Non-standard robots for NDT of pipe welds

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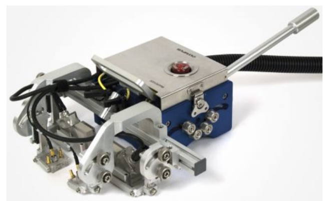
***Abstract*—Non Destructive Testing (NDT) is a field where the standard architecture of the robots (such as common industrial robots) may be hardly applicable. That fact stems from necessity to ensure not only high accuracy, repeatability and dexterity but especially appropriate robot architecture (joints, links and actuation systems layout) for minimizing the robot footprint as well as advanced control system including special and non-standard trajectory planning algorithms. The paper provides brief overview of the two NDT robots which were developed in cooperation with major czech companies dealing with non-destructive inspections (especially NDT of pipe welds in nuclear power plants). The main advantages of proposed robots in comparison with competitive solutions are unique and active pipe moving system (Vendy robot) and special architectures and trajectory planning algorithms for complex pipe welds inspection (Sava robot).**

***Keywords*—NDT, robotics, automated weld inspection, trajectory planning**

I. Introduction

In the field of Non-Destructive Testing (NDT), there is a growing demand for increase efficiency, quality and repeatability of measurements. One way to meet these requirements is to automate test procedures. In the case of inspections during manufacturing processes, for example in the aerospace industry, industrial robots are used to automate controls [1]. They allow performing a wide range of measuring movements on complex shaped surfaces. This approach, however, is only suitable in cases where there is enough space for conventional robots. If industrial robots cannot be used to automate test procedures, specialized manipulators are being used, which in most cases are developed for a specific type of inspection or specific type of welds. In order to serve the widest range of dimensions using one device, manufacturers use different kinds of modular systems. Several systems for NDT offers, for example, Olympus:

The WeldROVER [2] is a simple, industrial-strength, one-axis encoded scanner that provides a fully mechanized automated data acquisition (Fig.1(a)). It is designed to make fast and efficient phased array inspections on ferromagnetic pipes or vessel girth welds and long seams. It is equipped with driven magnetic wheels, enabling automated movement along the weld on ferromagnetic tubes. Although it allows use without additional guides or rigid circular tracks around the pipe, there is a limitation on the pipe material and also the movement direction correction must be done manually. The same principle of attaching to the pipe, and therefore the same disadvantages, as the WeldROVER uses the MapROVER [3], which, however, introduces a second motorized axis as a linear guide. This allows both weld inspection and surface inspection (Fig.1(b)). Another Olympus product is a fully automated girth weld inspection system called PipeWIZARD [4] designed to inspect welds by conventional ultrasonic technology (UT) and phased array (PA). This system is specially designed for on-site weld-to-weld inspection of pipelines in extreme environments. The system is mounted to the pipe with a rigid circular track which is fastened around the pipe. Although this track provides a sufficient grip on the pipeline made of various materials, it is required to place this track precisely along the weld, and it is also necessary to have different tracks for specific pipe diameters. An inspection system of a very similar construction designed for the same use as PipeWIZARD is offered also by General Electric [5]. The company ZETEC offers MPS series scanners [6]. MPS series is designed for rapid ultrasonic examination of various pipe weld configurations with either PA or conventional UT techniques. The MPS scanners are available in three configurations: Manual with two encoders for bidirectional scanning, Semi-manual with one encoded motor on the circumferential axis and one manual encoder on axial axis and Automated with two encoded motors for bidirectional scanning. The fixing of this manipulator to the pipeline is made using metal chain links bounded around.



(a) WeldROVER

(b) MapROVER

Fig. 1. Olympus Inspection systems suitable for ferromagnetic pipes

There are, of course, many types of constructions that serve as manual scanners. Their advantages are especially compact size and lower weight, primarily due to the absence of motors and controllers. For example, Olympus offers a COBRA [7]

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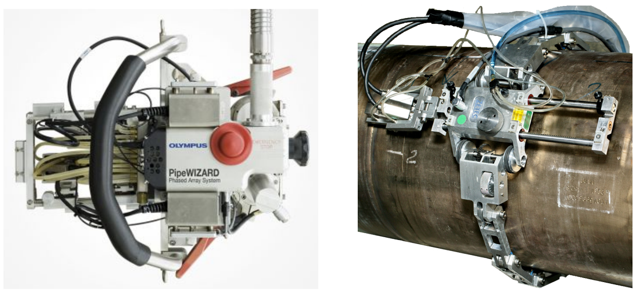


