

# Parametric optimization in virtual prototyping environment of the control device for a robotic system used in thin layers deposition

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**Abstract.** The paper deals with the optimal design of the control system for a 6-DOF robot used in thin layers deposition. The optimization is based on parametric technique, by modelling the design objective as a numerical function, and then establishing the optimal values of the design variables so that to minimize the objective function. The robotic system is a mechatronic product, which integrates the mechanical device and the controlled operating device. The mechanical device of the robot was designed in the CAD (Computer Aided Design) software CATIA, the 3D-model being then transferred to the MBS (Multi-Body Systems) environment ADAMS/View. The control system was developed in the concurrent engineering concept, through the integration with the MBS mechanical model, by using the DFC (Design for Control) software solution EASY5. The necessary angular motions in the six joints of the robot, in order to obtain the imposed trajectory of the end-effector, have been established by performing the inverse kinematic analysis. The positioning error in each joint of the robot is used as design objective, the optimization goal being to minimize the root mean square during simulation, which is a measure of the magnitude of the positioning error varying quantity.

## 1. Introduction

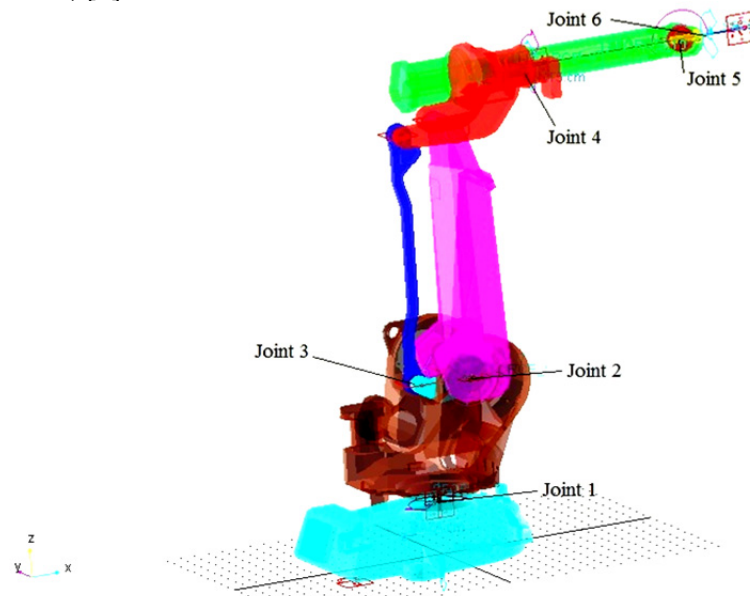
The purpose of the paper is to carry out the optimal design of the control system for an industrial robot (ABB IRB2400L) used in thin layers deposition (the substrate for solar energy conversion systems). Basically, the robotic system is a mechanical system, in this case with 6 DOF (Degrees of Freedom), corresponding to the six axes of the robot, which are controlled in order to assure the optimal trajectory of the end-effector (sprayer) on the entire deposition process.

The robotic system is designed in virtual environment with the help of the CAD software solution CATIA. Then, by using the STEP (Standard for the Exchange of Product Model Data) file format, the virtual model is transferred in the dynamic analysis environment ADAMS/View, where the connections between bodies and the actuating elements are modelled, thus obtaining the MBS (Multi-Body System) model of the mechanical device of the robotic system (figure 1).

The communication (data transfer) between the MBS (ADAMS/View) and DFC (EASY5 - Engineering Analysis Systems) models, through the input and output plants, is managed by using ADAMS/Controls, which is a plug-in to ADAMS/View [1]. The input of the control system is represented by the motion law of the industrial robot (in terms of imposed trajectory of the end-effector), which is transposed through inverse kinematics into the rotational motions in the six joints of the robot. The imposed trajectory of the end-effector was developed so that to obtain the optimal



parameters of the thin layers deposition process (in terms of spraying angle, height of spraying cone, trajectory step, time between two passes, carrier gas pressure, substrate temperature, spraying velocity and solver concentration) [3].



