Automatic Control and Its Means in Mechatronics and Robotics

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I. Introduction

This contribution deals with the investigation of automatic control and its means used in different applications of Mechatronics and Robotics (Fig. 1). Systems in engineering practice, not only in Mechatronics and Robotics, which are under automatic control, have not usually static properties. Their properties are changed whether from their fundament (changes of properties according to working point, nonlinear character etc.) or from wear reasons.

From mathematical point of view and also from theory of automatic control point of view, the key properties are being usually expressed by parameters included in a mathematical model, which is used for description of considered system. Some of the parameters may be more or less constant without any connection to system property changes or may be variable.

In control design, it is advantageous, if the information on changes can be involved in the computation of control actions. Model-based control strategies offer such possibility. These strategies usually use different types of parametric models. To obtain values of the system parameters, there are generally two ways. One way is to obtain parameters by mathematical-physical analysis. The second way is to use some experimental identification, at consideration of changeable parameters, running on-line. The both are dependent on means, which are used e.g. for measuring physical quantities, detecting occurrence of events or elements and signal processing.

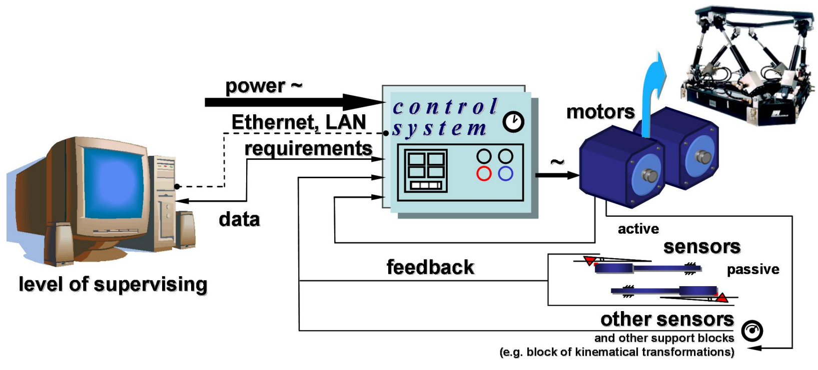

Figure 1: Example of robotic application

At the beginning of the paper, the technical terms 'Robot', 'Robotics' and 'Mechatronics' will be discussed in general context. In relation to these terms, control systems, measuring instruments and other means of automation will be briefly outlined both for industrial and for laboratory purposes. In subsequent parts of the contribution, the model-based predictive control, taken into account as one of up-to-date control strategies, will be briefly introduced from design, tuning and real-time application points of view.

II. Basic Definitions

Robotics and Mechatronics arise from deep grounds of mechanics, which guides human civilization for its whole history. Mechanics concerns with the behavior of physical bodies being subjected to forces or displacements, and the subsequent effect of the bodies on their environment. In the first part of 20th century, the term 'Robot' (by Karel Čapek, 1921 [1]), respectively, 'Robotics' (by Issac Asimov, 1941 [2]) were independently appeared of it as literary expressions in sci-fi novels, but later the both were being close related to Mechanics as follows:

- **Robot** is a self-containedly working mechanical or virtual artificial machine (agent), which is able to perform given tasks, respectively, to change its neighborhood without any external interventions.
- **Robotics** is the science and technology of robots, their design, manufacture and application, which investigates intelligent relations among input commands, sensors and output actions, actuators. It requires a knowledge of electronics, mechanics and software.

Consecutively, during rapid industrial development in the second part of 20th century, industrial machines and applications have begun to consist of many different elements:

◇ mechanical elements forming machine bodies (mechanisms),

◇ electromechanical elements powering the mechanisms (actuators - drive units),

◇ electrical elements monitoring (sensors) or controlling (control units) the machine itself.

Altogether, it represents combination of mechanics and electronics, in single word - 'Mechatronics' (by Tetsuro Mori, 1969, [3]).

