VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

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ANT COLONY TECHNOLOGIES FOR IMAGE PROCESSING

SUMMARY OF DOCTORAL DISSERTATION

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Introduction

Problem under Investigation

Ant Colony Optimization (ACO) is a common term describing various algorithms based on ants behaviour. ACO is a metaheuristic belonging to swarm intelligence.

It was noted that ants in nature are able to find the shortest path from food source to the nest. The research of ant behaviour in nature was used as a foundation for mathematical model of ant colony.

ACO is relatively new branch of optimization algorithms. First to provide detailed analysis and theoretical background was Marco Dorigo, who in 1992 defended his PhD, providing results and working Ant System model. Experimental results proved model to be suitable for solving optimization problems. Most known optimization problems are traveling salesman problem (TSP) and quadratic assignment problem. Today eight main ACO variations exist. Each year a lot of modifications of existing variations are presented.

ACO as metaheuristic is a common set of rules, which don't tell how to apply ACO for image processing. It is also not known what kind of image processing is reasonable to implement via ACO. It is not fully clear what will be the performance of ACO, when implementing it in Field Programmable Gate Arrays (FPGA).

Topicality of the Research Work

Image pre-processing is an inevitable process, preparing image for further analysis. Usual image processing methods are applicable when image processing operators' sequence is clear and suitable for a set of similar images. However not always it is clear what sequence of image processing operators should be used for a given set of images. It may take a lot of time for creating a new sequence for a new set of images.

Here various optimization techniques may be helpful. Evolutionary computation techniques such as genetic algorithms or genetic programming are widely used for image processing. However swarm intelligence techniques are relatively new and not investigated enough. ACO is one of the swarm intelligence branches that could be used for image processing, but it is not yet clear how.

Moreover it is not enough research work done on implementing ACO in embedded systems, which more often use FPGA because of it reprogrammable logic flexibility.

ACO application could make pre-processing of images easier, by automating image processing sequence selection. ACO application for image segmentation could lead to more accurate segmentation of objects. ACO implementation in FPGA may increase performance of optimization tasks in embedded systems.

Research Object

Research object is ant colony technologies for image processing and related to it matters: ACO algorithms, image processing methods and implementation in FPGA.

The Aim of the Work

The aim of the work is to propose and investigate image processing techniques and means based on ant colony optimization algorithms.

Tasks of the Work

1. Perform analytical review of ACO literature in order to reason selection of ACO and image processing methods for further research.
2. Propose and analyze original image processing methods based on ACO metaheuristic.
3. Investigate the possibility to implement ACO in embedded systems based on FPGA.

Applied Methods

In this work ACO, image pre-processing and image segmentation theory is applied. Computer modeling is done using MATLAB™ program. Algorithms are implemented via C programming language, specific FPGA device programmed using Xilinx EDK with MicroBlaze software processor.

Scientific Novelty and its Importance

1. Created new image pre-processing technique based on Max-Min Ant System automates image pre-processing.
2. Created new image segmentation technique based on competition of Multiple Ant Colonies. It gives more precise segmentation results for overlapped protein spots in two-dimensional gel images.
3. Obtained results of performance evaluation, implementing Ant System in FPGA. It reveals how to efficiently implement ACO in embedded systems.

Practical Value of the Work Results

Created image pre-processing by Max-Min Ant System technique may be applied as universal mean for image processing sequence selection for a given problem. Image pre-processing becomes more convenient because of automatic image processing sequence selection for a given set of source and destination images.

Image segmentation by ACO technique yields more precise segmentation of grayscale images, so it could be applied for: security surveillance systems (nighttime images), medicine (x-ray, ultrasonic and similar images), biochemistry (1D or 2D electrophoresis gel images).

ACO implementation in FPGA results were applied in successfully finished project “Ant Colony Optimization Implementation in Field Programmable Gate Array” (registration No. T-08127, contract No. T-112/08) supported by Lithuanian State Science and Studies Foundation. It was demonstrated that Ant Colony Optimization can be implemented in FPGA for modern, small and efficient devices design.

