducers (ultrasonic sensors).

The scan trajectory planning has a significant role in the preparation of a vessel welds inspection procedure. The aim of this step is to produce a set of points in the robot coordinate system the robot tool moves through during an inspection process, so that the entire weld volume is covered by all transducers. Before the trajectory can be planned, the weld and transducer parameters have to be defined. Generally, there are four different weld types to deal with:

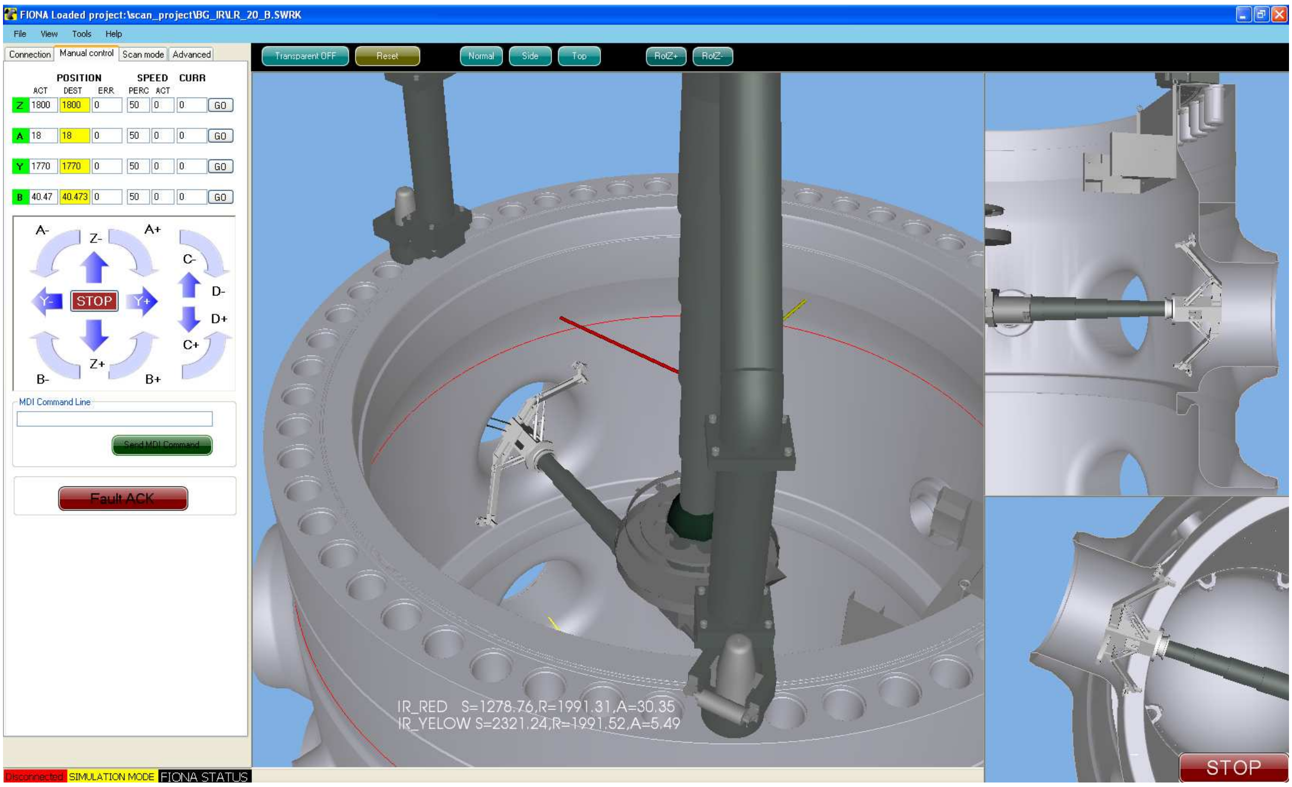


Fig. 5. The main screen of Fiona GUI

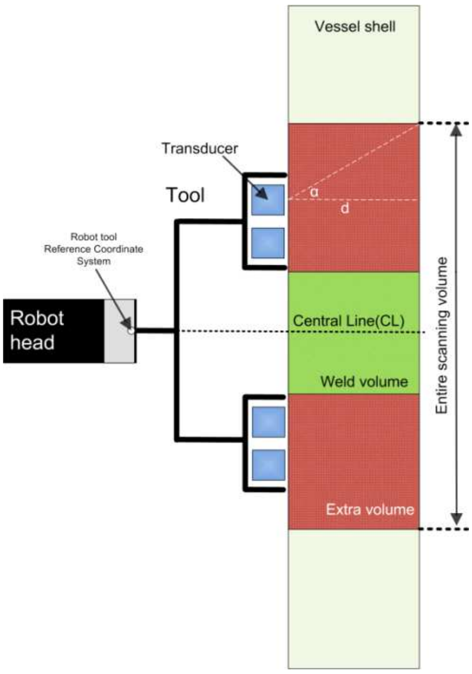
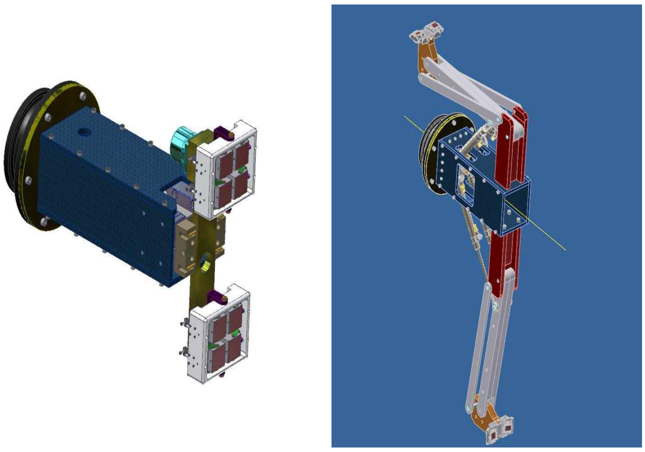


Fig. 6. Ultrasonic tool and vessel shell cross section

1. Shell welds,
2. Nozzle welds,
3. Bottom head welds,
4. Inner radius.

All the welds that need to be inspected can be defined in Fiona Weld Editor. This editor provides the definition of weld coordinates in vessel coordinate system, as well as the weld volume and extra volume parameters. Each transducer can be described using three parameters: *relative position* to the robot head reference coordinate system, *scan angle* (*alpha*) and *scan depth* (*d*) (Fig. 6). The configuration of all tool parameters is provided by Fiona Tool Editor. Another important step is definition of the inspection tool type. There are three different types of inspection tools, commonly used in vessel inspection process - two specially designed ultrasonic tools intended for shell and nozzle welds inspection, shown in Fig. 7, and a special camera for visual vessel surface inspection.

A specially designed ultrasonic tool for nozzle inspection, installed on the manipulator, is shown in Fig. 8. The tool contains two self-adjustable arms each comprising two transducers. Fig. 9 shows the nozzle inspection tool in two



(a) Shell weld inspection tool (b) Nozzle weld inspection tool

Fig. 7. Virtual models of two different ultrasonic weld inspection tools – for the shell weld and for the nozzle weld

(a) (b)

