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Conceptual Design and Control of a Robotic System for Welding

Kanstantsin Miatliuk
Dept. of Robotics and Mechatronics
Bialystok University of Technology
Bialystok, Poland
k.miatliuk@pb.edu.pl

Adam Wolniakowski
Dept. of Automation and Robotics
Bialystok University of Technology
Bialystok, Poland
a.wolniakowski@pb.edu.pl

Jose J. Quintana
IDeTIC
University Las Palmas Gran Canaria
Las Palmas, Spain
josejuan.quintana@ulpgc.es

Abstract— **The use of Hierarchical Systems (HS) method in design and control of a robotic system for welding (RSW) is suggested in the paper. Created conceptual model of the robotic system under consideration integrates connected systemic descriptions of the RSW mechatronic subsystems – IT, electronic, mechanic – which are given in the common HS theoretical basis. RSW structure and the motion planning task, RSW dynamic presentation in its environment, RSW control unit, and RSW learning by demonstration processes are also given in this basis. The examples of the RSW control processes, robot teaching and welding process simulation using Mimicking Kit and RobWork program system respectively are also described in the work.**

Keywords — conceptual design; robot; motion control; hierarchical systems; learning by demonstration

I. INTRODUCTION

The paper presents theoretical basis and conceptual model description of the laboratory Robotic Systems for Welding (RWS). Conceptual model creation of robotics system being designed at the stage of conceptual design (CD) is usually performed before the stage of detailed design (DD) of the system life cycle [1,2, 11].

Presently, many definitions of the conceptual design are used. From the definition by P. Childs [4], during conceptual design, a general idea of how the system will function and look like is created. In [3], conceptual design is defined as 'the design of interactions, experiences, processes and strategies'. M. French considers the conceptual design stage of the system life cycle as the stage where the formulation of the problem and development of broad solution to it in the schemes form is carried out [5]. Other formulations were considered by M. Hudspeth in [6].

In the paper, *conceptual design* is considered as the task of the conceptual systemic model development of the system being designed at the conceptual design phase of its life cycle just before the detailed design stage of concrete mathematical model selection and appropriate calculations execution [1,11]. RWS conceptual model being created have to integrate the coordinated models of mechatronic subsystems of various levels and nature. This model should be coordinated with numeric and geometric systems as well, i.e. well known means of information presentation in robotics and mechatronics.

Mathematical models and models of artificial intelligence used for systems design can't present the subsystems of objects being designed and technology of their interlevel relations in general formal basis. Theoretical basis of the conceptual design should have a hierarchical structure with its coordinating elements. Therefore, Hierarchical System (HS) [7] including its *aed* model [8-13] was selected in the paper as the formal basis for the conceptual model development and conceptual design of RW system. RWS model was created using the general conceptual description of mechatronic systems proposed [1,11,12,14,16].

To create conceptual model of RWS within Hierarchical Systems basis means to describe a RWS structure; dynamic model of RWS as the entity in the environment; RWS environment, RWS coordinator and the control task, processes performed by RWS subsystems. Theoretical basis of the conceptual design is presented first in the work. Next, the conceptual model of RWS is briefly given in the paper. UR5 robot teaching and RWS coordinator control processes are described after that.

II. FORMAL BASIS OF CONCEPTUAL DESIGN

Formal *aed* model S^{ℓ} described below integrates the models of two-level system [1,7-9], numeric positional systems L^{s}, geometrical system and cybernetic approaches; dynamical systems $(\bar{\rho},\bar{\varphi})$ [1,15] which are the basic means of the above mentioned models and codes description. *Aed* is a basic block of hierarchical systems [1,8-11], which implements the inter-level connections and the laws of system on each level. *Aed* S^{ℓ} integrates the dynamical ω^{ℓ} and structure σ^{ℓ} models tied by coordinator S_0^{ℓ}:

