PARALLEL LOGIC CONTROL ALGORITHM SEPARATION QUALITY ANALYSIS IN THE SYNTHESIS OF LOGIC MULTICONTROLLERS

Eduard I. Vatutin

Department of Computer Science
Kursk State Technical University
50 Let Oktyabrya, 94, 305040, RUSSIA
Tel: +7(4712) 58-71-05, E-mail: evatutin@rambler.ru, WWW: http://evatutin.narod.ru

Abstract — *A strategy for the comparison of the parallel logic control algorithm separation quality is briefly described. Based on the performed computational experiments we found out that the parallel-sequential method can be applied to the zones of strong and very strong technological restrictions. Changing of quality criteria tendencies during increasing average size of control algorithms are determined and functional dependencies of the calculation time growth are given.*

1. INTRODUCTION

One of modern tendencies of creating logic control systems (LCS) is general using principals of parallelism and modularity. Parallel modularity LCS also known as logic multicontrollers (LMC) are capable to execute complex control algorithms with theoretically unlimited complexity due to process of its decomposition to a number of components that assigned to LMC modules. Especially interesting LMC that consist of modules (controllers) of the same type and provide very large productivity with good flexibility and testability.

Synthesis of LMC is connected with necessity of solving a number of optimization problems on discrete structures. Most significant of them is a problem of getting separations of logic control algorithms that solved during process of its decomposition. Quality of its decision is directly affect on hardware complexity of multicontroller and executing time of control algorithm. The named problem is belong to a class of *NP*-hard problems and cannot be precisely solved for algorithms with over than $N = 15$ vertices (approximately) because excessive time growth (its asymptotical time complexity is $O(N!)$) whereas practice control algorithms has a lot more size (thousands – tens of thousands vertices).

Well known a number of heuristic methods (for example, [2, 3]) for solving the given problem. One of them [4-5] is realized with author participation and now it is develop as before [7]. During process of decision synthesis given methods are used different principles. Due to the fact that some of them don't optimize some important criteria like interblock traffic [1, 8] it is interesting to carrying out its comparison and determining best of them on established criteria. Some preliminary results that given with using developed by author instrumental program system PAE [9, 10] and based on using a sample of control algorithms with random structure [11] are published in [12]. This work is present results of carried out comparative quality analysis of separations that given with using program realizations of named above methods [6, 13, 14] with a number of quality improve modifications. For example, program realization [13] of S.I. Baranov method [2] had some errors and it was developed anew, and parallel-sequential method [4-5] was improved with a number of quality improve modifications shown in [7].

2. TARGET SETTING

As show above, problem of getting separations has pronounced combinatorial character and reduced to optimal presentation of source parallel control algorithm into a set of interconnected blocks [1, 4]. Generally each block consist of a number of untied fragments of source control algorithm. Set of blocks with corresponding connections are make up a mesh of source algorithm.

Given blocks in separation and mesh structure are imposed with a number of restrictions that determined by architecture of LMC and its modules, technological restrictions, structure organization of multicontroller, intermodule communications manner and so on. Formalized target setting is given below. Let H – block count in separation;

$W_{\max}$ – capacity of microprogram memory used for allocation of block microcommands (without auxiliary commands for intermodule communications); $n_{\text{LC}} = X_{\max}$ – number of pins on controller package using for receiving signals with logic conditions from control object; $n_{\text{MO}} = Y_{\max}$ – number of pins on controller package using for transmitting signals with microoperations to control object. It is necessary to get separation of a set of vertices A^0 of source control algorithm $Sep\left(A^0\right) = \{A_1, A_2, ..., A_H\}$ so, that carried out conditions:

$$\begin{aligned} &\bigcup_{i=1}^{H} A_i = A^0, \quad A_i \neq \varnothing, \quad A_i \cap A_j = \varnothing, \quad i, j = \overline{1, H}, \quad i \neq j, \\ &\neg\left(a_i \omega a_j\right) \forall a_i, a_j \in A_k, \quad i \neq j, \quad k = \overline{1, H}, \\ &W\left(A_i\right) \leq W_{\max}, \quad \left|X\left(A_i\right)\right| \leq n_{\text{LC}}, \quad \left|Y\left(A_i\right)\right| \leq n_{\text{MO}}, \quad i = \overline{1, H}, \end{aligned} \tag{1}$$