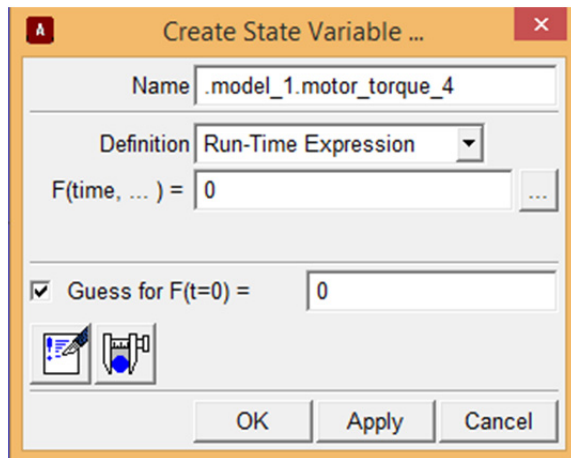
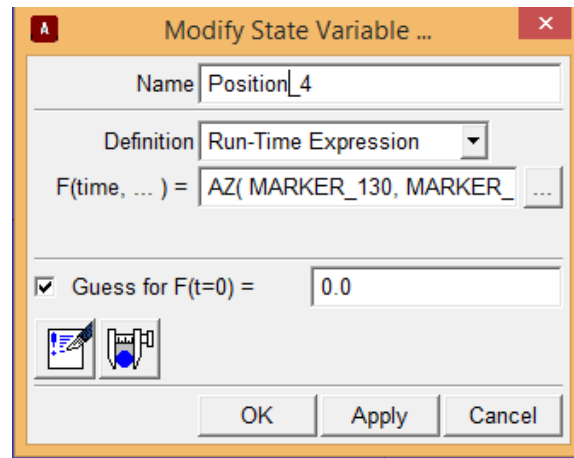
**Figure 1.** The virtual prototype of the robotic system.

The problem concerning the control of the robotic system can be approached by using different techniques (closed or open-loop systems) and controllers (P – Proportional, PI – Proportional Integral, PD – Proportional Derivative, PID – Proportional Integral Derivative) [4]. In this paper, the study was developed for a general PID controller that is implemented in the control system model, the proportional, integral and derivative factors being the independent design variables in the optimization study. The eighteen factors of the controllers (proportional, integral and derivative for each joint) are determined through a parametric optimization technique performed in ADAMS/Insight. The system is optimized so that the difference between the desired (imposed) and current (measured) angles in the revolute joints of the robot to be minimal. The paper is organized as follows: Section 2 presents the design of the robotic system (including the mechanical device, and the control system); Section 3 discusses the results; Section 4 shows the main research findings.