$$S^{\ell} \leftrightarrow \{\omega, S_0, \sigma\}^{\ell} \tag{1}$$

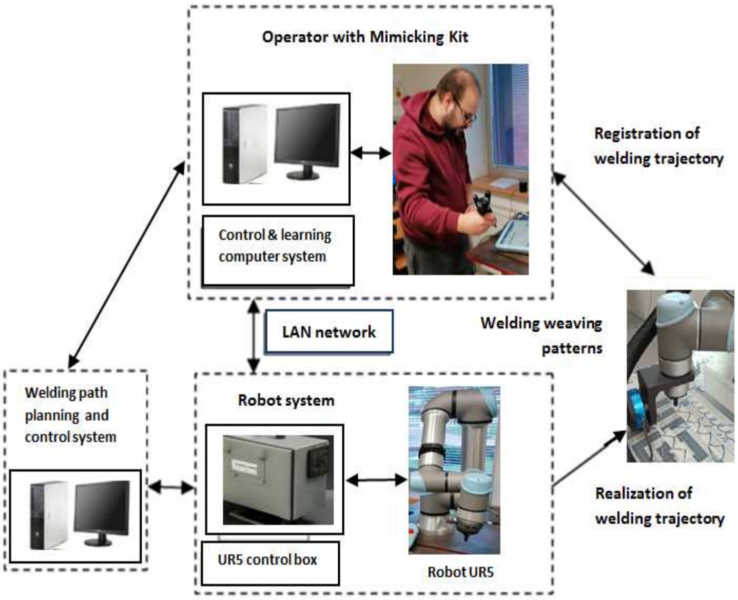

Fig. 2. Scheme of the laboratory robotic system for welding (RWS).

where ω^{ℓ} is a dynamic model of level ℓ system, ${}_{\omega}S^{\ell}$ is system environment, σ^{ℓ} is a structure, S_0^{ℓ} is a system coordinator. Scheme of *aed* S^{ℓ} is given in Fig.1.

Dynamic models ω^{ℓ} of the all *aed* elements, i.e. object ${}_{o}S^{\ell}$, processes ${}_{o}P^{\ell}$, ${}_{\omega}P^{\ell}$ and environment ${}_{\omega}S^{\ell}$ are given in the form of $(\overline{\rho},\overline{\varphi})^{\ell}$ as follows:

$$\overline{\rho}^{\ell} = \{\rho_t : C_t \times X_t \rightarrow Y_t \ \&\ t \in T\}^{\ell}$$
$$\overline{\varphi}^{\ell} = \{\varphi_{tt'} : C_t \times X_{tt'} \rightarrow C_{t'} \ \&\ t,t' \in T \ \&\ t' > t\}^{\ell} \quad (2)$$

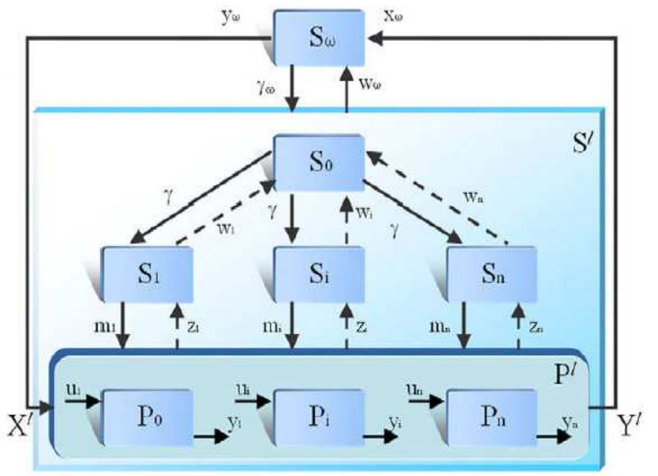

Fig. 1. *Aed* structure diagram – basic element of hierarchical system: S_0 - coordinator; S_ω – environment; S_i – sub-systems; P_i - sub-processes; P^l - process; X^l, Y^l - input and output of S^l system of level ℓ, $m_i, z_i, \gamma, w_i, u_i, y_i$ - interconnections.

where C^{ℓ} is state, X^{ℓ} is input, Y^{ℓ} is output, T^{ℓ} is time of level ℓ, $\overline{\rho}^{\ell}$ is the reaction and $\overline{\varphi}^{\ell}$ is the state transition function. Object ${}_{o}S^{\ell}$, its process ${}_{o}P^{\ell}$, system environment ${}_{\omega}S^{\ell}$ and its process ${}_{\omega}P^{\ell}$ are tied by their states, inputs and outputs [1, 8-12].

System structure is presented in the following form:

$$\sigma^{\ell} \leftrightarrow \{ S_0^{\ell} ,\{ \overline{\omega}^{\ell-1} , {}_{\sigma}U^{\ell} \}\} \leftrightarrow \{ S_0^{\ell} , \widetilde{\sigma}^{\ell} \} \quad (3)$$

where S_0^{ℓ} is coordinator, $\overline{\omega}^{\ell-1}$ are dynamic representations of subsystems $\overline{S}^{\ell-1} = \{S_i^{\ell-1} : i \in I^{\ell}\}$, and ${}_{\sigma}U^{\ell}$ are structural ties coordinated with the external ones ${}_{\omega}U^{\ell}$. $\widetilde{\sigma}^{\ell}$ is the connection of $\overline{\omega}^{\ell-1}$ models.