Statements Presented for Defense

1. Created new image pre-processing technique, based on Max-Min Ant System, finds solution about 30% quicker for complex problems in comparison to common Max-Min Ant System without control of initial position of pheromone.
2. Created new image segmentation technique, based on competition of Multiple Ant Colonies, provides more than 60% better segmentation results for 2D gel electrophoresis images with overlapped protein spots than threshold function based techniques.
3. Implementing Ant System in FPGA, 1.9 times quicker operating speed could be reached, using Floating Point and 32 bits Multiplier units, than MicroBlaze without additional units.

Approval of the Work Results

The results are presented in 6 papers, 5 of them were published in reviewed scientific journals. Moreover the results were presented in 10 scientific conferences:

- 13-th International Conference “Electronics”, 2009, Kaunas, Vilnius, Lithuania;
- 1-st International Conference “Bio-Inspired Signal and Image Processing”, 2008, Warsaw, Poland;
- 12-th International Conference “Electronics”, 2008, Kaunas, Vilnius, Lithuania;
- XI-th Lithuania Young Scientists Conference “Mokslas – Lietuvos Ateitis”, Electronics and Electrical Engineering, 2008, Vilnius, Lithuania;
- 11-th International Conference “Electronics”, 2007, Kaunas, Vilnius, Lithuania;
- International Conference “Fundamentals of Electrotechnics and Circuit Theory”, 2007, Gliwice, Ustron, Poland;
- X-th Lithuania Young Scientists Conference “Mokslas – Lietuvos Ateitis”, Electronics and Electrical Engineering, 2007, Vilnius, Lithuania;
- 10-th International Conference “Electronics”, 2006, Kaunas, Vilnius, Lithuania;

- IX-th Lithuania Young Scientists Conference "Mokslas – Lietuvos Ateitis", Electronics and Electrical Engineering, 2006, Vilnius, Lithuania;
- 5-th International Conference "Transport Systems Telematics", 2005, Gliwice, Ustron, Poland.

The Scope of the Scientific Work

Dissertation is written in Lithuanian. The explanatory part takes up 117 pages. The work contains 51 mathematical expressions, 26 figures, 8 tables, 10 algorithms and cites 142 references. The dissertation consists of: introduction, four chapters, conclusions, references, list of author's publications on the topic of dissertation and 2 annexes.

1. Review of Evolutionary Technologies for Image Processing

Review and analysis of evolutionary computation methods led to these PhD thesis tasks.

Max-Min Ant System is superior to other ant colony optimization algorithms for solving traveling salesman problem. Despite longer search for solution, quality of it is better, compared to other ant colony optimization algorithms. There were found no research results related to Max-Min Ant System application for image pre-processing, so it was decided to create technique, applying Max-Min Ant System for image pre-processing and suggest modifications to increase convergence speed.

Attempt of image segmentation via multiple ant colonies was presented by L. Bocchi, L. Ballerini and S. Hassler in 2005 and was performed on simple images where number of colonies was selected equal to the number of objects presented in image. Another attempt by C. Fernandes, V. Ramos and A. Rosa was to use multiple ant colonies with population control and watershed transformation. Both methods have their disadvantages, so it was decided to investigate this problem deeper and propose new technique based on multiple ant colonies with population control applying it to a more complex biochemical images.

A lot of research results starting from 1995 presented with implementation of evolutionary computation algorithms in field programmable gate array, however no extended research on performance of Ant System implemented in field programmable gate array was provided comparing Ant System with other methods, using MicroBlaze software processor. It is decided to implement Ant System and brute force method in field programmable gate array and evaluate internal MicroBlaze unit's influence on performance.

2. Development of Technique for Image Pre-processing by Max-Min Ant System

The main steps of image pre-processing by Max-Min Ant System technique are:

1. Ant system initialization.
2. Construction of solutions.
3. Local search.
4. Pheromone update.
5. Check-up of convergence condition.
6. If condition is not met return to step 2.