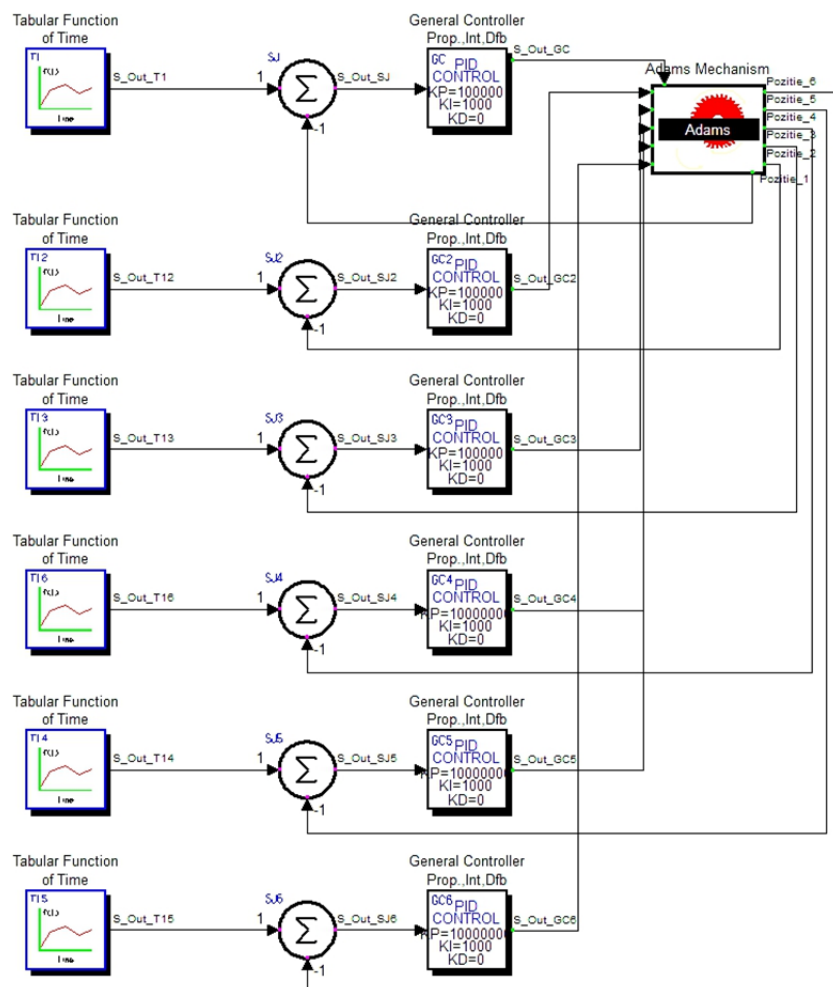
## 2. Designing the Robotic System

For this paper, the application is performed for a 6-DOF robotic system (ABB IRB 2400 L), which is used to deposit the substrate for solar energy conversion systems. The virtual prototype of the robotic system, which is identical to the real one, was realized in CATIA and contains information about the mass and inertia properties of the bodies. The robotic system contains: the CAD model of the ABB IRB 2400L robot, the worktable, a plate for heating the substrate, the system for attaching the sprayer on the robot, and the sprayer (end-effector).

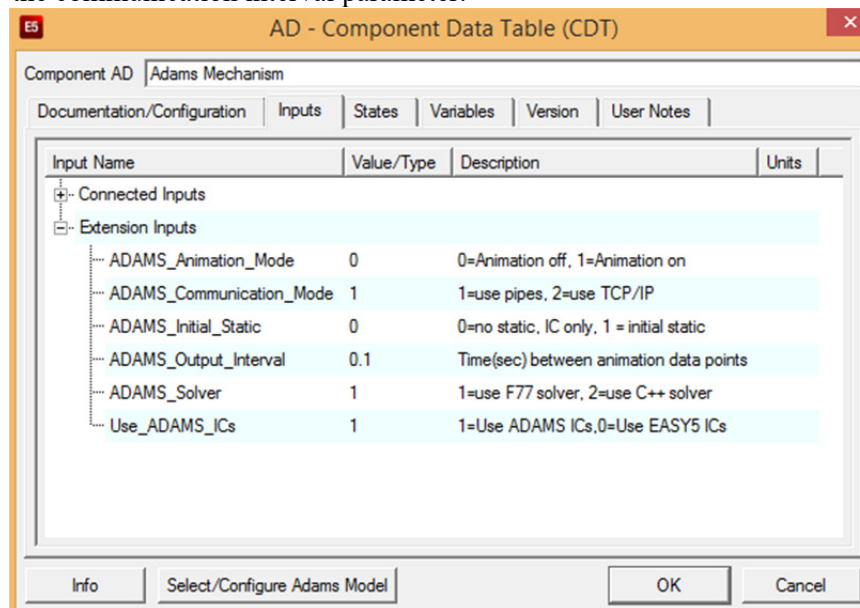
The motor torques generated by the six driving sources represent the input parameters in the mechanical model. The outputs transmitted to the controllers are the angular displacements in the revolute joints of the industrial robot. Because, the motor torques will get the values from the control system, which are develop in EASY5, the run-time function for the input variables are 0.0 during the simulation (see figure 2). The run-time functions for the output variables are defined using a specific ADAMS function – VARVAL (AZ), which returns the value of the given variable, in this case the rotational displacement of one coordinate system marker attached to a part about the motion local axis (Z-axis in ADAMS) of another marker attached to the adjacent part (figure 3).