Coordinator S_0^{ℓ} is the control element of hierarchical system which performs the tasks of system design and control [1,13]. It is described in concordance with *aed* presentation of equation (1) as follows:

$$S_0^{\ell} \leftrightarrow \{ \omega_0^{\ell} , S_{00}^{\ell} , \sigma_0^{\ell} \} \quad (4)$$

where ω_0^{ℓ} is dynamic model of S_0^{ℓ}, σ_0^{ℓ} is S_0^{ℓ} structure, S_{00}^{ℓ} is controlling unit of coordinator. Coordinator S_0^{ℓ} is constructed recursively. S_0^{ℓ} builds its aggregated dynamic representation ω_0^{ℓ} and structure model σ_0^{ℓ} by itself. S_0^{ℓ} solves the design and control problems on its selection, learning and self-coordination layers [1,11-13].

Metrical parameters μ of the systems being designed as well as their geometrical characteristics are defined within *aed* formal basis in codes of the numeric positional system L^S [1,10-12]. There are two main parameters of systems structure, i.e. connection defect ξ^ℓ and (constructive dimension δ^ℓ; μ^ℓ, ξ^ℓ and δ^ℓ are tied and presented in codes of positional L^S system [1,10-12]. For instance, constructive dimension $\delta^\ell \in \Delta^\ell$ of S^ℓ system is described in L^S code in the following form:

$$\widetilde{\delta}^\ell = (n_3 ... n_0)_\delta, \widetilde{\delta}^\ell \in \{\delta_\sigma^\ell, \delta_\omega^\ell\}$$
$$(n_i)_\delta = (n_{3-i})_\xi,\ (n_i)_\delta \in N,\ \iota=0,1,2,3 \qquad (5)$$

where δ_ω^ℓ and δ_σ^ℓ are constructive dimension of σ^ℓ and ω^ℓ accordingly. Given presentation of geometric systems makes possible the geometric information processing on computer by performing operations with the appropriate numerical codes. geometric images of mechatronic objects on computer as operations with numeric codes. *Aed* formal model presented in the paper gives the formal means for the Robotic Welding System (RWS) conceptual design and control as well as other mechatronic systems design.

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III. Robotic Welding System Conceptual Model

Conceptual model of the Robotic Welding System (RWS) given in theoretical basis of hierarchical systems is presented below. In the work we focused on the laboratory-level RWS developed in Bialystok University of Technology, Poland. RWS contains universal robot UR5 system, computer trajectory planning and control system, operator and Mimicking Kit used for welding trajectory registration and robot teaching. Conceptual model of the RWS is presented in Hierarchical Systems formal basis in the next *aed* form:

$$S^\ell \leftrightarrow \{\omega, S_0, \sigma\}^\ell \qquad (6)$$

where ω^ℓ is dynamic model of RWS S^ℓ, σ^ℓ is the RWS structure, S_0^ℓ is RWS coordinator (design & control system), ℓ is the index of level.

RWS system structure σ^ℓ (Fig. 2) includes the elements set $\overline{\omega}^{\ell-1}$ and structural interactions ${}_\sigma U^\ell$. Therefore, in accordance with model (3) the RWS elements $\overline{\omega}^{\ell-1}$ are:

- $\omega_1^{\ell-1}$: robot system (RS);
- $\omega_2^{\ell-1}$: welding path planning system (PP);
- $\omega_3^{\ell-1}$: operator with Mimicking Kit (MK);
- $\omega_4^{\ell-1}$: control computer system (CC).

Furthermore, each system of level ℓ*-1* has its own subsystems, i.e. mechatronic elements of ℓ*-2* level. As for the robotic system $\omega_1^{\ell-1}$ its subsystems are manipulator $\omega_{11}^{\ell-2}$ (mechanical), servo-drives $\omega_{12}^{\ell-2}$ (electro-mechanical), water-cooled welding gun $\omega_{13}^{\ell-2}$ (electro-hydraulic) and its own control system $\omega_{14}^{\ell-2}$ (computer subsystem). RWS computer system (CC) $\omega_4^{\ell-1}$ connects control units of UR5 robot, Mimicking Kit and welding path planning subsystem of RWS, and contains program modules developed by authors for subsystems integration.