Fig. 8. Two working positions of nozzle inspection tool

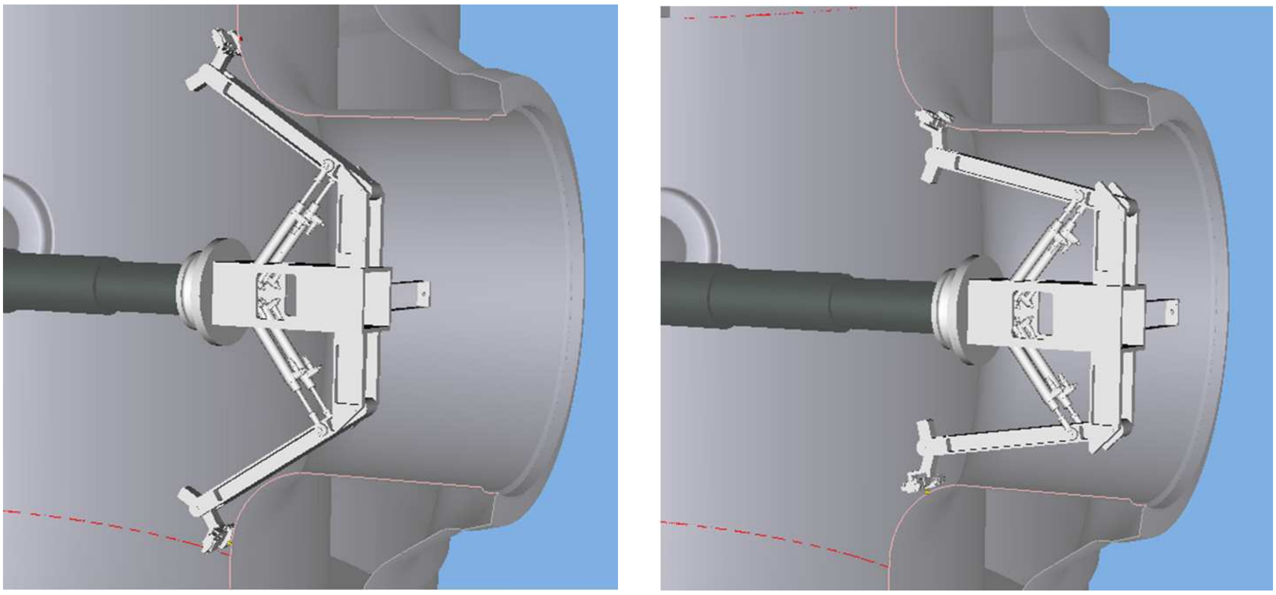
different locations within the nozzle, during the nozzle-scan execution. The arms of the tool force the transducers to stay in touch with the nozzle surface all the time during the inspection process.

When the tool geometry is defined, it is necessary to obtain the coordinates of the inspected points on the vessel surface in the robot tool coordinate system. In case of visual inspection, as well as by inspection using planar ultrasonic tool, the inspection area on the vessel's surface can be easily obtained. Small vessel curvature and simple tool geometry allows for easy calculation of the transducer position in the robot tool coordinate system. It is much more complex to obtain the transducer position during nozzle scan execution, since the nozzle tool geometry and the nozzle cross-section vary as the tool moves through the nozzle (Fig. 9). The solution is presented in Fig. 10.

A point denoting the pose of the transducer with respect to the robot head is recorded for every positioning angle of tool arms. In this way we have obtained a tool curve shown in white in Fig. 10. At each robot position, the algorithm computes the intersection of this curve with the vessel surface which corresponds to the actual position of the transducer.

Having defined the weld and tool types and parameters, it is possible to generate a weld scan trajectory. An automatic trajectory planning tool has been implemented within Fiona GUI environment, providing an easy generation of scanning trajectories for different types of welds and inspection tool geometries.

The tool trajectories are determined by weld position and tool geometry but also by vessel geometry. It may occur that automatically generated trajectories should be corrected on some sections to prevent possible tool collisions with the vessel. The cross-section of the reactor pressure vessel type WWER-1000 is shown in Fig. 11 [18]. The red line represents weld no. 5 which needs to be inspected.



(a) (b)