Let us comment the technique and one of it's implementation presented in Algorithm 1. Initial values are assigned for Ant System parameters. Source and final grayscale images are supplied for the system. Set of image processing operators together with parameters is prepared. Initial solutions are constructed from one operator and the similarity between received and supplied final images is evaluated. Construction of solutions is continued and length of sequence is increased to two operators. Again similarity between received and supplied final images is evaluated. If received similarity is better sequence is recorded. These actions are repeated until sequence reaches the maximum allowed length. Then the sequence which led to closest similarity is selected and that way indirect local search is performed.

Pheromone is left by ant only in these operators that belong to the sequence found. Main difference of proposed technique is ant starting position control via pheromone. Proposed two ways of start position control: first – based on direct dependence on pheromone level; second – based on a constant number of moved ants from operators with the lowest pheromone level to operators with the highest pheromone level. Pheromone evaporation is performed for all operators.

Convergence condition is met when the maximum number of iterations is reached or when the sequence of operators providing satisfactory result is found.

As was expected ants starting position control speeded up the convergence. Two suggested modifications gave similar increase in performance (Fig. 1). Comparing with common Max-Min Ant System, performance increase was apparent starting from sequence length of three operators $l = 3$, and the highest gain was about 30% compared with common Max-Min Ant System without starting position control, when solution length increased to six operators $l = 6$. MMAS Mod2 showed the best results when transferred number of ants was 20% of all, which led to about 5% increase in convergence speed over MMAS Mod1. Further increase of number of transferred ants led to solutions stuck in local minima.

Algorithm 1. Image pre-processing by MMAS Mod2

1. Assign initial values to parameters:

$$n = 84; \quad m = 84; \quad m_{\text{per}} = 0,20 \cdot m; \quad \alpha = 1; \quad \beta = 2; \tag{1}$$
$$\rho = 0,02; \quad l_{\max} = 6; \quad n_{\text{vid}} = n; \quad p_{\text{best}} = 1/n; \quad \tau_0^{\text{start}} = \tau_{\max}^{\text{start}},$$

   here:

$$\tau_{\max}^{\text{start}} = \frac{1}{1-\rho} \cdot \frac{1}{n}. \tag{2}$$

2. Prepare initial $\mathbf{V}_{\text{prd}}$ and final $\mathbf{V}_{\text{gal}}$ images.
3. Place ants one near each pair of operator with parameter.
4. Evaluate limits:

$$\begin{cases} \tau_{i,j}(t) = \tau_{\max}, & \text{when } \tau_{i,j}(t) > \tau_{\max}; \\ \tau_{i,j}(t) = \tau_{\min}, & \text{when } \tau_{i,j}(t) < \tau_{\min}. \end{cases} \tag{3}$$

5. Move ants from m_{per} operators with lowest pheromone leve to m_{per} cities with highest pheromone level.
6. Calculate η:

$$\eta = \frac{1}{1 + l_{\max} - l^{\text{op}}}. \tag{4}$$

7. Choose next operator:

$$p_{i,j}^k = \frac{(\tau_{i,j})^\alpha (\eta_{i,j})^\beta}{\Sigma_{l \in N_i^k} (\tau_{i,l})^\alpha (\eta_{i,l})^\beta}, \quad \text{kai } j \in \mathcal{N}_i^k. \tag{5}$$

8. Save used operator into ant's k list of operators l.
9. Evaluate solution, if better solution was found, remember it.
10. If $l_{\max}$ is not reached, return to step 6.
11. Evaporate pheromone:

$$\tau_{i,j}(t+1) = \rho \cdot \tau_{i,j}(t). \tag{6}$$

12. Ant which found the best solution, leaves pheromone trace:

$$\tau_{i,j}(t+1) = \tau_{i,j}(t) + \Delta\tau_{i,j}^{\text{best}}. \tag{7}$$

13. Ant which found the best solution, marks starting operator with pheromone:

$$\tau_i^{\text{start}}(t+1) = \tau_i^{\text{start}}(t) \cdot \rho + \sqrt[n]{\Delta\tau_i^{\text{best}}}. \tag{8}$$