CC is the element of RWS coordinator which executes design and control tasks. The RWS elements are tied by their structural connections ${}_\sigma U^{\ell-2}$. For instance, welding gun $\omega_{13}^{\ell-2}$ and manipulator $\omega_{11}^{\ell-2}$ are connected by the ending link ${}_\sigma U_{13}^{\ell-2}$ of UR5 manipulator kinematic chain. Similarly, the higher level subsystems $\overline{\omega}^{\ell-1}$ are tiered by their common elements, i.e. structural interconnections ${}_\sigma U^{\ell-1}$ that are the parts of lower levels. Mimicking kit $\omega_3^{\ell-1}$ and robot system $\omega_1^{\ell-1}$ are tied by their mutual part – communication program unit ${}_\sigma U_{13}^{\ell-1} = \omega_{14}^{\ell-2} = \omega_{34}^{\ell-2}$ of the CC system, where $\omega_{14}^{\ell-2}$ is dynamic presentation of the control program which is the element of robot $\omega_1^{\ell-1}$, and $\omega_{34}^{\ell-2}$ is the dynamic model of the program which is the element of the mimicking kit $\omega_3^{\ell-1}$.

Aggregated dynamic realizations $\overline{\omega}^{\ell-1}$, i.e. ${}_i(\overline{\rho}, \overline{\varphi})^{\ell-1}$ models (2) of RWS elements are constructed after defining their inputs and outputs. As for MK system $\omega_3^{\ell-1}$, regarding its welding trajectory generation process, $X_3^{\ell-1}$ input is the infra-red signal registered by MK receiver antenna, and $Y_3^{\ell-1}$ output is the welding trajectory coordinates collected in MK controller and CC system after that. State $C_3^{\ell-1}$ is the completeness degree of the trajectory generation process. This process is of the IT nature.

Concerning robotic subsystem $\omega_1^{\ell-1}$, regarding the mechanical process of its movement, the dynamic model $\omega_{11}^{\ell-1}$ given at the CD stage in form (2) can be transformed at the DD stage to equations [17] of inverse kinematics presented in the following form:

$$\dot{q} = J^+(q)\dot{x} \qquad (7)$$

Equation (7) ties velocities $\dot{q}$ of the manipulator joints as the output $Y_1^{\ell-1}$ with velocity $\dot{x}$ of the welding gun as input $X_1^{\ell-1}$, where J^+ is the pseudo inverse of Jacobian matrix.

Dynamic representation ω^ℓ of RWS and its subsystems presented in form $(\overline{\rho},\overline{\varphi})$ (2) at the conceptual design stage may be converted at the detailed design stage to the following state space equation:

$$\dot{x} = Ax + Bu,\ y = Cx. \tag{8}$$

In (8), first equation match to the function $\overline{\varphi}$ of states transition in (2) and the output equation match to the reaction $\overline{\rho}$. For the example of the manipulator welding instrument movement the elements of states vector $\boldsymbol{x}=[x_1\ x_2]^T$ are the position x_1 and speed x_2.

RWS environment has its own structure and integrates the next elements: ω_1^ℓ machine parts being welded (mechanical system) (Fig. 4); ω_2^ℓ: men-operator, which communicates with RWS via CC and MK subsystem (human-computer system) (Fig. 6); ω_3^ℓ other technological units being in interaction with RWS; ω_4^ℓ: coordinator, i.e. computer design system of higher level. All the subsystems are described at the CD stage in (2) form.

Coordinator S_0^ℓ is described according to (4) and implemented in a form of design and control system of the RWS, which realises its coordination functions by hunam-operator and computer system and performs the design tasks by computer design system of higher level. Metrical parameters of RWS systems used in the design process are given in the form of numerical system L^s [1,10-12]. RWS coordinator S_0^ℓ control functions are briefly described below in Section IV.

IV. Coordinator Control Processes

Control processes P_0^ℓ of RWS coordinator S_0^ℓ are executed by human-computer subsystem, i.e. man-operator with CC system. The coordination processes are:

1) robot control to follow welding trajectory generated ${}_1P_0^\ell$,

2) welding path planning, generation and processing ${}_2P_0^\ell$,

3) robot teaching by man-operator using Mimicking Kit ${}_3P_0^\ell$,

4) control processes integration ${}_4P_0^\ell$.