**Figure 2.** Modelling of the input variable.**Figure 3.** Modelling of the output variable.

The ADAMS plant files have been exported for the control application using the ADAMS/Controls interface. The input and output plants are saved in a specific file for EASY5 (\*.inf), which is used to create the control system diagram (figure 4). ADAMS/Controls generates a command file (\*.cmd) and a dataset file (\*.adm) that are used in the co-simulation process.

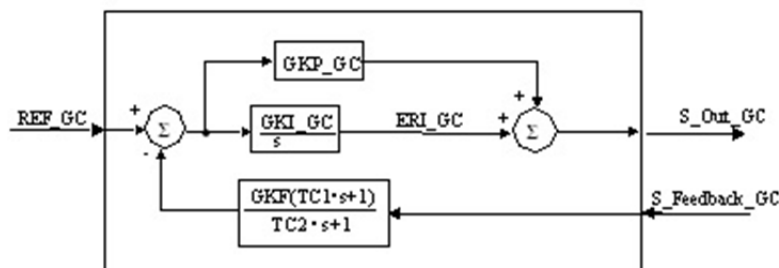
**Figure 4.** The control system block diagram.

The blocks involved in the control system diagram (shown in figure 4) have the following meanings: TB - Tabular Function of Time, which provides a table as a function of time (for modelling the input signal - the motion law in the specific revolute joint); SJ - Summing Junction, which is used to compare the imposed measure (line “1”) with the current measure (line “-1”); GC - General Controller, used for modelling the controller; ADAMS Mechanism -the interface link to the MSC.ADAMS model, which is based on the .inf file generated by ADAMS/Controls. The execution mode of the two models of the mechatronic robotic system (the mechanical device, and the control system), which is indicated by using the Select/Configure Adams Model button (figure 5), was set to co-simulation, the two solvers (EASY5 and ADAMS) exchanging input and output data at a rate determined by the communication interval parameter.



**Figure 5.** ADAMS Mechanism block from Easy5.

The PID controller block diagram is shown in figure 6, the involved parameters having the following meanings (the notations are that used in EASY5): REF -the controller input (which is used to input the reference command); S\_Feedback - the feedback signal; GKP - the proportional control gain; GKF - the gain in the feedback line; GKI -the integration control gain; TC1 -the derivative factor (which is used as a lag time constant to calculate an approximate derivative from the error signal ); TC2 - the feedback damping time constant (which is used to help prevent an implicit loop); S\_Out-the output of the controller (specifically, the motor torque transmitted to the MBS mechanical model); ERI - the integrated error signal; s -the Laplace transform. This type of PID controller diagram was used for all of the six joints.



**Figure 6.** PID controller diagram from Easy5

In these circumstances, the transfer function generated by the PID controller, which is used to characterize the relationship between the input and output system, has the next form:

$$S_{Out_{GC}} = ERI + GKP \cdot (REF_{GC} - FBS \cdot S_{Feedback}) \quad (1)$$

in which:

$$FBS = (ERV + S_{Feedback} \cdot TC1 \cdot GKF) / TC2 \quad (2)$$

$$d(ERV)/dt = GKF \cdot S_{Feedback} - FBS \quad (3)$$

$$d(ERI)/dt = GKI \cdot (REF_{GC} - FBS) \quad (4)$$

where ERV is the intermediate output.

To access the parametric optimization procedure included in the ADAMS software it is necessary that the control system shown in figure 4 to be transferred to ADAMS. The analysis and optimization of robotic system is exported from the interface EASY5 by using ESL (External System Library) format, specifying also the system parameters which will be identified in ADAMS as design variables (in this case, proportional, integral and derivative factors). Once imported into ADAMS, as a general equation of state (GSE - General State Equation), parameterized model of the control system connected with the MBS model, will be available for optimization.

