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Decreasing Dissemination of Disturbances within Network Systems by Neural Networks

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Abstract

We apply neural networks to locate initial sources of disturbances in network systems during coordinating them by a gradient coordination technique based on the earlier proposed necessary and sufficient coordinability conditions for locally organized hierarchies of dynamic systems. Thus we restrict spread of disturbances and save resources spent for maintaining of the system.

Keywords*: coordination, control, neural network*

1. Introduction

To improve general quality criteria of systems with decentralized control, it is reasonable to coordinate interactions among subsystems without any direct commands to them. With this goal, we had proposed some necessary and sufficient conditions of coordinability for a locally organized hierarchy of dynamic systems. By applying this technique, we widened stability ranges of the whole system under both external and internal disturbances [1, 2]. However, all local decision makers (DMs) had to react to any disturbance which does not look sound in practical life. So, below we try to decrease influence of the disturbances produced in certain nodes of the system on other nodes. This paper develops investigations described in [1, 2].

2. Research Method

2.1. Multipurpose System of Systems

Coordination of interactions among systems entered into a system of systems (SoS) is the main task of control theory here aimed at improving of the SoS' behavior in the sense of certain criteria.

Without any loss of generality, we follow the approach by Mesarovic [3] and consider a three-level system where the lowest level has a hierarchical or network structure, and the second level consists of locally informed control blocks (DMs); each of these blocks controls one of the lower-level systems. The coordinating block (the Coordinator) is on the upper level and can access any necessary information from every lower element [1, 2]. Every DM and the Coordinator have a specific general quality criterion depending on several scalar criteria.

Normally, every DM solves a multi-criteria optimization problem parameterized with adjusting parameters coming from the Coordinator. Input variables of a DM's general criterion usually represent certain output signals of the object subordinated to the DM. Let us assume that all adjusting parameters of all general criteria are known to all DMs; then we get a coordination task by means of interactions prognostication Mesarovic [3]. Thus every DM can acquire an integral state estimation for his/her subordinated node for every characteristic by using the criterion outlined, for instance, in [4]:

$$\Phi^{(s)} ::= \left(\frac{1}{m} \sum_{i=1}^{m} \left(\frac{a_i - a_{i0}}{\Delta a_i} \right)^s \right)^{1/s} ::= \left(\frac{1}{m} \sum_{i=1}^{m} \delta a_i{}^s \right)^{1/s}, \tag{1}$$

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Where s is an even positive integer;

a_i are some output resources of the given component of the SoS;

a_{i0} and $\Delta a_i > 0$ are adjusting parameters reflecting DM's preferences regarding a nominal (rated) value ai and admissible fluctuations of this value Δa_i respectively;

$\delta a_i ::= \frac{a_i - a_{i0}}{\Delta a_i}$ is a relative deviation of an actual value of a certain resource ai from its rated value a_{i0}.

If we interpret ai as scalar quality criteria for a SoS component having rated values a_{i0}, then (1) corresponds to a general criterion with significance coefficients inversely proportional to permissible variations of the signals [5], and so the latter statement does not contradict common sense. This criterion equals unity if all signals are on their permissible boundaries:

$$\Phi^{(s)} = 1 \text{, if } |a_i - a_{i0}| = \Delta a_i, \quad i = \overline{1, m}, \tag{2}$$

And does not exceed unity if all signals are within the boundaries.

The specific quantity of the criterion (1) change at changing one of its arguments:

$$\delta\Phi_i^{(s)} ::= \frac{\partial\Phi_i^{(s)} / \partial a_i}{\Delta a_i} = m^{s-1}\left(\Phi^{(s)}\right)^{s-1} \delta a_i^{s-1}, \tag{3}$$

Represents its relative flexibility to variations of this argument. As we will prove below, it can be used for investigation of most effective ways to correct the behavior of a node or a SoS.