Control processes are formally presented as coordinator S_0^ℓ functions in $(\overline{\rho},\overline{\varphi})_0^\ell$ form (2) or canonical form $(\varphi,\lambda)^\ell$ [1,11-15] after defining the states C_{0t}^ℓ, inputs X_{0t}^ℓ and outputs Y_{0t}^ℓ of RWS controlling elements. In accordance with diagram in Fig.1, the inputs and outputs of RWS coordinator are described on the sets of coordination G^ℓ and feedback W^ℓ signals in the following form::

$$X_0^\ell = \{G^{\ell+1}, W^\ell\},\qquad Y_0^\ell = \{G^\ell, W^{\ell+1}\} \tag{9}$$

where G^ℓ is coordination signal to $\overline{S}^{\ell-1}$ subsystems, W^ℓ is feedback signal from $\overline{S}^{\ell-1}$, $W^{\ell+1}$ is feedback signal from coordinator S_0^ℓ to the one $S_0^{\ell+1}$ of $\ell+1$ level, $G^{\ell+1}$ are signals from coordinator $S_0^{\ell+1}$ to S_0^ℓ [1,13,14].

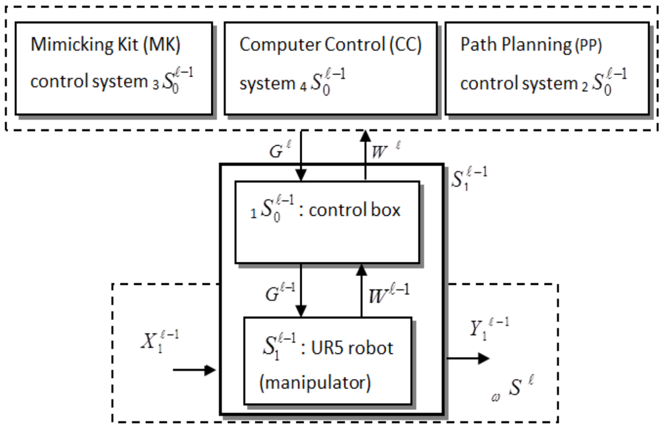

Fig. 3. RWS coordinator subsystems in control process of UR5 robot.

In RWS control task (Fig. 3) the inputs X_{0t}^ℓ are coordination signals G^ℓ which are coordinates of welding trajectory *[x(t), y(t), z(t)]* and feedbacks $W^{\ell-1}$ from encoders which transmit the values of the actual positions of UR5 manipulator joints. Outputs Y_{0t}^ℓ are electronic impulses $G^{\ell-1}$ which set the angular value θ_i of manipulator i joint (next position), $i=6$, and W^ℓ is feedback signal to PP and CC control systems that carries information about C_{0t}^ℓ state. State C_{0t}^ℓ is the current positions of UR5 robot joints and end-effector (welding gun) at t moment of time. State of RWS coordinating system S_0^ℓ is the input of the control process at the actual moment of time t.

As for the welding path following process controlled by CC system and robot control box ${}_1S_0^{\ell-1}$ the input $X_1^{\ell-1}$ of UR5 robot $S_1^{\ell-1}$ (Fig. 3) is input loads of manipulator drives (servo drives). The output $Y_1^{\ell-1}$ is UR5 end-effector actual position which is the input of environment ${}_\omega S^\ell$ element ω_1^ℓ,

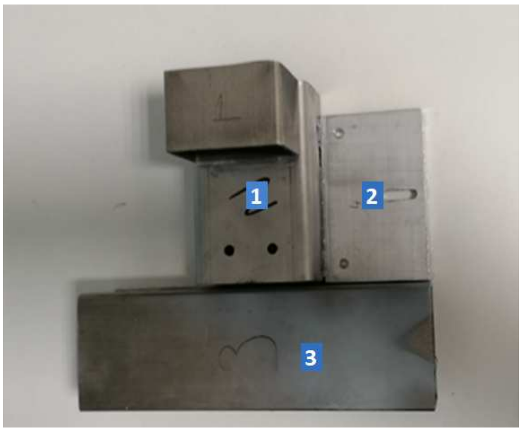

Fig. 4. Machine parts 1, 2 and 3 being welded.

i.e. welding path of the parts being welded (Fig. 4). Welding process is executed by UR5 after performing path following task simulation by RobWork program system [18] (Fig. 5) within computer control (CC) subsystem which activates coordination process ${}_{1}P_{0}^{\ell-1}$ of UR5 robot control unit ${}_{1}S_{0}^{\ell-1}$. Welding process was not carried out in the university laboratory environment. The experiments planned to be performed using real welding gun mounted on UR5 manipulator and MIG welding equipment in technological environment of the selected enterprise.