(a) WeldROVER (b) MapROVER

Fig. 2. Inspection systems suitable for non-ferromagnetic pipe materials

scanner designed for manual scanning of circumferential welds on small diameter pipes. With its very slim design, this manual scanner inspects pipes in limited access areas where minimal clearance is required. The company ZETEC offers very versatile and modular system called WELD Crawler [8], which allows scanning both circumferential and longitudinal welds with minimal rebuilding. Another advantage of this system is again the low construction frame allowing the inspection in limited access areas. Magnetic wheels again restrict use only on ferromagnetic pipes. The main drawbacks common to all manual scanner solutions include the need for constant operator presence, the impossibility of continuous motion measurement along welds, and often also their specialization on a particular type of inspection.

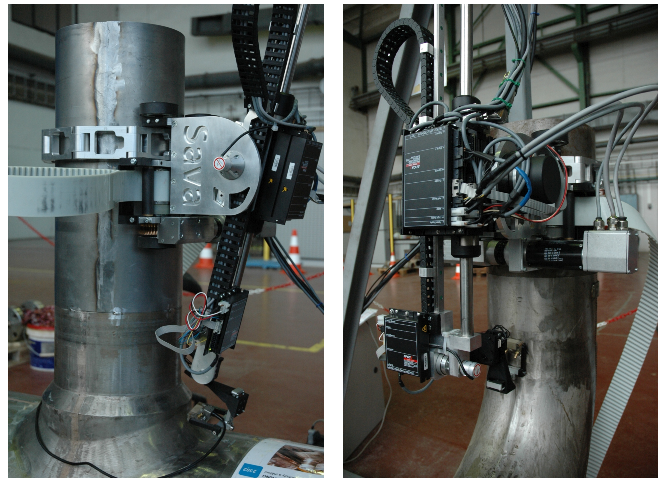
II. Sava robot

A. Introduction

The robotic manipulator Sava was built to automatically test pipe welds with complex geometry inside nuclear power plants. It is applicable on circumferential, branch, longitudinal and both types of elbow welds. The robotic manipulator introduced better accuracy and repeatability. The end-effector of this manipulator is equipped with UT probe and measured data together with robot position are recorded and offline evaluated by means of discontinuities or defects.

B. Kinematic structure

Kinematic architecture of Sava robot was chosen as a result of simulation and optimization analysis - 5 DoF serial manipulator of type RRPRR. End-effector probe mounting system adds two more passive DoFs so the probe can set its orientation according to the contact with cylindrical surface. The cart is mounted using toothed belt around the tested pipe and performs rotational movement. Metal chain alongside the toothed belt prevents robot from falling off the pipe and assures perpendicular tightening to the pipe which is essential for robot precision. Only one motor is used for cart movement. Therefore the cart adhere to the pipe surface with force resulting from semi automatic belt tightening procedure. The mechanical construction was designed with emphasis on minimal dimensions and robot weight.



(a) Branch weld (b) Inside elbow weld

Fig. 3. Sava robot testing complex welds

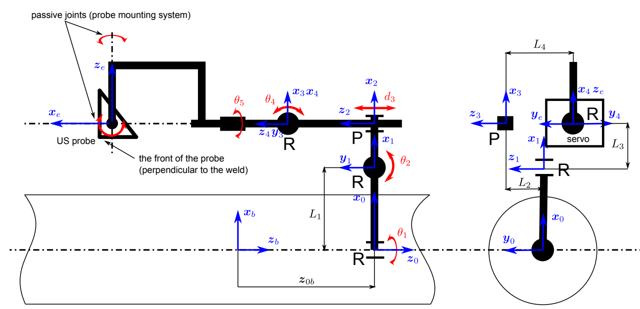


Fig. 4. Kinematics of Sava robot

The kinematics of Sava robot, see Fig. 4, is completely different from standard 6 DoF industrial manipulator because of the following reasons: i) there can be found combination between active (5 DoF) and passive (2 DoF) joints therefore the kinematic model of the passive probe mounting system together with the pipe surface contact model has to be introduced, ii) high variability of the robot which makes possible to test simple (circumferential, longitudinal) or complex (elbow, branch) welds results in the necessity to use different kinematic model of the robot for solving the inverse kinematics, iii) non-standard architecture brings some computational problems regarding the inverse kinematics. The inverse kinematic problem of the Sava robot can be summarized as follows, for more details see [10] : Generalized coordinates (the end-effector position and the last link tilt): x, y, z, ϕ, joint coordinates θ_1, θ_2, d_3, θ_4, θ_5.