14. If image processing sequence is not found and maximum number of iterations is not reached, return to step 3.

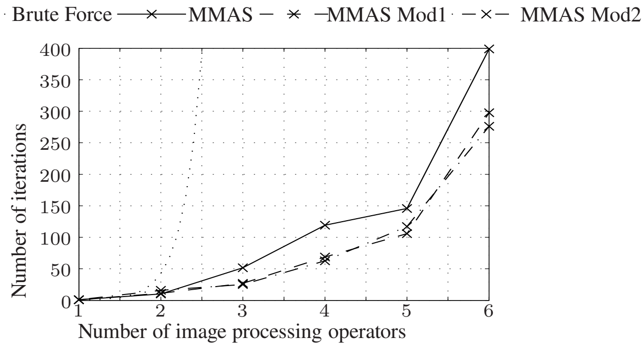

Fig. 1. MMAS algorithm convergence speed

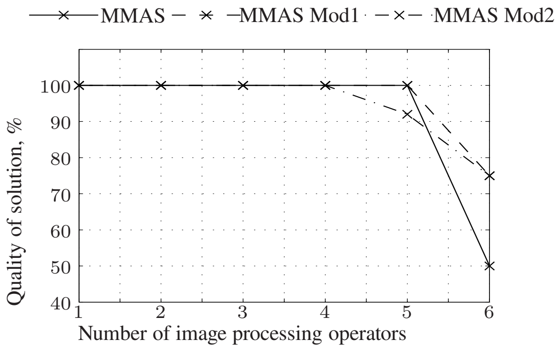

Fig. 2. Solution quality dependence on complexity of the problem

Evaluation of the quality of solution found (Fig. 2) let us estimate algorithms behavior with different solution length. From all supplied problems all models are able to find the best solution if solution length is no longer than 4 operators. When solution length increases to 6 operators, then common MMAS is able to find the best solution in 50% of supplied problems, MMAS Mod1 and MMAS Mod2 found the best solution in 75% of supplied problems. For MMAS Mod2 it was experimentally estimated that 20% of all ants should be transferred from operators with low pheromone level to operators with high pheromone level to achieve similar results as MMAS Mod1. Sudden decrease in percentage of found solutions when solution length is more than 5 operators could be explained by increase of search space. For 5 operators there are about $4.2 \cdot 10^9$ possible solutions and for 6 operators length there are about $3.5 \cdot 10^{11}$ possible solutions. So the number of ants should be increased to cover such a wide space of feasible solutions.

3. Development of Technique for Image Segmentation by Ant Colonies

The main steps of technique for image segmentation by multiple ant colonies are:

1. Initialization.
2. Movement of ants on the surface of the image.
3. Pheromone update and competition.
4. Energy update.
5. Reproduction.
6. Mask application.
7. Check-up of convergence condition.
8. If condition is not met return to step 2.

Let us comment the technique and one of it's implementation presented in Algorithm 2. During initialization initial values are assigned to variables. Selected number of ants are randomly placed over the image surface. Each ant is assigned to different colony and marks its path with pheromone of its kind. Ants are moving over the image surface being attracted by protein spots and by pheromone of its own kind. After each step ants are leaving amount of pheromone that depends on the gradient found.

The main difference of proposed technique is in pheromone update. Ant colonies are competing via the pheromone. If ant detects pheromone of its own kind it is being attracted by it, if the pheromone belongs to other colony, then ant is being repelled by it. The higher the concentration of pheromone the higher the influence on ant decision it has. The new level of pheromone depends on current level and ant's found gradient. If pheromone belongs to the same colony, pheromone quantity increases by the amount generated by ant, if different colony – decreases by the same amount.

Each ant has initial energy, which is being decreased after each step. When ant finds image gradient which is higher than the one found earlier, energy of ant increases. When ant's energy reaches zero, then that ant is removed from the colony.

Ant has an ability to breed, when in neighborhood there is at least one ant and there is a free cell for the offspring. Offspring has high probability to belong to the same colony as the majority of surrounding ants. Reproduction has higher probability to be triggered when the current gradient level found by ant is high.

To increase segmentation speed it is suggested to remove ants from those places of image, where no protein spots are present. For that purpose mask is created and repeatedly applied after given number of iterations. For comparison two algorithms were created, one without mask and the other – with mask (cf. Algorithm 2).