Assuming that every signal is equally important for reaching a DM goal (possible generalization is evident), we can estimate the specific value of generalized expenses on reaching the goal per every argument as:

$$\eta_i ::= \frac{1}{m} \delta \Phi_i^{(s)}. \tag{4}$$

Further on, we will dwell on the simplest form of the criterion (1), namely, the quadratic criterion $\Phi^{(2)}$. For the quadratic criterion, as we can see from formulas (1-4), the generalized expense ηi does not exceed unity. It is this value that we suggest to use as an index of specific inherent expenses for both the SoS as a whole and any it's component. If this component consumes any (material) resources from other components, total expenses have to include expenses for getting the input resources. Then formula (4) transforms into the following one:

$$\eta_i ::= \Phi^{(2)} \delta a_i + \frac{1}{m} \sum_{j=1}^{n} \eta_j, \tag{5}$$

Where n is the number of input resources for the given component and $\boldsymbol{\eta_j}$ are specific expenses for getting those input resources calculated the same way.

Usage the expenses (4), (5) makes it possible to compare different situations and structures within a SoS.

Advantages of using the criterion (1) can be reasoned as follows:

it explicitly reflects requirements for performance of a node or a SoS;

it allows to readily construct invariants to aggregate generalized expenses;

it may well be used within any node of the SoS to provide every DM with accordant and coherent information.

The listed features provide a natural normalization of signals among SoS components and ease the search for nodes whose performance deviates from desirable limits.

Thus, the Coordinator whose quality criterion is Φ0 sends adjusting parameters ai0 to DMs and receives feedbacks as $\delta \mathbf{a}_i$ (see Figure 1). Lower-level systems may interact, but DMs receive information from the Coordinator and their subordinated systems only.

To provide functioning of a system with elements whose preferences can differ, the preferences need some coordination.

The developed coordination technique is based on the necessary and sufficient conditions of coordinability for a locally organized hierarchy of dynamic systems containing several DMs with peer ranks [1, 2]. It is impossible to directly determine their decisions; that is why the whole network is a System of Systems. Similar interconnected and collaborative networks appear when a virtual enterprise is established Sokolov [6, 7]. To coordinate such structures on intervals between reconfigurations, we propose usage the criterion (1) initially developed for classification of situations in [4].

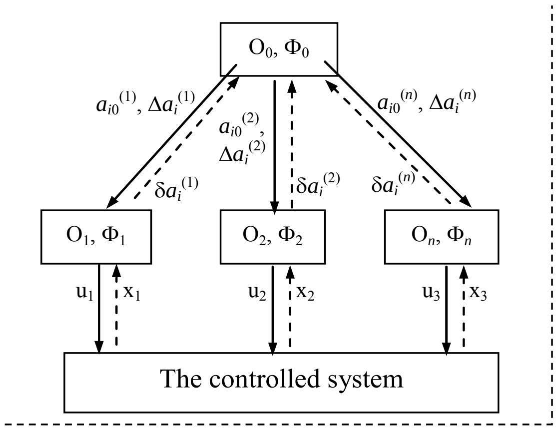


Figure 1. A Three-level SoS

2.2. Gradient (incremental) Coordination of a SOS

The relation (1) shows that our model provides coordination by predicting of interactions [3]. The global task is set by choosing a dominating scalar criterion whose input in the global criterion (1) has to be minimal. Let it be the criterion $a_{10}(0)$ for determinacy.

According to systems analysis, the coordination principle that we propose corresponds to the external (objective) approach to estimation of performance efficiency of a system belonging to a meta-system. The principle is as follows: the tasks of the lower-level systems will be coordinated regarding the task of the Coordinator, if the gradient of the Coordinator's criterion on its current dominating scalar criterion has the same sign as all gradients of this criterion on the current dominating scalar criteria of the sub-objects.