• From the given pipe weld trajectory generator, see bellow, set x, y, z (probe center point) and required the last link tilt ϕ.

• The active serial kinematic chain (actuated part of the robot) and the passive serial kinematic chain (virtual passive model of the probe contact and the probe mounting system) are compared leading to the active joints recomputation.

Simulation model of the robot kinematics was developed

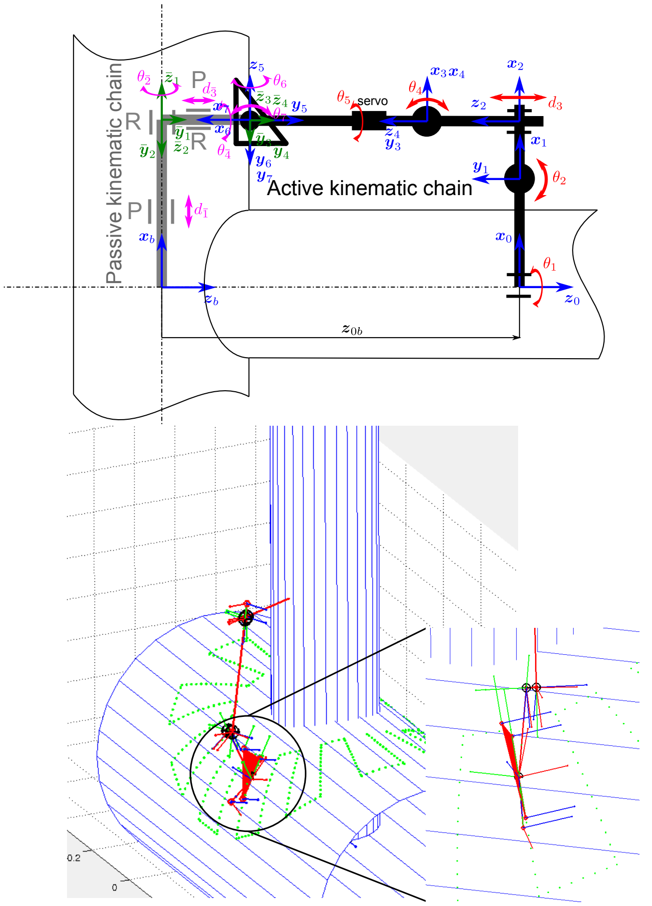


Fig. 5. Kinematic model of Sava robot and its visualization in SimMechanics

in Matlab/Simulink/SimMechanics and it is depicted in Fig. 5 for the case of the branch weld.

In order to compute the end-effector trajectory of the Sava manipulator the Matlab GUI stand-alone application (WeldGenerator, see Fig. 6) was developed which ensured that all required types of welds and appropriate parameters could be chosen and set. The interpolation of the (position) coincide points (general coordinates of the end-effector) was implemented through a new interpolation method in order to ensure required (trapezoidal) velocity profile along the weld curve. The proposed method was based on the trajectory segmentation where each segment (between two consecutive points) was interpolated by a cubic spline. Boundary conditions of the segments were relaxed as much as possible and only the continuity of velocity and acceleration was taken into account. In addition, the numeric iterative algorithm was used for the feedrate computation which ensured that the moving along cubic spline segments exactly fulfilled the requirements on the prescribed NDT probe speed. The smoothness of the end-effector trajectory which naturally leads to the limitation of vibrations of the robot mechanics is the main advantage of proposed interpolation algorithm. For more detail see [11].