Algorithm 2. Image segmentation by multicolony ACO with mask

1. Calculate image mask, assign initial values to parameters:

$$\begin{aligned} &\mu = 0,06; \quad \Delta E = 0,025; \quad \alpha = 3,5; \quad \delta = 0,2; \\ &\tau_{\mathrm{p}} = 0,07; \quad g = 1,5; \quad \rho = 0,01; \quad E(0) = \Delta E + 1. \end{aligned} \tag{9}$$

2. Choose initial number of ants $S = 30\%$ of image size.
3. Assign each ant to different colony.
4. Move ants:

$$p_{i,j} = \frac{W(\tau_j)w(\Delta_\Theta)}{\Sigma_{l \in N_i^k} W(\tau)w(\Delta_\Theta)}, \quad \text{when } j \in \mathcal{N}_i^k. \tag{10}$$

5. After each step leave pheromone:

$$\tau_{i,j}(t) = \begin{cases} |\tau_{i,j}(t-1) - \Delta\tau|, & \text{different colonies;} \\ \tau_{i,j}(t-1) + \Delta\tau, & \text{same colonies.} \end{cases} \tag{11}$$

according to condition:

$$W_{\mathrm{S}}(\tau) = \begin{cases} \dfrac{1}{W(\tau)}, & \text{different colonies;} \\ W(\tau), & \text{same colonies.} \end{cases} \tag{12}$$

6. Calculate ant's energy:

$$E(t) = E(t-1) - \Delta E + \Delta E \frac{\Delta_{\mathrm{gl}}}{\max \Delta_{\mathrm{gl}}} \tag{13}$$

7. Remove ants without energy.
8. Perform reproduction:

$$P_{\mathrm{R}} = R(n)\left(\mu + \frac{(1-\mu)\Delta_{\mathrm{gl}}}{\max \Delta_{\mathrm{gl}}}\right). \tag{14}$$

9. Evaporate pheromone:

$$\tau(t) = \frac{\tau(t-1)}{\rho + 1}. \tag{15}$$

10. Each second step apply mask:

$$A_{i,j} = A_{i,j} \cdot B_{i,j}, \tag{16a}$$

$$\tau_{i,j} = \tau_{i,j} \cdot B_{i,j}. \tag{16b}$$

11. If stopping condition is not met, return to step 4.

Table 1. The results of 2D electrophoresis gel image segmentation

Experiment number	Number of iterations	Segmented spots, %
1	1200	55.5
2	200	62.5
3	350	75.0
4	200	75.0
5	1000	44.4
6	500	50.0
7	**325**	**100.0**

The use of mask led not only to better segmentation (Table 1), but also speeded up the whole segmentation process. On 40 × 30 pixels image, segmentation took 108 seconds for 200 iterations with mask, and 408 seconds – without mask. Full processing (2600 iterations) took 1440 seconds with mask and 5400 seconds without mask on Intel Mobile 1.6 GHz processor.

Another difference of suggested technique is in convergence condition. It is proposed to use all colonies population size fluctuations as stopping criteria. Because of ant colonies competition, death and breeding, colonies population size fluctuation curve (Fig. 3) has peaks and valleys. First peak occurs after placement of ants and crossover, then population size decreased, because of mask application, which is applied each second iteration. First valley (after about 45 iterations) appears because of removal of ants with zero energy, as they were not able to find high gradient level (protein spots). Second peak (after about 200 iterations) is because of crossover of ants which reached high gradient level. Now simulation should be stopped, because if continued, ants from same colonies start to occupy different protein spots and segmentation will degrade. So after second peak of population size, the highest number of segmented spots is obtained.

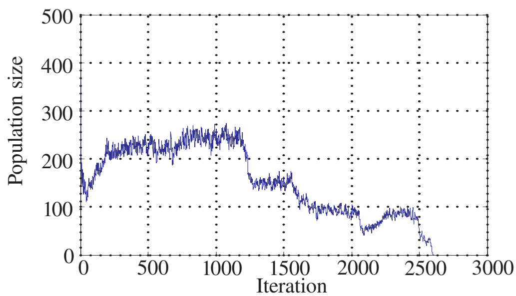

Fig. 3. Ant colonies population fluctuation during the fourth experiment

4. Ant System Implementation in FPGA Device

Experiments were performed on DiniGroup multi-FPGA DN8000K10PSX board. This board with PCI connector consists of three Virtex-4 FPGA's: one LX100 and two SX55. Each of them is directly connected to DDR2 type memory. DN8000K10PSX board uses Spartan-2 type FPGA for programming and managing link between Virtex-4 FPGA's. Also board has Ethernet, RS232, JTAG, USB and CompactFlash ports.