To substantiate feasibility of this principle, we can use the following equality derived from (1).

$$\frac{\partial \Phi_k}{\partial a_i^{(k)}} = \frac{2}{m_k} \frac{a_i^{(k)} - a_{i0}^{(k)}}{\Delta^2 a_i^{(k)}}, \tag{6}$$

The relation (6) shows that we can choose any sign of this derivative by defining the value of $a_{i0}^{(k)}$ greater or less than $a_i^{(k)}$. On the other hand, if we suppose functioning of all sub-objects equally important for reaching the Coordinator's goal (considering a more general supposition is evident), then:

$$\begin{aligned} \frac{\partial \Phi_0}{\partial a_i^{(k)}} &= \sum_{j=1}^{m_0} \frac{\partial \Phi_0}{\partial a_j^{(0)}} \frac{\partial a_j^{(0)}}{\partial a_i^{(0)}} = \frac{2}{m_0} \sum_{j=1}^{m_0} \mu_j \frac{\partial a_j^{(0)}}{\partial a_i^{(0)}} \approx \\ &\approx \frac{2}{n m_0} \sum_{j=1}^{m_0} \mu_j \frac{\mathrm{Inc}\,[a_j^{(0)}]}{\mathrm{Inc}\,[a_i^{(0)}]}, \end{aligned} \tag{7}$$

Where $\mu_j = \frac{a_j^{(0)} - a_{j0}^{(0)}}{\Delta^2 a_j^{(0)}}$, and Inc[*] is an increment of the parameter in brackets for the latter time step.

The whole system will be coordinated, if the Coordinator chooses all $a_{i0}^{(k)}$ to have the same signs of all values (6) (for k = 0 и i = 1) and (7) (for all k from 1 to n and all i for all sub-objects).

So, we have proved that the whole system will be coordinated, if the Coordinator can choose all adjusting parameters it sends to the DMs so as the gradient (increment–for discrete systems) of its generalised criterion on its current dominating scalar criterion has the same sign with all gradients of the Coordinator's criterion on current dominating scalar criteria of local DMs [1, 2]. The proposed sufficient conditions of coordinability resemble the ideas for providing stability of local controls in groups of automata described in [8] where it is necessary to have positive partial derivatives of a general criterion on input parameters of a corresponding element of the group.

3. Results and Analysis

3.1. Simulation as a Case Study

To confirm our theoretical results, we have investigated the stability of the decentralized controls based on increments of the local quality criteria as well as the possibility to optimize (speed up) the whole SoS. We considered two kinds of disturbances, namely external ones coming from outside of the SoS and internal ones simulating some neglected interactions among parts of the controlled system.

To exemplify our incremental coordination technique, we simulated a simple SoS by means of the VisSim. It is a block diagram language for creating complex nonlinear dynamic systems. The lowest level of the SoS contained a simple linear network object with 9 interconnected nodes [1, 2]. Every node simulated a first order transfer function.

The accomplished simulation comprised the following stages.

a) Checking stability against minor external and internal disturbances included measuring stability ranges at absence and presence of the disturbances and comparing these ranges for locally uncontrolled and controlled network. A 10-percent increase of the global input signal simulated the external disturbance, and internal disturbances were created by varying feedback coefficients in the arcs of the controlled system. A certain variant of the network with disturbances was considered a stable one if its output signal differed from the "ideal" signal (output of the network with no disturbances) no more than by 5 percent. Only asymptotically stable schemes were taken into account.

Control signals ui equalled gradients (6). Stability ranges were investigated for control signals connected to each node separately and to all nodes.

b) At the next stage of simulation, coordinating signals proportional to (7) were applied to local control blocks (DMs). The coordinating signals changed nominal values in local criteria according to the relations:

$$a_{i0}' = a_{i0} + \Delta a_{i0}, \tag{8}$$

Where $\Delta a_{i0} = k_i \delta a_i$.

Stability ranges and speed of the whole system were determined in the same way as it was done at the stage a). To change the speed, positive coefficients k_i ranged within values resulting in stable trajectories.

According to their stability ranges, we had to divide feedbacks into two groups, namely the "strong" and the "weak" ones. Strong feedbacks impacted on the stability much stronger than the weak ones. They mostly affected the inputs of the nodes 1, 2 and 3.

Generally speaking, inputting of coordination signals according to the proposed algorithm improved convergence of real and ideal trajectories (lowered asymptotical errors) by several times. As for stability ranges, they became even wider that they had been after successive application of local control signals. This can be interpreted as a substantiation of efficiency of the developed coordination technique. However, a drawback of this method is in subjecting all DMs a disturbance from the Coordinator any time another DM produces a wrong feedback.