Thus, **Mechatronics** is the synergistic combination of mechanical engineering ('mecha' for mechanisms, i.e., machines that 'move'), electronic engineering ('tronics' for electronics), and software engineering. The purpose of this interdisciplinary engineering field is the study of automata from an engineering perspective and serves the purposes of controlling advanced hybrid systems (Fig. 2).

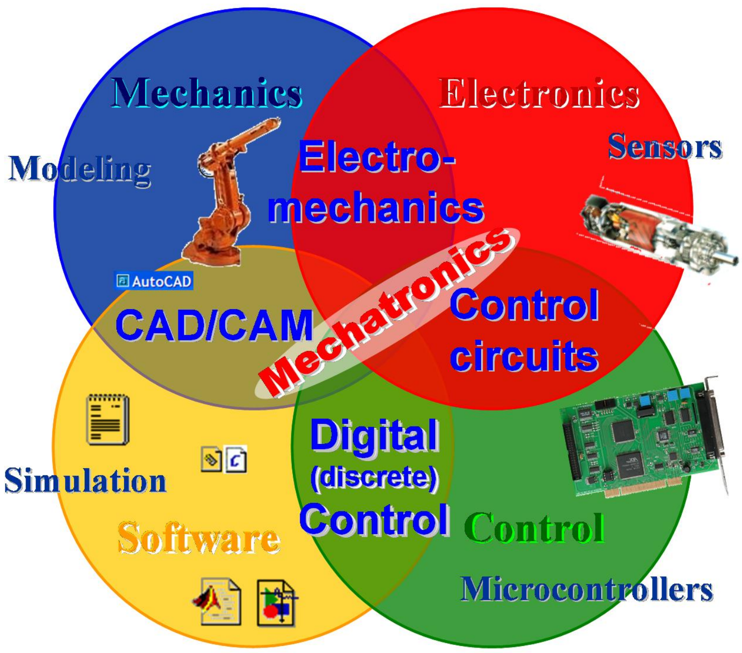

Figure 2: Diagram of Mechatronics

III. Automatic Model-Based Control

Automatic control of robotic and mechatronic systems is provided by different ways. One of powerful ways is model-based control, which offers solution on global level of whole controlled system. The fundament of control consists either in only comparison of topical value of output with required value or better supplemented with comparison of future expected (predicted) values with future required values. This comparison is generally included in optimization of control actions, which should ensure as best as possible meeting the required values.

In this regard, that control action represents in mechatronic and robotic applications amount of energy, which is necessary feed for controlled system, 'optimal' control action is searched as smallest as possible, i.e. the minimization of value of assessment criterion, which is based on specific cost function, is provided. The cost function expresses relations among control actions and differences among real, predicted and required output quantities.

The following section will illustrate the propositions applied to design of predictive control as powerful model-based control strategy. The explanation will concern with discrete realization that naturally provides time for computation of control at real control process.

IV. Predictive Control - Main Steps of Design

Predictive control belongs among popular model-based control strategies [4]. It is a multi-step control strategy, of which design consists of two main parts - Prediction and Minimization.

1. Prediction

The way of prediction (Fig. 3) forms the basis of predictive control design.

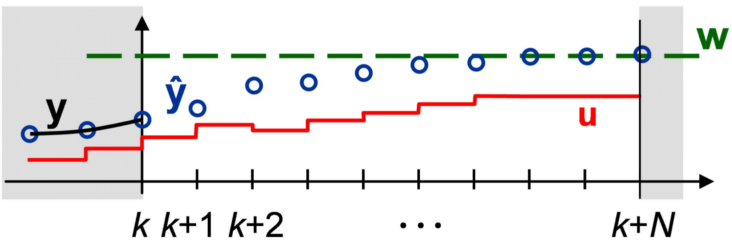

Figure 3: Prediction of future system outputs

Future expected system outputs can be expressed by equations of predictions, which predetermine character of resultant control algorithm as follows:

- positional (full-value) algorithms,
- incremental algorithms.