where $W\left(A_i\right) = \sum_{a_j \in A_i} W\left(a_j\right)$ – total weight of all vertices to be a part of *i*-s block, $X\left(A_i\right) = \bigcup_{a_j \in A_i} X\left(a_j\right)$ – set of logical conditions to be a part of *i*-s block, $Y\left(A_i\right) = \bigcup_{a_j \in A_i} X\left(a_j\right)$ – set of microoperations to be a part of *i*-s block so, that

$$\begin{aligned} &H \to \min; \\ &Z_1 = \sum_{i=1}^{H} \sum_{j=1, j\neq i}^{H} \alpha\left(A_i, A_j\right) \to \min; \\ &Z_2 = \sum_{i=1}^{H-1} \sum_{j=i+1}^{H} \delta\left(A_i, A_j\right) \to \min; \\ &Z_3 = \sum_{i=1}^{H} \left|X\left(A_i\right)\right| - \left|X\left(A^0\right)\right| \to \min; \\ &Z_4 = \sum_{i=1}^{H} \left|Y\left(A_i\right)\right| - \left|Y\left(A^0\right)\right| \to \min, \end{aligned} \tag{2}$$

where Z_1 – interblock mesh complexity for separation $Sep\left(A^0\right)$; $\alpha\left(A_i, A_j\right)$ – coefficient of blocks connectivity (it is equal 1 in a case of blocks is connected on control from A_i to A_j and 0 elsewhere); Z_2 – total number of interblock communications (interblock traffic); $\delta\left(A_i, A_j\right)$ – interblock traffic between A_i to A_j blocks; Z_3 – number of doubled logic conditions; Z_4 – number of doubled microoperations.

So a given problem is a problem of multicriteria optimization on discrete structure (as graph). For the purpose of rating quality of given separations in [15] was proposed an integral value (estimation function)

$$\begin{aligned} f\left(Sep_{B_k}\left(A_l^0\right)\right) = &\frac{K_H}{\omega_{\max}} H + \frac{K_X}{\left|X\left(A^0\right)\right|}\left(\sum_{i=1}^{H}\left|X\left(A_i\right)\right| - \left|X\left(A_l^0\right)\right|\right) + \frac{K_Y}{\left|Y\left(A^0\right)\right|}\left(\sum_{i=1}^{H}\left|Y\left(A_i\right)\right| - \left|Y\left(A_l^0\right)\right|\right) + \\ &+ \frac{K_\delta}{\delta\left(A^0\right)} \sum_{i=1}^{H-1} \sum_{j=i+1}^{H} \delta\left(A_i, A_j\right) + \frac{K_\alpha}{\omega_{\max}\left(\omega_{\max} - 1\right)} \sum_{i=1}^{H-1} \sum_{j=i+1}^{H} \alpha\left(A_i, A_j\right) + K_W \Delta W, \end{aligned} \tag{3}$$

where $Sep_{B_k}\left(A_l^0\right)$ – separation of *l*-s algorithm given by method B_k, K_i, $i \in \{H, X, Y, \alpha, \delta\}$ – weight coefficients, $\omega_{\max}$ – parallelism degree of algorithm (ω-power of basic section of algorithm [1, 16], lower bound of number of modules in the LCS), $\Delta W = \max_{i=\overline{1,H}} W\left(A_i\right) - \min_{i=\overline{1,H}} W\left(A_i\right)$ – difference between component algorithms complexity. Taking into consideration criteria (2) let us assume that separation with $f\left(Sep_{B_i}\left(A_j^0\right)\right) \to \min$ is best.

3. EXPERIMENTAL COMPARISON OF METHODS

Using abilities of program system PAE [9, 10] was carried out a number of computing experiments. For the purpose of most objective rating of quality criteria values was accomplished generation of sample with *K* algorithms with random structure. For all given quality criteria values (2) and (3) of each method was calculated average value

$\overline{\gamma}(x)$ and probability of getting separation with minimal value of selected criteria $\rho(x)$, where $x \in \{H, X, Y, \alpha, \delta, f\}$. Given results that examine influence of technological restrictions on separation quality are shown in table 1 (t – computing experiment time for single threaded realization of components of program system that measured in hours on computer with processor Intel Core 2 Duo E6300, 1,86 GHz, 2 Mb L2, CPUID=06F6h).