A proportional - integral - derivative (PID) controller is used for each motor drive. The positioning error in each joint of the robot (defined by the difference between the imposed/desired angular position and the current/measured position) is used as design objective for the optimization process, while the proportional, integral and derivative gains of the position controllers are the design variables. The goal of the research is to minimize the root mean square during simulation, which is a measure of the magnitude of the positioning error varying quantity.

### 3. Numerical simulation

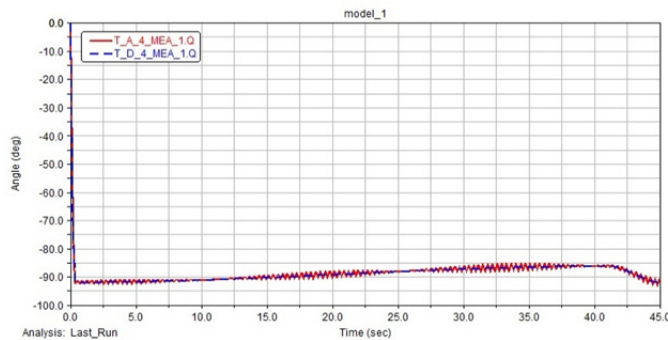
To access the parametric optimization procedure implemented in ADAMS/View, the control system model was transferred (exported) from the EASY5 interface through the ESL (External System Library) format, specifying the system parameters that will be identified in ADAMS as design parameters. Once imported in ADAMS, in the form of a general state equation (GSE), the parameterized model of the control system, connected to the MBS model of the mechanical device of the 6-DOF robot, becomes available for optimization, which was conducted in ADAMS/View by using the OptDes-GRG (Generalized Reduced Gradient) algorithm.

The virtual prototype of the robotic system is then used for a comparative analysis between the specific types of controllers from the PID family (P - PI - PD - PID), with the aim to determine the simpler controller that assures appropriate dynamic behavior of the robotic system. In this study, several DOE investigation strategies (Screening, Response Surface) and design types (Full Factorial, PlackettBurman, D-Optimal) have been tested, with the aim to identify the factors and combinations of factors that most affect the responses.

The best results (in terms of goodness of fit) have been obtained for the DOE Screening strategy with D - Optimal design [5, 7], so the design space and the work space of the experiment have been created based on the design specifications. This strategy produces a model that minimizes uncertainty factors. The technique is characterized by flexibility, allowing specifying the total number of runs in an experiment, supplementation of other experiments runs and indicating different levels for each factor [2, 6, 8].

The design space is presented in Table 1 (in this case for the PD controller), which is a matrix with the rows representing the runs (trials), and the columns representing the factors settings ("1" corresponds to the minimum value of the factor, "1" is for the maximum value). The work space is a matrix with the rows indicating the runs and the columns identifying the factors settings and resulting response values [1]. The optimal values of the PID controller factors have been obtained for the fourth axis, as follows:  $KP = 10^8$ ,  $KI = 10$ ,  $KD = 10^4$ . With these values, the time-history variation of the

error of the forth axis is shown in Figure 7. These are represented by overlapping the desired angle diagram and the actual angle diagram.



**Figure 7.** The actual and desired angle for the fourth joint.

**Table 1.** Design space of the first joint.

<i>Trials</i>	<i>Kp_1</i>	<i>Kd_1</i>
<i>Trial 1</i>	-1	-1
<i>Trial 2</i>	1	-1
<i>Trial 3</i>	-1	1
<i>Trial 4</i>	1	1

**Table 2.** Fit for regression of the 1 joint.

	DOF	SS	MS	F	P
Model	3	241	80.2	$10^{20}$	0
Error	0	$3.29 \cdot 10^{-29}$	0		
Total	3	241			
R2	1				
R2adj	1				
R/V	$10^{20}$				