Fig. 9. Examples of transducer positions by nozzle inspection

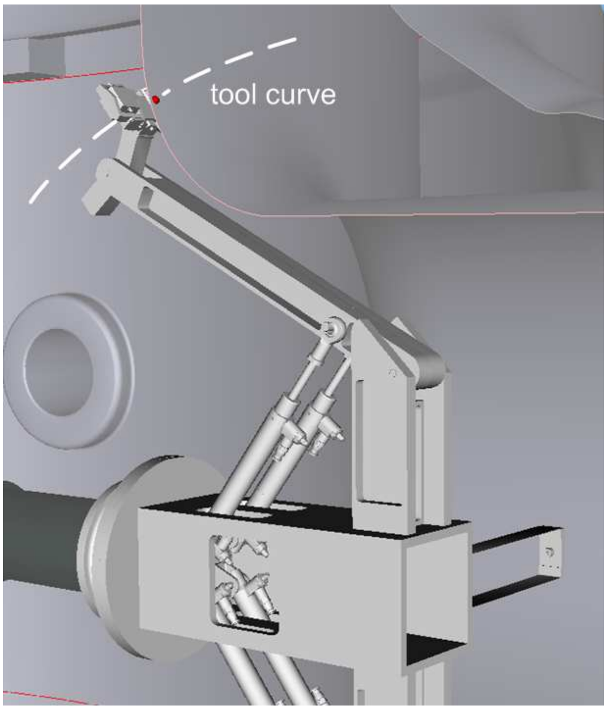


Fig. 10. Tool collision detection

As shown, there are ten shaded areas (C1 – C10) that represent the feasible inspection volume. It should be noted that tool movement is limited by the inner vessel geometry like nozzle connections; instrumentation pipes etc. (see Fig. 12).

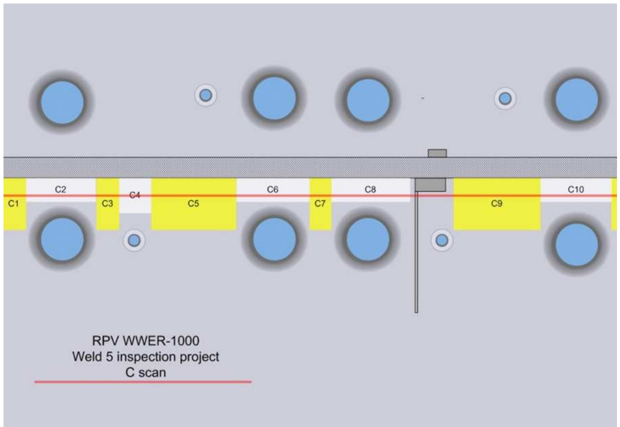


Fig. 11. Weld no. 5 inspection trajectories

There are two basic types of vessel shell scanning trajectories - *A*-scan, and *Z*-scan (Fig. 13). To execute the *A*-scan, the inspection tool is moved by the BOOM ROTATE axis along the weld in the horizontal plane. Having scanned a section of the weld, the vertical tool position is incremented by the HOIST axis (Fig. 13(a)). When performing *Z*-scans, the inspection tool is moved perpendicular to the weld by enforcing vertical motion of the HOIST axis. A tool position along the weld is incremented by clockwise motion of the BOOM ROTATE axis (Fig. 13(b)).

