Method of analytical synthesis of coording control systems

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Abstract. The problems of coordinating control are discussed. The method of analytical synthesis of coordinating automatic systems is proposed. Their purpose of control is formulated in the form of the task of control relations between the state variables of a multi-channel object or a group of objects. The problem of coordination is studied in a different formulation compared to the classical papers. Control processes are formed by means of two multi-dimensional contours: the contour of aggregate control by the dynamics of the object as a whole, and the contour of regulation of inter-coordinate relations. The autonomy of the second contour plays a key role in the proposed solutions. The procedures for calculating the control contours are based on the devise of the transfer matrices apparatus.

1. Introduction

The rapid development of the modern technology poses for the automatic systems using in industry, energetics and transport more complicated, nontraditional problems. Among them is the special class of the automatic control problems, so called problems of the coordinating (coordinative, coordinated) control by multiply connected objects [1]. Here the standard problem of ensuring usual requirements on quality of controlled process is added to the specific problem of the ensuring required coordination (i.e. the observance of the given relations) of controlled values of the object. The automatic systems intended for the solution of the given problem are called the systems of the coordinating (coordinative, coordinated) control (SCC) or the systems the relations regulation [1].

In spite of the urgency and perspectivity of the coordinating control problem the modern theory and practice of the automatic systems has no the necessary methodological foundation, permitting to solve it successfully. As L M Boychuk emphasizes on the basis of the review of the foreign sources, the coordination “is one of the problems set by the practice for a relatively long time, which to date has not been practically studied at all” [2]. And here it should be stated, that synthesis of SCC still does not find the sufficient reflection not only in home literature, but in the foreign one, numbering only several tens of the papers.

The purpose of the present paper is to elucidate some problem aspects of the coordinating control and to propose simple engineering methodology of the analytical synthesis of two-contour SCC. The
results of this work are a natural development and generalization of the authors' works \[3, 4\].

2. Retrospective and modern state of the coordinating control problem
The term “coordination” \([from the Latin. co (cum) means “jointly” and ordinatio means “ordering”]\) implies the agreement. The sense of the concept “coordination” is interpreted in literature very widely and variously. In the papers dedicated to the control processes the different aspects of the coordination’s problem or the coordinating control by complex objects are considered. They are analyzed as the problems of the security of the coordinated functioning of the separate connected subsystems or the channels of the object which are subordinate to the general aim of the control.

The problem of the coordination has the history for a long time, more than 100 years. For the first time the notion of the coordination as the most important independent function of control process was introduced by the outstanding French manager, «the father of the scientific control» H. Fayol as long ago as in 1923 y. in his fundamental work “The general and industrial control” \[5\]. In the modern management \[6\] the coordinating control is the pivotal function of control. It provides the coordination advance under the operating conditions of all links of the organization by means of the establishment of the rational connections (communications) and information exchange between them.

The problem of coordination has received further development only 40 years later in two independent scientific directions. They essentially have extended the area of the practical application of SCC.

The first direction of the development of the coordination problem was formed in the “great systems” theory considered as totality of correlated subsystems \[7\] being hierarchical organized. Within the limits of the given direction the idea of multilevel organization of control process by such systems was advanced in the paper of the well-known systemologist M D Mesarovic \[8\] (decompositions of control system into series of the interacting, subordinate levels). Here the central place escapes by the coordination being the problem of controlling subsystem standing above, providing the coordinated functioning of controlled subsystems standing below. As a result the given idea has got the appearance in the form of the theory of multilevel systems \[9\], called sometimes as the theory of coordination \[10\].

The second direction of the development of the coordination problem was formed in the automatic control theory by multi-objects, multichannel and multiply connected systems \[11\]. The coordination along with the stabilization and tracking regulation is one of the main ways of the automatic control. Here by the coordination we understand the automatic observance of the given relations (consistent conditions) of controlled variables or state variables of multichannel object or the group of the objects in the process of their functioning. The given relations between the controlled variables in SCC must be carry out both in the established and in the transition condition. Moreover the necessary coordination is realized both by means of use already available interior natural cross connections of controlled object and by means of the connecting of the additional exterior artificial cross connections.

The papers of N N Ivaschenko \[12\], A A Voronov \[13\], M B Ignatjev \[14\], V A Romanov \[15\], G E Pukhov and K D Zhuk \[16\] ranked among the early papers of the given direction. First of all, the papers of L M Boychuk \[2, 17, 18\] and I V Miroshnik \[19, 20\] made the important contribution to the formation and the development of the given direction.