Table 1. Influence of technological restrictions on separation quality*

Experiment number	Restriction values range	Additional parameters	Result
1	$3 \le X_{\max} \le 20$	$K = 500$ $N = 100 \pm 5$ $t = 4,5$	An analysis of given results shown that there are present two different regions (called zones) with different correlation of values of quality criterias: weak restrinctions zone $(9-15 < X_{\max})$ and strong restrictions zone $(X_{\max} < 9-15)$. In the weak restrictions zone S.I. Baranov method provide commensurable with parallel-sequential method number of blocks in separations $(\overline{\gamma}_{Bar}(H) \approx \overline{\gamma}_{PSM}(H))$. Best quality of optimization of criteria $\overline{\gamma}(X), \overline{\gamma}(\alpha), \overline{\gamma}(\delta)$ is provided by S.I. Baranov method. Parallel-sequential method provide least value of criteria $\overline{\gamma}(Y)$. During increasing power of restriction is observed gradual changing zone type to strong restrictions zone. Parallel-sequential method is now provide least values of criteria $\overline{\gamma}(H), \overline{\gamma}(Y), \overline{\gamma}(\alpha), \overline{\gamma}(\delta)$, and S.I. Baranov method is now provide best value only for $\overline{\gamma}(X)$ criteria. An integral value $\overline{\gamma}(f)$ is shown that within weak restrictions zone S.I. Baranov method is preferable, but during transition into strong restrictions zone parallel-sequential method is became more and more preferable.
2	$3 \le W_{\max} \le 40$	$K = 200$ $N = 100 \pm 5$ $t = 2$	In this experiment can be picked out three zones: weak restrictions zone $(32-36 < W_{\max})$, strong restrictions zone $(11-12 < W_{\max} < 32-36)$ and very strong restrictions zone $(W_{\max} < 11-12)$. In the weak restrictions zone there are $\overline{\gamma}_{Bar}(H) \approx \overline{\gamma}_{PSM}(H)$ and $\overline{\gamma}_{Bar}(\delta) \approx \overline{\gamma}_{PSM}(\delta)$, parallel-sequential method is provide some least values of criteria $\overline{\gamma}(Y), \overline{\gamma}(\alpha)$, S.I. Baranov method – $\overline{\gamma}(X)$. Transition into strong restrictions zone is leave S.I. Baranov method with best values of $\overline{\gamma}(X)$ criteria, all other criteria has least values in separations that given with parallel-sequential method. In the very strong restrictions zone S.I. Baranov method is provide best values for $\overline{\gamma}(X)$ and $\overline{\gamma}(Y)$ criteria. An integral value provide preferableness of S.I. Baranov method only within weak restrictions zone. Within strong and very strong restrictions zones parallel-sequential method is preferable.

* A.D. Zakrevsky method don't support technological restrictions and therefore not shown in experiments 1 and 2.

Also we run experiments 3 $(5 \le N \le 100,\ K = 300,\ X_{\max} = Y_{\max} = W_{\max} = \infty,\ t = 5)$ and 4 $(5 \le N \le 100,\ K = 300,\ W_{\max} = 4,\ t = 4,5)$. In this experiments is checked out tendencies of changing correlation of quality criteria during increasing average size of control algorithms without technological restrictions (experiment 3) and with strong technological restriction (experiment 4). First, given experiments again [12] confirm more poor quality of separations that synthesized by A.D. Zakrevsky method (especially for most significant criteria $\overline{\gamma}(H)$ that has indirect influence on all other critaria) and, second, shows that during average algorithm size growth correlation between quality criteria values is not changed. Given results are provide that parallel-sequential method is preferable within strong and very strong restrictions zones for control algorithms with any vertices count and S.I. Baranov method – within weak restrictions zone. An interesting feature [17] is that observed nearly linear growth of $\overline{\gamma}(H)$ criteria value as well as growth of difference $\Delta\overline{\gamma}(H)=\overline{\gamma}_{PSM}(H)-\overline{\gamma}_{Bar}(H)$ during increasing average control algorithm size. Difference $\Delta\overline{\gamma}(H)$ is can be up to 6,5% of total blocks count (modules in LCS).