3.2. Detection of Disturbing Nodes: NNs

To prevent this effect, we developed a neural network (NN) responsible for determining an initial source of any disturbance earlier than this disturbance has spread all over the rest part of the SoS [9, 10]. Then the Coordinator can adjust only its impact on the certain DM controlling the corresponding node of the SoS. This way we protect other DMs from unnecessary decisions and minimise disturbances in the whole SoS. Figure 2 shows how we connected our NNs to the controlled system.

To protect "innocent" DMs from the disturbances induced by other nodes of the controlled network, we decided to teach neural networks (NNs) to detect disturbed node(s) and then coordinate their criteria only.

We connected a Kohonen NN to the output of every node and taught it for the undisturbed SoS. The learned NNs were tested under external and internal disturbances ranged from 10 to 100 percent of the teaching disturbance and generated within the period from 10 to 100 percent of the total modeling time.

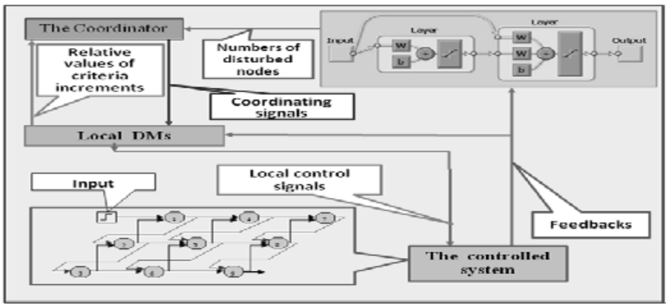
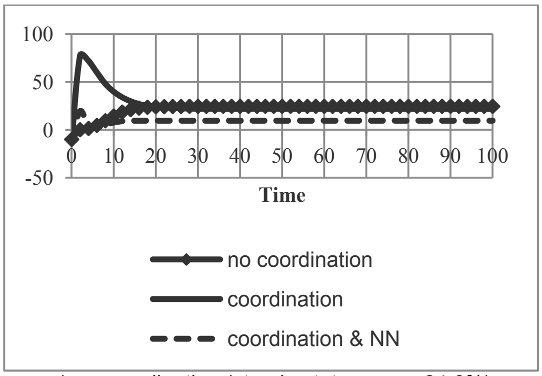


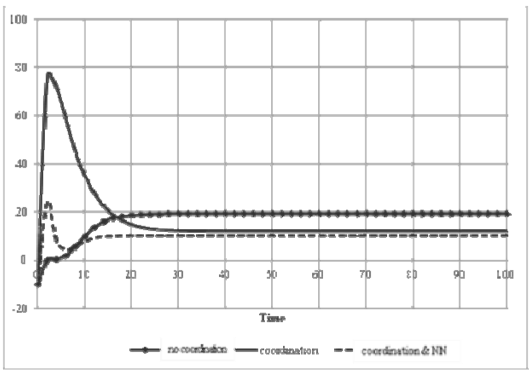
Figure 2. The Scheme of Gradient Coordination with NNs

The ideal output trajectories of the nodes served the training signals for the corresponding NNs, and the real trajectories were used during recognition. The differences between categories assigned by an NN to every node in disturbed and undisturbed modes scaled the coefficients ki of the corresponding coordination signals (8). Thus we provide "automatic" coordination of the disturbed nodes only.



a) no coordination (steady-state error – 24.6%)
b) complete coordination (steady-state error – 21.9%, transition time 23 sec)
c) complete coordination and NN (steady-state error – 9.6%, transition time 12 sec)

Figure 3. Internal disturbance on the disturbed 1st node of the controlled system



a) no coordination (steady-state error – 19.51%)
b) complete coordination (steady-state error – 12.13%, transition time 23 sec)
c) complete coordination and NN (steady-state error – 10.2%, transition time 10 sec)

Figure 4. Reaction of an undisturbed (3rd) node to an internal disturbance on the 1st node of the controlled system

Figure 3 and 4 display typical reactions of a disturbed and an undisturbed node correspondingly. Each of the figures comprises three charts, namely outputs of the nodes at no coordination, with gradient coordination for all nodes and with “selective” gradient coordination (only for nodes detected by an NN).