It should be noted that chines learned Tu Xu-Yen introduced SCC class into the automatic control theory for the first time in 1961 y under the name for harmonic control systems (that is the systems, realizing “the harmonic principle of control” providing the maintenance of the definite “harmony”, “harmonic relation” between the controlled variables) \[21\]. In the native literature the given class of the systems was first entered into consideration in the paper of M. B. Ignatjev \[14\] under the name for holonomic automatic systems. Their purpose is to complete the tasks in the form of the equations connecting the output variables of the controlled object. At the same time in the papers of M V Meerov \[22\] as early as 1960 y the multiply regulation systems was proposed to subdivide into two classes. The quality of the regulation of the first class systems is determined by the indexes of the regulation of every regulative variable, and the quality of the regulation of the second class systems is determined by the generalized indexes, represented some functionals from the regulative variables. The second
class of the systems just belongs to SCC class. In the papers of L M Boychuk the given class of the systems was often called as the systems of the functioning control [17], and in the papers of I. V. Miroshnik the given class was called as the system of the coordinated control [19].

Let us note wide diversity of the application sphere of SCC. They are the problems of the coordinated variations of the controlled values, the stabilization of the relations between variables, the synchronization of the controlled movements and so forth.

The questions of the movement’s coordination of the linear multiply systems containing the identical or one-type channels were first considered in the papers [23, 24]. They have got the practical development for the coordination problems of multimotive electrodriVers of the production lines (see f.e. [25]). It should be noted that in some control problems by multichannel and multiply connected objects the desired coordination of controlled variables is provided itself with the methods of the autonomous control. Here the given relations of the controlled variables are supported by means of the coordination of the given action. In this case the coordination takes place, but it has the passive character.

The functioning of two or some objects or processes, coordinated in time that is the reduction of these objects to the synchronous flowing is called the synchronization. In contrast to the natural synchronization property of the complex systems namely self-synchronization, the wide practical application finds so-called compulsory, forced or controlled synchronization, connected with the adding to the system of the coordinating actions. Here it should be indicated the papers [26, 27].

Two types of SCC are recognized: technological and trajectory [2].

The examples of the technological problems of the coordinating control are the following: the regulation of the relation fuel-air in energy installations; the regulation of the rotation frequency of the executive drives in multi-motive technological lines; the synchronous control by aggregates (f.e. by the electric generators, turned on the general network; by the electric motors having the general load and so on).

The examples of the trajectory problems of the coordinating control are the following: the programmed control by the machine-tools (transfer of the executive device in the machine-tools with numerical programmed control (NPC) according to form of the piece being worked); control by the objects movement or by the group of the objects along the space trajectories; the control by the relative position (formation) of the mobile objects; the exact space orientation of multi-components mechanical systems (f.e. by the elements of radio-telescope antenna, the kinematic links of robot and so on).

At present the technological and trajectory problems of the coordinating control by the dynamical objects have very extensive bibliography and we can find them in different statements. This is the problem of the coordinating control [28–33], the consistent control [34], the functioning regulation [35], the control on the given manifold [36–38], the problem of the synergetic control [39], etc.

3. Singularities of the classical conception of the coordinating control

Let us briefly turn our attention to the base positions of the classical conception of the coordinating control of L M Boychuk. In general we’ll be lean upon the materials of the first extended paper on SCC both in our country and abroad [2].

The totality of the coordinated connections between output (controlled) variables of the object gives the coordinative purpose manifold (CPM) in variables space. The problem of the coordination consists in the localization of the controlled trajectory of the movement on the given manifold.

The functioning of SCC is subjected to two connected purposes: the working off the outer giving action and the coordination of the variables. In this connection the problem of the coordinating control is decomposed into two sub-problems generated by the indicated purposes. For their solution in [2] vector of the controlled variables is decomposed into two components: stabilizing and varying. The first component motivates the motion to CPM, and the second component motivates the motion along CPM in the process of the working off the task. In this connection the principle of the movements separation is realized [40]: the stabilizing of CPM is realized in the “fast motions” condition, and the consequent working off the tasks on the output is realized in the “slow motions” conditions. The slow mo-
tions for the component object are interpreted as neutralized dynamics of the simple objects.

According to [2] the synthesized SCC includes two blocks. One of them is block of one-type standard regulators (PID regulators). The second one is block of the coordinating connections (either by input or by output) of the regulators’ block.

One more limited singularities of the proposed solutions in [2] is the stationary state of the purpose established condition.