Experiment 5 is carried out for the purpose of time cost investigation during increasing average control algorithms size. Given empirical function dependencies for all methods was approximated with least-squares method using polynomials with power one (for S.I. Baranov method) and three (for A.D. Zakrevsky and parallel-sequential methods):

$$\begin{gathered} t_{Bar}(N)=-1,064+9,698\cdot 10^{-2}N, \\ t_{Zak}(N)=-6,756+1,143N-4,524\cdot 10^{-2}N^2+6,326\cdot 10^{-4}N^3, \\ t_{PSM}(N)=-15,475+3,143N+0,146N^2+2,809\cdot 10^{-3}N^3. \end{gathered} \tag{4}$$

Given functional dependencies for S.I. Baranov and A.D. Zakrevsky methods don't include time cost for building relation matrix [1, 5, 18]. Functional dependencies (4) can be extrapolated to algorithms with a significant more vertices. For example, synthesis of separations of control algorithms with $N=10000$ vertices will need one second for S.I. Baranov method, one week for A.D. Zakrevsky method and over one month for parallel-sequential method (in a best way). I.e. synthesis LCS with real complexity will need to be satisfied with low quality of S.I. Baranov separations or need to realize optimization/parallelization of program realization of parallel-sequential method and/or replace most time cost operations for its hardware-level analogues by working out specialized device (accelerator). Analogous hardware-level tasks are described in [19]. Synthesis of hardware-level accelerator is offered as most perspective way and actively evaluated at present time [20-22].

6. CONCLUSION

1. A number of zones within ranges of values of technological restrictions is discovered.
2. Field of application of parallel-sequential method is strong and very strong restrictions zones (practice case).
3. Field of application of S.I. Baranov method is weak restrictions zone (ideal case).
4. A.D. Zakrevsky method (at least in realization [14]) don't support technological restrictions and provide most low quality separations.
5. Correlation between quality criteria values is indifferent during increasing control algorithms size. This allow to extrapolate given above recommendations to the control algorithms with any size.
6. High-quality synthesis of separations of parallel logic control algorithms with real complexity (10000 vertices and higher) will need some months of computing time. That is obstacle to operative change-over of LCS.
7. Requirement of synthesis of separations of logic control algorithms with a big size is bring to be satisfied with low quality of S.I. Baranov separations or need to optimization, parallelization of program realization of parallel-sequential method or replace some steps of method with its hardware-level analogs.

7. REFERENCES

[1] I.V. Zotov, V.A. Koloskov, V.S. Titov at al., *Organization and synthesis of microprogram multimicrocontrollers*, Kursk: GUIPP "Kursk", 1999. 368 p. (in Russian).
[2] S.I. Baranov, L.N. Zhuravina, V.A. Peschansky, "Method for representation of parallel flow-charts with a set of sequential flow-charts", *Automation and computing engineering*, No. 5, 1984, pp. 74–81. (in Russian).
[3] A.D. Zakrevsky, *Parallel logic control algorithms*, Minsk: ITK NAN B., 1999. 202 p. (in Russian)
[4] I.V. Zotov, V.A. Koloskov, V.S. Titov, "Optimal algorithm separation in the design of microcontroller networks", *Automatic control and computer sciences*, No. 5, 1997, pp. 41–52.