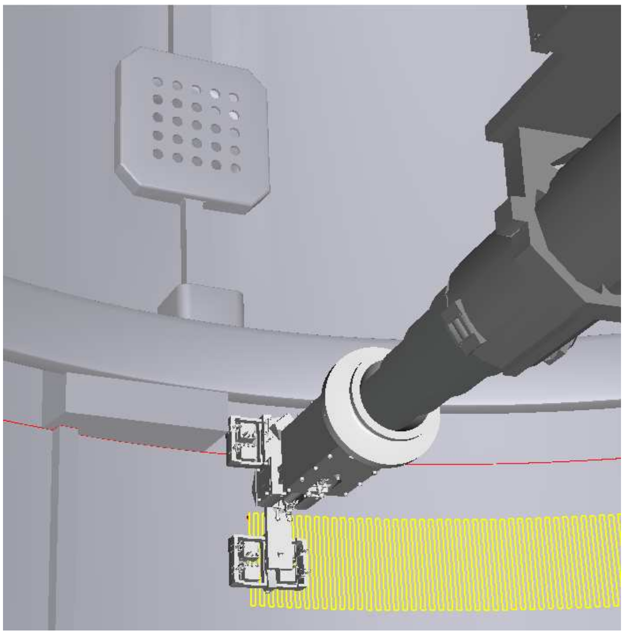


Fig. 12. Weld no. 5 – C9 trajectory, instrumentation pipes on the left

4.3 Scan trajectory execution

During inspection, Fiona GUI executes the scan trajectory by commanding a point to point move for one robot axis at the time. This command defines a desired robot joint position and moving velocity. When received on the server side, these values are immediately passed to the corresponding servo drive via the Nmotion SMC controller, representing the position and velocity loop set points. Having received new position and velocity references, the servo drive starts robot joint motion control using its onboard digital controllers. When the position error between the commanded and actual axis position becomes smaller than a predefined value, the Fiona GUI issues a new command to move the robot tool in the next point lying on the scan trajectory. This process continues until the robot reaches the last point of the scan trajectory. The feedback values (axes positions, velocities and currents) are received by Fiona Server and sent to Fiona GUI all the time during an inspection.

The planned scan trajectory can be verified by simulation in the virtual 3D scene and by execution on the remotely controlled robot using the Scan dialog as a part of Fiona GUI. All trajectory points displayed in the dialog are expressed in the robot coordinate system. Before final execution on the inspection robot, each coordinate can be easily modified based on the simulation results obtained. In addition, the Scan dialog provides the operator with an option to execute the trajectory in the step by step mode in which the manipulator moves to the next trajectory point and stops; or in the auto scan mode in which the manipulator executes the whole trajectory without stopping.

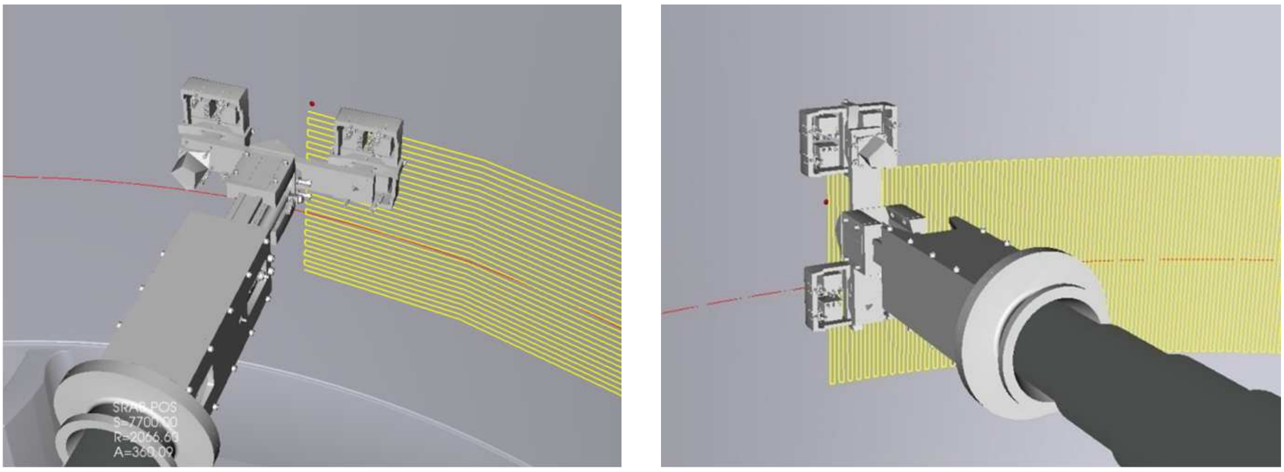
5 CLIENT-SERVER COMMUNICATION

5.1 Protocol Descriptions

After accepting a client connection, the server starts processing client's requests. As mentioned above, a client-server communication is carried out by exchanging simple string commands using TCP sockets. For example, while performing point to point motion, the client sends string command AxisMove(AxisName, Distance, Velocity);, the arguments of which define name of axis to be moved, desired absolute position, and moving velocity, respectively. Once the command has been received on the server side, Fiona Server sets the position and velocity reference values to the Ndrive HP servo drives. To start the feedback information updating, including actual joint positions, velocities and motor currents, the FeedbackON(Interval); command is sent to the server, where argument Interval defines the desired update rate. This information is used on the client side to refresh the virtual model joint positions and velocities, and to display them in Fiona GUI form, as well as in the Fiona Trends form. The server answers to this command by sending the actual feedback values for all axes in the following reply: *CurrFdbValues(pos, vel, curr);*. A similar request-reply strategy is implemented for all other functions, like axes enabling, disabling, jogging, homing, reading analog and digital inputs on the servo drive, controller parameter adjustments, etc. The complete client-server command base contains a total of 49 defined string commands.