Initial model for construction of the equations can have various forms. Usually, the following two general forms are considered for the design:

- ARX model:

$$\mathbf{y}(k) = \sum_{i=0}^{n} \mathbf{B}_i \, \mathbf{u}(k-i) - \sum_{i=1}^{n} \mathbf{A}_i \, \mathbf{y}(k-i) + \mathbf{v}(k) \tag{1}$$

- State-space model:

$$\begin{aligned} \mathbf{x}(k+1) &= \mathbf{A}_k \, \mathbf{x}(k) + \mathbf{B}_k \, \mathbf{u}(k) + \mathbf{G}_k \, \mathbf{w}(k) \\ \mathbf{y}(k) &= \mathbf{C}_k \, \mathbf{x}(k) \quad \mathbf{D}_k \, \mathbf{u}(k) + \mathbf{v}(k) \end{aligned} \tag{2}$$

The both forms Eq. (1) and Eq. (2) are expressed in general Multi-Input Multi-Output form. For real composition of equations of predictions, the ARX model (Eq. (1)) is suitable to transform to state-space like form (Eq. (2)). Furthermore, let obtained or initial state-space model represents mean values for $\mathbf{x}(k+1)$ and $\mathbf{y}(k)$, where means of disturbances $\mathbf{w}(k)$ and $\mathbf{v}(k)$ have zero values.

Thus, if the zero means of disturbances are considered, the model Eq. (2) will express mean values, i.e.

$$\begin{array}{rcl} \mathbf{x}(k+1) & = & \mathbf{A}_k \ \ \mathbf{x}(k) \ + \ \mathbf{B}_k \ \ \mathbf{u}(k) \\ \mathbf{y}(k) & = & \mathbf{C}_k \ \ \mathbf{x}(k) \ \ \ \ \ \mathbf{D}_k \ \ \mathbf{u}(k) \end{array}, \quad \begin{array}{l} \text{without direct} \\ \text{feed-through} \quad \mathbf{D}_k = \mathbf{0} \end{array} \tag{3}$$

then the equations of predictions have following form:

$$\begin{array}{rcl} \hat{\mathbf{x}}(k+1) & = & \mathbf{A}_k \ \mathbf{x}(k) + \mathbf{B}_k \ \mathbf{u}(k) \\ \hat{\mathbf{y}}(k+1) & = & \mathbf{C}_k \ \mathbf{A}_k \ \mathbf{x}(k) + \mathbf{C}_k \ \mathbf{B}_k \ \mathbf{u}(k) \\ \cdots & & \cdots \\ \hat{\mathbf{x}}(k+N) & = & \mathbf{A}_k^N \ \mathbf{x}(k) + \mathbf{A}_k^{N-1} \ \mathbf{B}_k \ \mathbf{u}(k) \ \cdots + \mathbf{B}_k \ \mathbf{u}(k+N-1) \\ \hat{\mathbf{y}}(k+N) & = & \mathbf{C}_k \ \mathbf{A}_k^N \ \mathbf{x}(k) + \mathbf{C}_k \ \mathbf{A}_k^{N-1} \ \mathbf{B}_k \ \mathbf{u}(k) \ \cdots + \mathbf{C}_k \ \mathbf{B}_k \ \mathbf{u}(k+N-1) \end{array} \tag{4}$$

In Eq. (4), the matrices $\mathbf{A}_k, \mathbf{B}_k$ and $\mathbf{C}_k$ are considered to be constant within topically given time interval determined by horizon N.