In the present paper the problem of coordination is researched in the other statement in comparison with [2]. In the first place the control objects of general type are considered. For them the projective transformations of control vector suggested in [2] are prevented from sense. Secondly the structure of the synthesized SCC is not the suspension above matrix of one-type standard regulators. In the third, the external tasks for SCC are subject to variation in an arbitrary way, that is the processes of the tracking regulation are considered. In the fourth, the calculation processes of the regulation contours are based on the device of the transfer matrices. In the fifth, the principle of the motions separation is realized by the schemes of autonomous regulation

4. The structure of SCC
Let us reduce to the problem of synthesis of the linear stationary SCC.

Let the control object is represented by the equations:

\[ \dot{x} = Ax + Bu, \]  
\[ y = Cx, \]  

where \( t \geq 0 \), \( u \in \mathbb{R}^r \) is the input, \( x \in \mathbb{R}^n \) is the state, \( y \in \mathbb{R}^m \) is the controlled output, \( A \in \mathbb{R}^{n \times n} \), \( B \in \mathbb{R}^{n \times r} \), \( C \in \mathbb{R}^{m \times n} \) are constant coefficient matrices of the system, and also we suppose that \( r \geq m > 1 \).

The coordinating control is subjected to two purposes. The principle purpose is the working off the external task of the arbitrary command signals \( y^*(t) \):

\[ y \approx y^*(t). \]  

The subordinate purpose is the observance of the given relations between the output variables of the object:

\[ \Phi_i(y) = 0, \quad i = 1, q, \]  

where \( \Phi_i(y) \) are some functions, and also \( q < m \). These functional connections, which are the conditions of the coordination we'll call the regulated relations.

Let us note that the functions \( \Phi_i(y) \) we may interpret as invariants of the ideal process of the coordinated control.

If we use vector-function

\[ \Phi = [\Phi_1, \Phi_2, ..., \Phi_q]^T, \]

then the equalities (4) will be rewrite in vector form:

\[ \Phi(y) = 0. \]  

Also let us introduce vector of residuals for the regulative relations \( \xi \in \mathbb{R}^q \):

\[ \xi = \Phi(y). \]

Then the coordinative purpose of the regulation corresponds to the requirements (5)
$$\xi \approx \xi^* = 0.$$  \hspace{1cm} (6)

Then we’ll be suppose, that vector-function $\Phi(y)$ is the linear function:

$$\Phi(y) = Qy,$$  \hspace{1cm} (7)

where $Q \in \mathbb{R}^{q \times m}$, moreover $\text{rank}(Q) = q$.

So the considered control problem is added from two correlating sub-problems: the working off the command signals and the working off the regulative relations. For the solution of these sub-problems we’ll be form the corresponding multivariate regulation contours.

In this purpose the input and output of the object are decomposed into two components:

$$u = H_1v + H_2\eta,$$  \hspace{1cm} (8)

$$z = Py,$$  \hspace{1cm} (9)

$$\xi = Qy.$$  \hspace{1cm} (10)

Here $v \in \mathbb{R}^{r_1}$, $\eta \in \mathbb{R}^{r_2}$, $z \in \mathbb{R}^p$, $H_1 \in \mathbb{R}^{r \times r_1}$, $H_2 \in \mathbb{R}^{r \times r_2}$, $P \in \mathbb{R}^{p \times m}$, $Q \in \mathbb{R}^{q \times m}$, and also

$$m = p + q, \quad r = r_1 + r_2, \quad r_1 \geq m_1, \quad r_2 \geq m_2.$$  

By means of the controlling input $\eta$ we’ll be realize the coordinative stabilization (6), and by means of the controlling input $v$ we’ll be realize the working off the given actions (3). For this case the separate regulations channels of the variables $z$ and $\xi$ are formed.

The vector variable $z$ has the smaller dimension in comparison with output $y$ ($p < m$) and with respect to it plays a part in the controlled aggregate (that is the enlarger information about output). By means of this aggregate the contour of the output regulation is closed.

Two-channels control structure the scheme of SCC is embodied. It is represented in figure 1.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{Two-channels_structure.png}
\caption{Two-channels control structure the scheme of SCC.}
\end{figure}

Here two channels are selected: the channel of the aggregate control (AC) by the dynamics of the object as a whole, and the channel of the relations regulation (RR) between output variables. Blocks in the regulation structure corresponding to them we’ll be call AC block and RR block. The chosen channels form two multivariate control contours: AC contour and RR contour. As far as relations (4) are to be established and supported in the process of the complete of the command signal (3), then the second contour are to be more fast in comparison with the first contour.