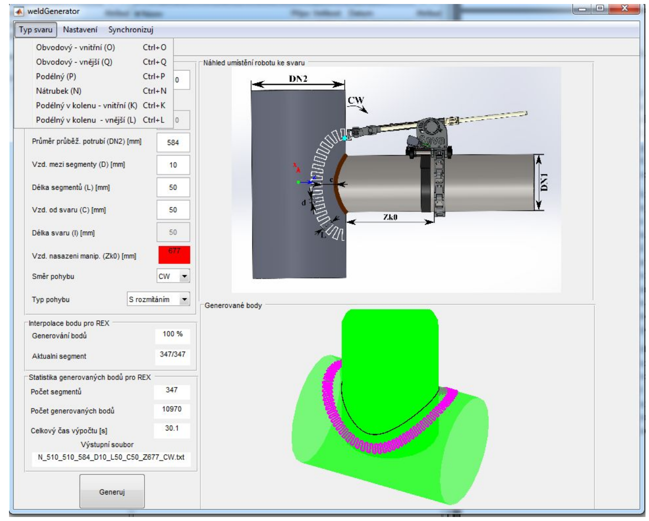


Fig. 6. WeldGenerator GUI for Sava robot (branch weld)

C. Control system

Major research task in Sava robot design and development was its control system. This prototype application is controlled by REX Control System [9]. The REX Control System is a family of software products for automation, robotics, measurement and monitoring projects. In our case the RexCore runtime runs on Alix PC Engines with OpenWRT Linux distribution. The REX Control System supports various industrial field buses such as CAN / CANopen, EtherCAT, Modbus TCP / RTU, Ethernet Powerlink and also integrates valid PLCopen Motion Control standard. PLCopen Motion Control standard includes function blocks libraries for Single axis, Multi axes and Coordinated motion. Robotic manipulator Sava is controlled by means of Single axis library for manual operation in joint coordinates and Coordinated motion library for both manual operation in world coordinate system and automatic inspection mode.

Essential part of control system are both forward and inverse robot kinematics. The REX Control System is developed at our department which is a huge advantage when it comes to implementation of custom robot kinematics with non-standard structures. This prerequisite also allows us to integrate advanced motion control algorithms and path planners to the control system with minimal effort.

Human-machine interface (HMI) is built over the control system. It is used to perform basic manipulator settings, manual control and setup of automatic test mode. Diagnostic messages are shown to inform operator about robot states and possible errors. Embedded web server is a part of the REX Control System that provides all the necessary information for HMI. Therefore, HMI can be displayed on any device with a common web browser.

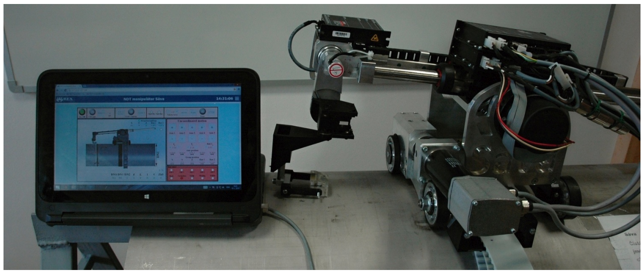


Fig. 7. Sava robot with HMI control panel

III. Vendy robot

A. Introduction

Main requirement on research and development of Vendy robotic manipulator was to minimize external dimension and weight with special emphasis on height. The robot was supposed to replace manual measurements in places where access for human operators is limited. Another requirement was capability of inspection on a non-ferromagnetic pipelines, which makes impossible to use the magnetic wheels. Most pipeline welds tested in the primary circuit area of the nuclear power plant are circumferential welds, so we have only focused on these. It is assumed that inspections will be carried out on a large range of pipe diameters resulting from a complex pipework in nuclear power plants.

The robot end-effector can perform a linear or typical meandering measuring motion. Therefore the robot is able to carry both UT or PA test probe. Repeating automatic periodical measurements allows us to monitor the development of the indicated defects and afterwards it is possible to predict and optimize their repair.

The last requirement was the industrial design of the complete solution, the ease of assembly and the operator's control, as well as the possibility of safe transport.

B. Robot design

The result of this development task is a two-axis robotic manipulator composed of a carriage and a linear arm parallel to the main axis of the pipeline. Two independent motors placed on the carriage provide the necessary downforce for the robot to adhere to the pipeline and the peripheral movement of the carriage along the pipe surface at the same time. At the end of the linear motor, an UT or PA probe is placed to test the pipeline for defects and cracks.

Due to the need of permanent contact of the UT probe and the tested material, the area under the probe is filled with water. Therefore, it was necessary to design the robot construction to be resistant to dripping water. Water resistance is also advantageous in terms of decontamination when transferring a robot between nuclear power plants and other sites.