5.2 Safety

In remotely controlled systems, safety is one of main concerns. Both the software and hardware aspects of system safety have been considered. The first level of software safety in the presented control system is protection in case of communication problems. Under normal conditions, the active client sends a message in a predefined time interval. The message may be a regular command or an echo. If no message is received within a predefined time-out period, it is assumed that the client was either deadlocked or the connection was not properly terminated. In this case the implemented safety mechanism takes care to stop all robot joints, paying attention to joint deceleration and velocity limits. The case of server deadlock has also been considered. The most critical scenario can occur while the operator performs so called free run axis motion characterized by a constant axis velocity (jog mode). The motion starts by issuing jog start command and continues until the



(a) *A*-scan (b) *Z*-scan

Fig. 13. Two basic vessel shell scan types – A- and Z-scan

jog stop command has been received. If a server deadlock occurred in the interval between jog start and jog stop command issuing moments, the axis would keep moving without control. This has required the implementation of another safety mechanism that prevents the inspection tool to hit the vessel. This problem has been solved in Fiona Server by substituting velocity control with equivalent position control. In case of server deadlock, the position set point is no longer updated, and the motion stops at the last given position. Normally, the motion is stopped once the jog stop command has been received from the client. In addition, Fiona Server stops the robot motion if the predefined axis over-current limit or position error limit has been reached.

The second level of software safety is detection and prevention of robot-vessel collisions. For the presented remote control system a collision-avoidance algorithm has been implemented to prevent collisions which might have resided in predefined scan trajectories. Also it is important to implement software mechanisms that provide safe robot driving in jog mode and thus prevent potential problems caused by operator's fatigue. The idea behind that is the development of a supervisory control system by using active virtual 3D models in-the-loop [19]. Based on the factory layout design, physical modeling, control synthesis and performance analysis, it is possible to detect collisions in the virtual world in the very precise manner and prevent the same in the real world [20].

The purpose of hardware safety is to prevent accidents in case of servo drive power failure. Hardware safety is ensured by mechanical brakes installed on each robot joint motor, which are automatically activated in case of such failure.

6 CONCLUSIONS

The safety of nuclear power plants is of great importance both from the people's safety and the environment safety points of view. Strict regulations dictate thorough inspection of all equipment in the prescribed time intervals. Many of such inspections are extremely hazardous for the people being involved. The inspection of the nuclear reactor vessel comes to the top of such list.

This paper presents development and implementation of a remote control system for a manipulator used for inspection of nuclear reactor vessels. The developed system has a client-server TCP/IP architecture which allows communication and control of different system levels. Servo control of four robot axes is performed at the lowest level, while supervisory control application, called Fiona is executed at the highest level.

Fiona comprises two main parts - Fiona GUI (client) and Fiona Server. Fiona GUI enables the operator to plan trajectories for reactor vessel inspection scans, test and verify planned trajectories within virtual environment containing virtual models of a robot and a vessel. The integrated collision detection algorithm enables planning of collision free scan trajectories. Also, Fiona GUI supports on-line control and visualization of manipulator via local Ethernet network or Internet. During the inspection process, Fiona GUI executes the scan trajectory by commanding point to point motion for one axis at the time. The motion command defines desired robot position and moving velocity. Fiona Server arbitrates multiple client connections giving control permission to only one client at the time. When the client-server connection is established, Fiona Server executes incoming commands and controls robot motion along the planned trajectory. The commanded position and velocity values received on the server side are immediately passed to the corresponding robot servo drive.

During implementation of the presented control system software and hardware aspects of system safety have been considered including communication and power failure problems.

Further development will be focused on the integration of the developed robot control system and the system for inspection data acquisition and processing.

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REFERENCES

[1] T. Moore, **Robots for nuclear power plants**, IAEA BULLETIN, 1985.