The equations of predictions can be expressed in condensed matrix form as follows:

$$\hat{\mathbf{y}} = \mathbf{f} + \mathbf{G}\,\mathbf{u}, \quad \begin{array}{l} \hat{\mathbf{y}} = [\hat{\mathbf{y}}(k+1) \ \ \hat{\mathbf{y}}(k+2) \ \ \cdots \ \ \hat{\mathbf{y}}(k+N)]^T \\ \mathbf{u} = [\mathbf{u}(k) \ \ \mathbf{u}(k+1) \ \ \cdots \ \ \mathbf{u}(k+N-1)]^T \end{array} \tag{5}$$

This condensed form (Eq. (5)) is transparent for real computation of optimal control actions, resp. process of minimization, which will be briefly described in the following subsection.

2. Minimization (Computation of Optimal Control Actions)

A minimization is a second main part of control design. It is performed on quadratic criterion

$$J_k \stackrel{!}{=} \min \tag{6}$$

operated on quadratic cost function Eq. (7)

$$J_k = \sum_{j=No+1}^{N} \left\| (\hat{\mathbf{y}}(k+j) - \mathbf{w}(k+j)) \, \overline{\mathbf{Q}}_{\mathbf{y}} \right\|^2 + \sum_{j=1}^{Nu} \left\| \, \mathbf{u}(k+j-1) \, \overline{\mathbf{Q}}_{\mathbf{u}} \right\|^2 \tag{7}$$

in brief notation

$$J_k = [(\hat{\mathbf{y}} - \mathbf{w})^T \ \mathbf{u}^T] \begin{bmatrix} \mathbf{Q}_{\mathbf{y}} & \mathbf{0} \\ \mathbf{0} & \mathbf{Q}_{\mathbf{u}} \end{bmatrix}^T \begin{bmatrix} \mathbf{Q}_{\mathbf{y}} & \mathbf{0} \\ \mathbf{0} & \mathbf{Q}_{\mathbf{u}} \end{bmatrix} \begin{bmatrix} \hat{\mathbf{y}} - \mathbf{w} \\ \mathbf{u} \end{bmatrix} \tag{8}$$

in which the predictions (Eq. (4)) or (Eq. (5)) are involved, respectively. To minimize the criterion (Eq. (6)), only square root of the cost function (Eq. (8)) is needed.

$$\mathbf{J} = \begin{bmatrix} \mathbf{Q}_{\mathbf{y}} & \mathbf{0} \\ \mathbf{0} & \mathbf{Q}_{\mathbf{u}} \end{bmatrix} \begin{bmatrix} \hat{\mathbf{y}} - \mathbf{w} \\ \mathbf{u} \end{bmatrix} = \begin{bmatrix} \mathbf{Q}_{\mathbf{y}} \, \mathbf{G} \\ \mathbf{Q}_{\mathbf{u}} \end{bmatrix} \mathbf{u} - \begin{bmatrix} \mathbf{Q}_{\mathbf{y}} \, (\mathbf{w} - \mathbf{f}) \\ \mathbf{0} \end{bmatrix} \tag{9}$$

The minimization leads to the solution of algebraic equations [] for unknown control actions

$$\begin{array}{c} \begin{bmatrix} \mathbf{Q}_{\mathbf{y}} \, \mathbf{G} \\ \mathbf{Q}_{\mathbf{u}} \end{bmatrix} \mathbf{u} - \begin{bmatrix} \mathbf{Q}_{\mathbf{y}} \, (\mathbf{w} - \mathbf{f}) \\ \mathbf{0} \end{bmatrix} = \mathbf{0} \\ \mathbf{A} \quad \mathbf{u} - \quad \mathbf{b} \quad = \mathbf{0} \end{array} \tag{10}$$

Obtained vector represents control actions for whole horizon N. However, only first appropriate actions are really applied to the robot. The process of minimization is repeated in every time step for appropriately updated model (Eq. (3)).

V. Variants and Tuning of Control Algorithms

In engineering practice, there exist a lot of different systems, which can be described by different types of models. The models should put well characteristics of considered system. As mentioned in section 'Introduction', they can be obtained either on the basis of mathematical-physical analysis or by some experimental identification. From both ways, Input/Output models are obtained, from mathematical-physical analysis usually continuous models (differential equations) and from experimental identification models in discrete form (autoregressive models).