5. The formation of the regulation channels

The structure (figure 1) of the formed regulation channels is determined by the given matrix $Q$ and
unknown matrices $H_1$, $H_2$ and $P$, in deciding on which it’s necessary to observe the following conditions:

$$\text{rank}[H_1 \mid H_2] = r, \quad \text{rank}\left[\begin{array}{c} P \\ Q \end{array}\right] = m.$$ 

Let us construct matrices $G_1 \in \mathbb{R}^{r \times r}$, $G_2 \in \mathbb{R}^{r \times r}$, $L \in \mathbb{R}^{m \times p}$, $M \in \mathbb{R}^{m \times q}$ satisfying the equalities

$$\begin{bmatrix} G_1 \\ G_2 \end{bmatrix} [H_1 \mid H_2] = E_r, \quad \begin{bmatrix} L \mid M \end{bmatrix} \begin{bmatrix} P \\ Q \end{bmatrix} = E_m, \quad (11)$$

where $E_k$ is unit matrix $k$ order.

In the force of (8)–(11) the following relations are realized

$$v = G_1 u, \quad \eta = G_2 u, \quad y = Lz + M\xi.$$ 

From the last equality carrying out the condition (6) we’ll get

$$y \cong Lz.$$ 

Consequently the regulating process $z(t)$ defines the reaction of the object’s output $y(t)$.

The given action $y^*$ is to fulfill the requirement (5), so according to (7) the condition

$$Qy^* = 0$$

will be realized.

Hence according to (9) we’ll get the task for AC contour

$$z^* = Py^*.$$ 

**Remark:** The equations of the relations (4) define CPM. In the linear case (7) this manifold is defined as the hyper plane. The purposeful meaning of the output is to imply the localization of the corresponding purpose state of the object on this hyper plane. So in the process of the coordinating control the trajectory of the object’s motion is to attract to it.

### 6. Autonomization of RR contour

The main idea of the proposed method of SCC synthesis consists in the autonomization of RR contour with respect to AC contour. For its realization we may use the exact or approximate compensation of disturbances or the schemes of the great coefficients of the extension.

For the description of the control processes let us resort to the formalism of the operational calculus. Let us agree to transfer the graphic notations of the originals to their laplace-forms. Then $s$ is complex frequency.

The constructed separate channels of regulation in the supposition of zero initial conditions are described by the equations

$$z(s) = W_{zv}(s)v(s) + W_{z\eta}(s)\eta(s),$$

$$\xi(s) = W_{\xi v}(s)v(s) + W_{\xi\eta}(s)\eta(s). \quad (13)$$

Here laplace-forms of the output signals $z(s)$ and $\xi(s)$ are expressed by laplace-forms of the input signals $v(s)$ and $\eta(s)$. The transfer matrices of the object $W_{zv}(s)$, $W_{z\eta}(s)$, $W_{\xi v}(s)$, $W_{\xi\eta}(s)$ in according to (1), (2), (8)–(10) are equal to
\[ W_{21}(s) = PC(E_n s - A)^{-1} \beta_1 H_1, \quad W_{2\eta}(s) = PC(E_n s - A)^{-1} \beta_2 H_2, \]
\[ W_{\xi_1}(s) = QC(E_n s - A)^{-1} \beta_1 H_1, \quad W_{\xi\eta}(s) = QC(E_n s - A)^{-1} \beta_2 H_2. \]

Let blocks of AC and RR regulator realize the control laws
\[ v(s) = R_1(s)(z^* - z(s)) \quad (14) \]
\[ \eta(s) = R_2(s)(\xi^* - \xi(s)) + R_{21}(s) v(s) \quad (15) \]

Thus the regulating feedbacks described by the transfer matrices \( R_1(s) \) and \( R_2(s) \) are formed by these blocks. Besides in RR block the chain of the influence compensation of AC contour on RR contour is provided. Its action is defined by the second summand in (15), in other words it is defined by transfer matrix \( R_{21}(s) \).

The permutation (14), (15) in (12), (13) gives the equations for the considered contours of the regulation:
\[ (E_p + W_{2v}(s) R_1(s)) z(s) = W_{2v}(s) R_1(s) z^*(s) + \psi_1(s), \]
\[ (E_q + W_{\xi\eta}(s) R_2(s)) \xi(s) = W_{\xi\eta}(s) R_2(s) \xi^*(s) + \psi_2(s), \quad (16) \]

where
\[ \psi_1(s) = W_{2\eta}(s) \eta(s), \]
\[ \psi_2(s) = (W_{\xi v}(s) + W_{\xi\eta}(s) R_{21}(s)) v(s). \quad (17) \]

The functions \( \psi_1(s) \) and \( \psi_2(s) \) describe inter-influence of the regulation contours.