The charts show that for both disturbed and undisturbed nodes, NNs provide halving of transition time and steady-state error.

Table 1 summarizes simulation results for internal disturbances. It confirms that coordination with an NN widens stability ranges to some extent and lower transition times twice.

Table 1. Stability Ranges for Little Internal Disturbances

"Strong" links		"Weak" links	
Scheme	Stability range	Scheme	Stability range
Link 3-1		Link 5-4	
complete control and coordination	0.00005 ÷ -0.00005	complete control and coordination.	0.35 ÷ -0.24
complete coordination and NN	0.000052 ÷ -0.00005	complete coordination and NN	0.39÷-0.25
Link 4-3		Link 9-8	
complete control and coordination	0.000005 ÷ -0.000005	complete control and coordination	0.1 ÷ -0.1
complete coordination and NN	0.000007 ÷ -0.000007	complete coordination and NN	0.15÷-0.15
Link 9-1		Link 9-1	
complete control and coordination	0.0000005 ÷ -0.0000005	complete control and coordination	0.01 ÷ -0.06
complete coordination and NN	0.0000006 ÷ -0.0000006	complete coordination and NN	0.015÷ -0.065
Link 7-1		Link 8-2	
complete control and coordination	0.0000005 ÷ -0.0000005	complete control and coordination	0.002 ÷ -0.002
complete coordination and NN	0.0000006 ÷ -0.0000006	complete coordination and NN	0.0025 ÷ -0.0023

4. Conclusion

1. According to their stability ranges, we had to divide network feedbacks into two groups, namely "strong" and "weak" ones. Strong feedbacks had outputs in nodes 1, 2 and 3 in the Fig. 1. The coordination gave the best effect to the link 3-1 and the worst effect to the link 7-1. It had the same effect on all weak feedbacks.

2. Applying local control signals to every node in turn (individual control) widened stability ranges for strong feedbacks significantly (ten times on the average compared to the initial network) and almost did not change these ranges for weak feedbacks. Besides, when we tested applying small disturbances this way, nodes 4 and 8 reacted to them every time no matter which node was disturbed.

3. Generally, local control blocks compensated small external and internal disturbances fairly well as long as they worked in turns.

4. When modelling simultaneous operation of local control blocks compared to their functioning in turns, we registered almost the same stability ranges for the node 1, stability ranges for the rest nodes narrowed by 2-4 times. Above this, "persistent reaction" featured only nodes 4 and 8 at the previous modelling stage appeared in nodes 5 and 7 as well. So, we can state that non-coordinated local control impacts interfered with each other. This conclusion does not contradict the general theory of hierarchical systems.

5. Coordination signals improved convergence of real and ideal trajectories (lowered asymptotical errors) by several times. As for stability ranges, they became even wider that they had been for successive application of local control signals. This can be interpreted as a substantiation of efficiency of the proposed coordination technique.

6. Coordination affected the speed of the whole SoS, but this matter needs a more detail investigation.
7. Gradient techniques are fairly simple to implement, but they need fairly good feedbacks. The problem is that it is not easy to determine the quality of feedbacks in real systems.
8. When simulating both internal and external disturbances, usage of a neural net block did not let to localize these disturbances within a “guilty” node totally, but such a selective coordination widened the stability ranges of the modelled SoS, thus saving resources spent for maintaining of the SoS.
9. The neural net block provided protecting the undisturbed nodes by a decrease in the disturbances they were subjected and by halving their transition times.
10. The efficiency of the neural net block decreased with increasing in the number of the disturbed nodes in terms both the steady-state errors and the transition times.

We plan to conduct future research in the following directions: developing algorithms to choose amplification coefficients of coordinating signals (k_i) for better performance of the SoS (in the given research, we did it manually or used NN’s categories as factors); looking for possibilities to apply the proposed technique to dynamic intelligent systems; testing responses of the studied hierarchical and network systems to external and internal disturbances applied to different points of the systems; developing real-life case studies.

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