Coordinators ${}_{i}S_{0}^{\ell-1}$ (control units) of RWS sub-systems, i.e. MK, CC, PP systems, UR5 robotic system, presented in Fig. 3 create a common RWS coordinator S_{0}^{ℓ}.

V. Robot Teaching

To generate weaving pattern of the welding path for the manipulator's instrument to carry out the welding task in the robot's working space the UR5 robot teaching by human-operator was executed in Robotic Systems Lab., Bialystok University of Technology (BUT), Poland (Fig. 6). For this purpose, the man-operator teaches the robot by generating the path to be followed that presents the welding task.

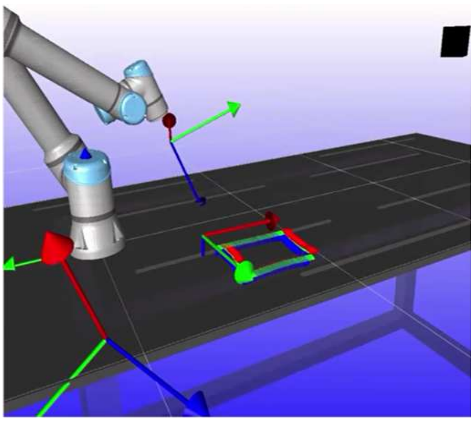

Fig. 5. RobWork screenshot simulating path following by UR5.

Fig. 6. UR5 teaching by man-operator using Mimicking Kit tracker in laboratory environments: 1 is the infra-red Transmitter sensor, 2 is the Receiver antenna, 3 is MK joystick hold in operator's hand.

To record human hand movement and create the path to follow by UR5 robot, the Mimicking Kit tracker [19] was utilized, which gives high position and orientation precision, i.e., 0.5 mm and 0.5 degrees respectively.

To perform UR5 robot teaching in the laboratory environment, the infra-red Transmitter sensor of the Mimicking Kit was placed at 1500 mm distance from UR5 manipulator base, while the Receiver antenna wireless connected with the sensor was placed at MK joystick hold in operator's hands or at the UR5 manipulator ending-effector flange (Fig. 6). For generating the robot trajectory to follow, the human operator was holding the Mimicking Kit joystick and moving it along the predefined weaving pattern of the welding trajectory in 3D space.

The generated trajectory was registered by Mimicking Kit at the sample frequency of 80 Hz and fed to UR5 manipulator, i.e., all welding path points were saved in the robot's computer memory. To carry out the trajectory following task with UR5, the welding trajectory was processed and smoothed, the inverse kinematics problem was solved at each point of the learned weaving trajectory and the calculated manipulator joints angles were sent to the UR5 control box and manipulator servomotors after that. The robot control was achieved through a built-in control loop for UR5 position operating at a frequency of 125 Hz. The weaving trajectory generation and robot learning from demonstration, i.e., teaching task executed by the human operator, can be repeated for the same or another trajectory type required for the welding path following task performance by UR5 robot.

VI. Conclusions

Conceptual model of the robotic system for welding (RWS) described in the formal basis of hierarchical systems for conceptual design and control implementation is briefly described in the work. In contrast with widely used mathematical models, RWS conceptual model developed integrates the tied representation of the robotic structure, dynamic model of the system, and the model of RWS environment. All these models are integrated by RWS coordinator which carries out the design and control tasks. Representation of RWS subsystems in form of dynamic systems – generalizations of known mathematical models [1,15] – allows the easy transition from the CD to the DD design stage in the RWS life cycle. The transition requires concretization of RWS subsystems models only. The examples of the RSW control processes, robot teaching and welding process simulation using Mimicking Kit and RobWork program system respectively are presented in the paper as well.

Conceptual model described in the work is coordinated with widespread forms of information presentation in robotics: numerical and geometric systems. RWS model described meets the general requirements of the design and control systems [1,11], presents the parts of RWS conceptual model and the coupled RWS mechatronic subsystems of various nature within *aed* formal basis of hierarchical systems. It gives new capabilities in the development of a formal language for the conceptual design of RWS and other robotic systems. The results of RWS conceptual design were implemented in laboratory environment and planned to be implemented in machine building enterprises of EU. Application of the proposed conceptual design method in the other robotic problems [20-25] is among the future tasks.

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