[2] T. Demler and W. Issler, **Reliability engineering**, IAEA BULLETIN, 1984.

[3] Areva np webpage, February 2009, http://www.areva.com

[4] L. Briones, P. Bustamante, M.A. Serna, **Wall-climbing robot for inspection in nuclear power plants**, in Proc. of the 1994 IEEE International Conference on Robotics and Automation, pp. 1409–1414, 1994.

[5] R. T. Pack, J. L. Christopher, K. Jr. Kawamura, **A Rubbertuator-based structure-climbing inspection robot**, in Proc. of the 1997 IEEE International Conference on Robotics and Automation, pp. 1869–1874, 1997.

[6] S. Chen, T. Sattar, A. Khalid and B. Bridge, **Climbing Robots-off the Shelf**, Industrial Robot, vol. 21, no. 5, pp. 27–30, 1994.

[7] J.C. Prieto, M. Armada, P. Gonzales de Santos, **A six-legged climbing robot for high payloads**, in Proc. of the 1998 IEEE International Conference on Control Applications, pp. 446–450, 1998.

[8] K. Berns, C. Hillenbrand, T. Luksch, **Climbing Robots for Commercial Applications – A Survey**, in Proc. of the 6th International Conference on Climbing and Walking Robots CLAWAR 2003, September 2003, Professional Engineering Publishing, Catania, Italy, pp.771-776.

[9] J.H. Kim, H.S. Eom, K.R. Kim, J.C. Lee, and Y.-R. Choi, **Laserguided underwater wall climbing robot for reactor pressure vessel inspection**, Patent 5 809 099, September, 1998, http://www.freepatentsonline.com/5809099.html

[10] B.L. Luk, A.A. Collie, D.S. Cooke and S. Chen, **Walking and Climbing Service Robots for Safety Inspection of Nuclear Pressure Vessels**, Asia Pacific Conference on Risk Management and Safety, pp. 432–438, December 2005.

[11] G.Ricciardi, S. Bellizzi, B. Collard, B. Cochelin, **Trajectory-tracking control of underwater inspection robot for nuclear reactor internals using Time Delay Control**, Nuclear Engineering and Design, pp.2543–2550, September 2009.

[12] K. Koji, **Underwater inspection robot-AIRIS 21(R)**, Nuclear Engineering and Design, vol. 188, no. 3, pp. 367–371, May 1999.

[13] J. B. Fallon, S. B. Shooter, C. F. Reinholtz, F. Charles, **URSULA: Design of an Underwater Robot for Nuclear Reactor Vessel Inspection**, American Society of Civil Engineers, USA, 1994, pp. 311.

[14] N. R. Corby, Jr., and C. A. Nafis, **Augmented reality telemanipulation system for nuclear reactor inspection**, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, H. Das, Ed., vol. 2351, no. 1. pp. 360–365, December 1995.

[15] Aerotech, Ndrive hp digital servo amplifier, Product Information, Feb. 2009., http://www.aerotech.com/products/amps/nd.html.

[16] W. Schroeder, K. Martin, and B. Lorensen, **Visualization Toolkit: An Object-Oriented Approach to 3D Graphics**, 4th Edition, Kitware, December 2006.

[17] R. J. Schilling, **Fundamentals of Robotics: Analysis and Control**. Simon & Schuster Trade, 1996.

[18] **WWER-100 reactor simulator**, International Atomic Energy Agency, Workshop material, 2003.

[19] T. Reichenbach, D. Miklić, Z. Kovačić, **Supervisory Control by Using Active Virtual 3D Models in-the-loop**, IEEE International Symposium on Intelligent Control, pp.1409–1413, Oct. 2006.

[20] A. Mutka, I. Draganjac, Z. Kovačić, Ž. Postružin, R. Munk, **Control System for Reactor Vessel Inspection Manipulator**, Proceedings of the 18th IEEE International Conference on Control Applications, Part of 2009 IEEE Multiconference on Systems and Control, Saint Petersburg, Russia, pp. 1312–1318, 2009.

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