C. Mounting system

The main benefit of the robot is a unique mounting system around the pipeline. The toothed belt is wound around the pipeline and both ends are guided on the pulleys of two motors located at the opposite ends of the carriage. In order to prevent free belt ends from jamming, the belt has trapezoidal cross section. After placing the robot near the test weld, the belt is tightened to the desired tension by the motors.

When the carriage is moving, the control system actively controls desired tension in the belt by independent commands of both motors. One motor is driven in position mode and desired position is fed by the control system. The other motor is switched to torque mode to ensure the constant predefined belt tension. This also protects the manipulator from sliding off the pipeline and actively compensates for surface unevennesses compared to single-motor carriages.

This solution allows fastening and use of the robot on pipes with diameters of at least 200 mm. The largest diameter of the pipe is limited by the length of the toothed belt.

D. Control system and HMI

Robot Vendy is equipped with the REX Control System. It is a comprehensive tool for a machine and process automation. The control system is responsible for all of the manipulator features such as adhesion control, management and control of motor drives, safety functions, manipulator software configuration or human-machine interface.

The control system implementation is divided into two main tasks - $task\_axes$ and $task\_reg$. Task $task\_axes$ provides complete motion control, defines the manipulator structure and manage individual robot modes including safety features. Each axis of the manipulator must have defined parameters such as axis type, range, possible range limits and all the dynamic parameters limiting its movement - speed, acceleration and jerk limits.

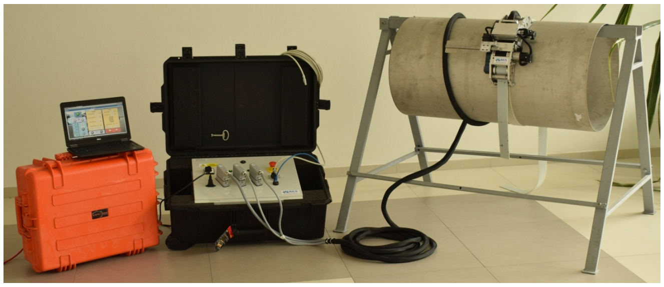
Switching between operation modes is managed by a finite state machine. It contents all possible operate modes in which the robot can be found including error states and their evaluation.

The position or torque requirements of both motors is sent to $task\_reg$. This task communicates via the CAN bus directly with the motor drives and commands the desired setpoints with 4 ms period. The control system regularly receives important parameters for motor control and diagnosis. The position and speed information from the motor encoder, the actual winding current, the temperature and the state of the drive, as well as error messages, are transmitted.

HMI (Fig. 8(c)) is specially designed for work in industrial conditions where the use of double gloves is common due to radiation.

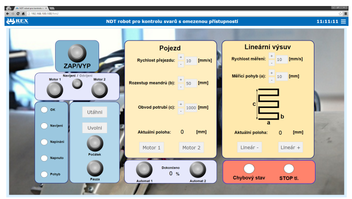
IV. Conclusion

In this paper, development special robotic manipulators for non-destructive testing was discussed. The first mentioned robot Sava was developed as a complex configurable manipulator for inspecting various types of pipe welds (circumferential, longitudinal, elbow, branch). It was necessary to optimize both the structure and parameters of the robot manipulator so that the resulting prototype is able to reliably test the above-stated welds. The entire process of design, prototype



(a) Complete setup with transportation cases

(b) Mounting system testing



(c) HMI

Fig. 8. Robotic manipulator Vendy

production, and implementation of the control system has been successfully completed by us or under our leadership. The prototype operational tests were performed at our NDT industrial partner.

The lightweight easy-to-use robot manipulator Vendy was primarily intended for industrial use and is currently used to evaluate selected welds of the primary circuit of nuclear power plants in the Czech Republic. The result of the development is the complex industrial solution of the robotic manipulator, including the control system, electrical distribution board, transport boxes and HMI. The mechanical design of the robot including the mounting system is patented in Czech republic [12] and we applied for international patent.

Future development is focused on a robot combining the benefits of both approaches - a robot with compact dimensions capable of handling welds with complex geometry. We are dealing mainly with the concept of snake-like multiredundant robot architecture. Another NDT application involves automated robotic inspection system for evaluation of control rod guide tube welds on vessel head inside surface.

Acknowledgment

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