**Table 3.** Fit for regression of the 2 joint.

	DOF	SS	MS	F	P
Model	3	$3.8 \cdot 10^{03}$	$1.27 \cdot 10^{03}$	$10^{20}$	0
Error	0	$5.58 \cdot 10^{-28}$	0		
Total	3	$3.8 \cdot 10^{03}$			
R2	1				
R2adj	1				
R/V	$10^{20}$				

**Table 4.** Fit for regression of the 3 joint.

	DOF	SS	MS	F	P
Model	3	7.74	2.58	$10^{20}$	0
Error	0	$3.17 \cdot 10^{-31}$	0		
Total	3	7.74			
R2	1				
R2adj	1				
R/V	$10^{20}$				

**Table 5.** Fit for regression of the 4 joint.

	DOF	SS	MS	F	P
<b>Model</b>	3	$5.5 \cdot 10^{03}$	$1.83 \cdot 10^{03}$	$10^{20}$	0
<b>Error</b>	0	$1.84 \cdot 10^{-27}$	0		
<b>Total</b>	3	$5.5 \cdot 10^{03}$			
<b>R2</b>	1				
<b>R2adj</b>	1				
<b>R/V</b>	$10^{20}$				

**Table 6.** Fit for regression of the 5 joint.

	DOF	SS	MS	F	P
Model	3	543	181	$10^{20}$	0
Error	0	$4.27 \cdot 10^{-29}$	0		
Total	3	543			
R2	1				
R2adj	1				
R/V	$10^{20}$				

**Table 7.** Fit for regression of the 6 joint.

	DOF	SS	MS	F	P
Model	3	$4.13 \cdot 10^{03}$	$1.38 \cdot 10^{03}$	$10^{20}$	0
Error	0	$2.28 \cdot 10^{-28}$	0		
Total	3	$4.13 \cdot 10^{03}$			
R2	1				
R2adj	1				
R/V	$10^{20}$				

The root mean square value is small,  $RMS = 0.840214$ , and this demonstrates the viability of the adopted optimization technique. The algorithm was applied to the other types of controllers from the PID family (PI, PD, and P), as follows: controller PI:  $KP = 10^8$ ,  $KI = 100$ ;  $RMS = 0.847258$ ; controller PD:  $KP = 10^8$ ,  $KD = 10^4$ ;  $RMS = 0.843904$ ; controller P:  $KP = 10^8$ ;  $RMS = 0.842054$ . Analyzing the results, it was concluded that all types of controllers (PID, PI, PD, and P) ensure appropriate behaviour of the robotic system. Under these circumstances, the optimal variant retains the cheapest controller type, namely the proportional controller P.

Tables 2-7 show the fit for regression of each of the six joints, where: R-squared ( $R^2$ ), Rsquared-adjusted ( $R^2_{adj}$ ), regression significance (P), range-to-variance (R/V), and F-ratio (F). Rsquared indicates the variance in the predicted results versus the real data. This is the proportion of total variability in the data which is explained by the regression model, a score of "1" indicating a perfect fit. R-squared-adjusted is similar to R-squared but is adjusted to account for the number of terms. Regression significance indicates the probability that the fitted model has no useful terms, small values indicating that the fit does have useful terms. Range-to-variance ratio indicates how well the model predicts values at the data points. F-ratio is used to test the significance of the regression, high values suggesting that the regression is significant, and the model is useful. The fit table contains also: DOF - the number of independent variables that go into the estimation of a parameter, SS - the sum of squares, MS - the mean square (MS), for the regression model, residual error and total.

#### 4. Conclusions

The proposed technique is a good example regarding the optimisation of the virtual prototyping model in the design process of the robotic systems. One of the important advantages of this analysis is that it is possible to create virtual measurements in any point of the robotic system and also, for any parameter (energy, force, motion). The optimization strategy was based on the minimization of the angular motion for the six joints of the robotic system. The positioning error in each joint of the robot is used as design objective, the optimization goal being to minimize the root mean square during simulation, which is a measure of the magnitude of the positioning error varying quantity. In this way, the predictions of the performance have been obtained earlier in the design process of the robotic system.

#### 5. References

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