The processes of the regulation in the contours are determined by choice of the transfer matrices \( R_1(s), R_2(s) \) and \( R_{21}(s) \).

If \( R_{21}(s) \) provides the equality
\[ W_{\xi v}(s) + W_{\xi\eta}(s) R_{21}(s) = 0, \quad (18) \]
then according to (17) it will be realized full compensation of disturbances of RR contour:
\[ \psi_2(s) = 0 \]

But the inversion or pseudoinversion of the rational matrix \( W_{\xi\eta}(s) \) for the achievement of the condition (18) generates two problems. In the first place it’s physical nonrealizability of the compensating chains of RR block and secondly it’s the transformation of the right transfer zeroes of matrix \( W_{\xi\eta}(s) \) to instability poles in the given chains.

Another way of the autonomization RR contour is based on the inclusion it in the great amplification factors. Thus it has been possible to relax its disturbances from side of AC contour to the admissible level. We’ll explain this concept.

From (16) we’ll get
\[ \xi(s) = W_{\xi^*}(s) \xi^*(s) + W_{\xi v}(s) \psi_2(s), \quad (19) \]

where
\[ W_{\xi^*}(s) = (E_q + W_{\xi\eta}(s) R_2(s))^{-1} W_{\xi\eta}(s) R_2(s), \]
\[ W_{\xi\psi_2}(s) = (E_q + W_{\xi\eta}(s)R_2(s))^{-1}. \]

According to (19) the disturbance level of the regulative process \( \xi(t) \) as a result of the action \( \psi_2(t) \) one may define as norm of the transfer matrix \( W_{\xi\psi_2}(s) \) in Hardy space \( H_\infty \) [41]. This norm will be gone down as a result of the increase of transmission coefficients in the structure of the transfer matrix \( R_2(s) \) of RR block.

As far as RR contour is to be more fast in comparison with AC contour as a result of the regulator’s tuning, then this requirement is in excellent agreement with the mechanism of the great amplification factor. The methodology of modal control may be only used in synthesis of the given contours.

**An example.** Let us turn to the example from [2]. Let us assume: \( m=n=r=2 \) and the object is characterized by the equations

\[
\begin{bmatrix}
-1 & -2 \\
3 & -1
\end{bmatrix}
\begin{bmatrix}
x \\
y
\end{bmatrix}
= \begin{bmatrix} \xi \end{bmatrix}, \quad \begin{bmatrix} x \\
y
\end{bmatrix} = \begin{bmatrix} \eta \end{bmatrix}.
\]

In the regulation process it’s necessary to support the relations between output variables: \( x_1 / x_2 = 2 \). Linear RR corresponds to it

\[ \Phi(y_1, y_2) = y_1 - 2y_2 = 0. \]

Let’s introduce RR discrepancy:

\[ \xi = y_1 - 2y_2. \]

In the calacity of the output aggregate we’ll take arithmetic mean of the output variables:

\[ z = (y_1 + y_2) / 2. \]  \( (20) \)

Assuming \( v = u_2, \eta = u_1 \) we’ll get the equations of the regulation channels

\[ \begin{aligned}
\dot{z} &= -1.5v + 2\eta, \\
\dot{\xi} &= -5\eta.
\end{aligned} \]

Let us choose the following transfer functions of the regulator:

\[ R_1(s) = -\frac{8}{3}(1 + \frac{1}{s}), \quad R_2(s) = -3, \quad R_{21}(s) = 0. \]

As a result the autonomy of RR contour will be provide without the additional contrivances, moreover the poles of AC and RR contours are equal to \( \{-2,-2\} \) and \(-15\) respectively, that is they essentially differ in damping value.

In figure 2 we’ll represent the transfer processes in SCC for the initial state of the object \( x(0) = \text{col}(0,2) \) and the task

\[ y^* = \text{col}(2,1). \]  \( (21) \)

According to (20) and (21) setpoint for RR contour is equal to \( z^* = 1.5 \).

In figure 3 the corresponding trajectory of the regulation process in the space of the output variables is represented. Figure 4 illustrates the working off SCC of command signal (its scalar components are represented as the dotted line in the figure)

\[ y^* = (y_1^*, y_2^*) = \text{col}(2,1)(1,5 + 0.5\sin(2\pi t / 10)) \]

under zero initial conditions.
Figure 2. The transfer processes in SCC for the initial state of the object.

Figure 3. The trajectory of the regulation process in the space of the output variables.

Figure 4. The working off SCC of command signal.

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