Due to control design, often in Multidimensional cases, the more transparent state-space model is useful. In former case, mathematical-physical analysis, the transformation to such model do not represent any problem. Obtained state-space models keep physical meaning of the state. In latter case, experimental identification, it is a little bit difficult. Usual transformation of discrete autoregressive model does not lead to state-space formulation preserving physical interpretation. In such cases, different pseudo state-space forms are used. Finally, in all cases, some possibility always exists to obtain required suitable state-space model, which is suitable not only for Single-Input Single-Output systems, but also mentioned Multi-Input Multi-Output systems.

Another question is if the system has linear or nonlinear character. In case of appearance of some nonlinearities, it is necessary to adapt the model (its parameters) to topical state (working point etc.) continuously. Thus, individual elements of matrices $\mathbf{f} = \mathbf{f}(\mathbf{x}(k))$ and $\mathbf{G}$ in Eq. (5) are not constant and for every new system state have to recomputed.

In regard to tuning of the algorithms, at the first, it depends on algorithm character (alg. generating absolute (full) actions $\mathbf{u}$ or incremental alg. generating increments of actions $\triangle\mathbf{u}$. Furthermore, the tuning depends on accuracy of the model whether obtained from mathematical-physical analysis or from experimental identification. Focusing just on real utilization of predictive control, only few parameters are necessary to set:

- rate (sampling period) $<$ system time constant,
- horizon of prediction $N \geq$ system order and $\leq$ velocity character of desired values,
- penalty matrices $\mathbf{Q_u}$ and $\mathbf{Q_y} \Leftarrow$ equivalence of inputs and outputs and controller stiffness.

Note: The symbols $<$, $\geq$, $\leq$ and $\Leftarrow$ indicate upper, lower restrictions and dependencies.

VI. Examples of Laboratory Models of Mechatronic Systems

Besides robotic applications, which naturally belong to wider family of mechatronic systems, usual automatic self-operated mechanisms appeared in normal life like automatic door openers, bars and train gates, elevators, windscreen wipers and a lot of others represent mechatronic systems, which themselves combine mechanic and electronic elements with self-control systems of hard or flexible (software-based) type.

As an example for better imagination, let us consider two laboratory models, which are used as school aids in automatic control subjects. The first is model 'Ball on rod', which represents example of system with Single-Input and Single-Output. Input is angle of rod and output is position of the ball.

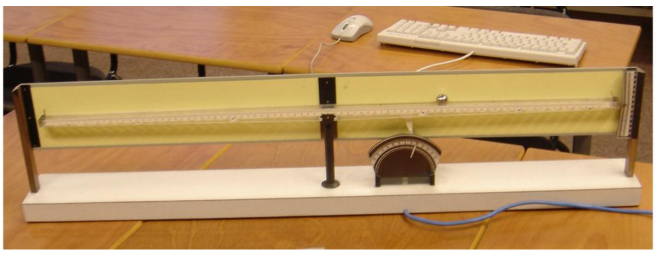

Figure 4: Laboratory model 'Ball on rod'

The second laboratory model is a model of helicopter representing Two-Input Two-Output system (TITO, resp. in general, MIMO system). Two inputs are voltages for two motors and two outputs are angles of elevation – horizontal axis perpendicular to horizontal central axis of the helicopter; and azimut – vertical central axis.

Figure 5: Laboratory model ‘Ball on rod’

The both models are used for real-time experiments with different control algorithms [5].

VII. Conclusion

At present, there exist more and more means of automatic control for industrial or for laboratory purposes of different kinds. The adequate and save control depends on right selection both just means of automation and control algorithms. The all has to be taken into account at construction of real machines or systems. The contribution shows example of successful solutions in robotics and mechatronics.

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