[5] E.I. Vatutin, I.V. Zotov, “Method for getting suboptimal separations of parallel logic control algorithms”, *Parallel computations and control problems (PACO’08)*, Moscow: Institute of control sciences of RAS, 2004, pp. 884–917. (in Russian).
[6] E.I. Vatutin, I.V. Zotov, “Parallel-sequential method for getting separations of parallel logic control algorithms”, *Certificate of official registration program for computer No. 2005613091 from 28.11.05.*
[7] E.I. Vatutin, I.V. Zotov, “Improving quality of algorithms separations in the synthesis of logic milticontrollers using parallel-sequential method”, Perspectives of development weapon control systems, Moscow: “Betretdinov and K”, 2007, pp. 84–92. (in Russian).
[8] E.I. Vatutin, “Interblock traffic calculation problem in a task of getting separations of parallel logic control algorithms”, *Education, Science, Production*, Belgorod, 2006. (in Russian).
[9] E.I. Vatutin, I.V. Zotov, “Program system for getting separations of parallel logic control algorithms”, *Systems identification and control problems (SICPRO’06)*, Moscow: Institute of control sciences of RAS, 2006, pp. 2239–2250. (in Russian).
[10] E.I. Vatutin, I.V. Zotov, “Visual environment for synthesis of separations of parallel logic control algorithms”, *Certificate of official registration program for computer No. 2007613222 from 30.07.07.*
[11] Vatutin E.I. Constructing Random Sample Parallel Logic Control Algorithms // *11th International Student Olympiad on Automatic Control (Baltic Olympiad BOAC’06)*. Saint-Petersburg, 2006. P. 162–166.
[12] E.I. Vatutin, S.V. Volobuev, I.V. Zotov, “Comprehensive comparative evaluation of separation methods in the design of logic multicontrollers”, *Systems identification and control problems (SICPRO’06)*, Moscow: Institute of control sciences of RAS, 2008, pp. 1917–1940. (in Russian).
[13] A.V. Tarlovsky, I.V. Zotov, “Library of functions for getting separations of parallel logic control algorithms with using modified Baranov method”, *Certificate of official registration program for computer No. 2006612337 from 05.07.06.*
[14] S.V. Volobuev, K.O. Evglevsky, I.V. Zotov, “Library of functions for getting separations of parallel logic control algorithms with using Zakrevsky method”, *Certificate of official registration program for computer No. 2006613146 from 06.09.06.*
[15] E.I. Vatutin, “Estimation of quality of separations of parallel logic control algorithms into sequential subalgorithms with using weight function”, *Intellectual and informational systems (Intellect – 2005)*, Tula, 2005, pp. 29–30. (in Russian).
[16] E.I. Vatutin, I.V. Zotov, “Getting base section in a task of building separations of parallel algorithms”, *Dep. In VINITI 24.11.03, № 2036-B2003.*
[17] E.I. Vatutin, E. Yu. Kobzar’, “Analysis of changing quality criteria tendencies during increasing average size of control algorithms”, *Optoelectronic instruments and devices in the pattern recognition, image analysis and processing symbol information systems (Recognition – 2008)*, Vol. 1, Kursk: KurskSTU, 2008, pp. 89–90. (in Russian).
[18] E.I. Vatutin, I.V. Zotov, “Relation matrix building in a task of getting optimal separations of parallel logic control algorithms”, *Proceedings of the Kursk state technical university*, Kursk: KurskSTU, 2004, No. 2, pp. 85–89. (in Russian).
[19] V.M. Kureychik, V.M. Glushan’, L.I. Sherbakov, *Combinatorial hardware-level models and algorithms in CAD systems*, Moscow: Radio and Svyaz’, 1990, 216 p. (in Russian).
[20] D.B. Borzov, E.I. Vatutin, I.V. Zotov, V.S. Titov, “To the task of getting suboptimal separations of parallel algorithms”, *Proceedings of institutes of higher education. Instrument-making*, Vol. 12, Saint-Petersburg, 2004, pp. 34–39. (in Russian).
[21] E.I. Vatutin, I.V. Zotov, “Hardware-level model for determining block count during decomposition of parallel logic control algorithms”, *Proceedings of institutes of higher education. Instrument-making*, Vol. 51, No. 2, Saint-Petersburg, 2008, pp. 39–43. (in Russian).
[22] E.I. Vatutin, “Uniform environment of electronic model of tree for hardware-oriented processing of R-expressions”, *Optoelectronic instruments and devices in the pattern recognition, image analysis and processing symbol information systems (Recognition – 2008)*, Vol. 1, Kursk: KurskSTU, 2008, pp. 90–92. (in Russian).