Xilinx company created MicroBlaze soft core processor to be used in embedded systems. MicroBlaze works on Virtex and Spartan families of FPGAs. MicroBlaze soft core processor is a part of Platform Studio / EDK software package, together with other software modules, dedicated to interact with external devices. MicroBlaze processor simplifies development of embedded devices, by allowing to execute code written in C programming language. MicroBlaze is capable of performing calculations with floating point numbers. The use of software processor speeds up the development, but generated circuit is generally slower and takes larger area on FPGA.

Taking into account that MicroBlaze possibilities implementing ant colony optimization algorithms are not covered enough in literature, also limited resources and MicroBlaze programming flexibility, 32 bits MicroBlaze was chosen for implementation of ant colony optimization algorithms.

In order to adapt Ant System for MicroBlaze soft processor to solve traveling salesman problem, few modifications to Ant System were made:

- All ants start from one city.
- Only the iteration best ant leaves pheromone trace.
- As the number of cities increases, evaporation coefficient is increased too.

Ant System uses random numbers for probabilistic selection of movement direction (Dorigo *et al.* 1996). For implementation of Ant System, random number generator with uniform distribution is required. In order to receive same results on computer and FPGA device, pseudo random number generator based on multiply-with-carry algorithm (Couture, L'Ecuyer 1995, 1997; Marsaglia 1994) was used. Random number generator was tested by solving number π calculation problem by Monte-Carlo method. Problem was implemented in MicroBlaze soft core processor and computer. Identical results were obtained, so pseudo random number generator was accepted for further experiments.

Additional unit's influence on performance gain (Table 2) was evaluated comparing Ant System and brute force methods. For evaluation purposes problem with 14 cities was chosen for Ant System and problem with 9 cities for brute force method, because of close execution times. Additional units have different impact on performance. Integer divider had no influence on performance, however ba-

Table 2. MicroBlaze core units evaluation

MicroBlaze units	Calculation time, s	
	Brute force	Ant System
Core only	54.0	57.0
Basic FPU	53.0	33.4
Extended FPU	53.0	–
32 bits multiplier	53.5	43.0
64 bits multiplier	–	–
Shift	–	–
Integer divider	54.0	57.0
State register	54.0	57.0
Comparator	54.0	57.0
Basic FPU with 32 bits multiplier	**52.0**	**23.0**

sic FPU performance gain was about 1.7 times. Another unit, which gave significant performance gain was 32 bits integer multiplier. Total gain of both units was 2.47 times for Ant System and only 1.04 times for brute force method. Such result may be explained by highly iterative nature of brute force method and simplicity of calculations. Further increase of problem complexity (Fig. 4), showed decrease of performance gain for Ant System and stabilization near 1.9 times.

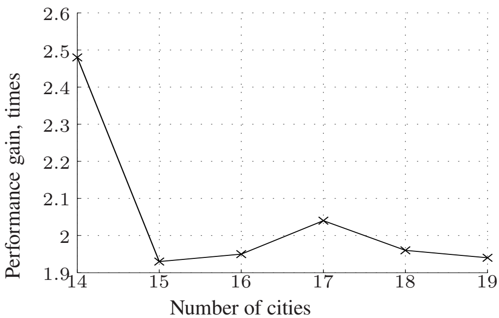

Fig. 4. Performance gain

During experiment standard deviation of solution was observed (Fig.5). It was noted that standard deviation may be used as an indicator of the need to change system parameters. Sudden increase of standard deviation when number of cities was 16, required the number of ants to be increased. After increasing the number of ants from 9 to 16, standard deviation decreased. Another sudden increase of standard deviation when number of cities was 20, again by increasing the number

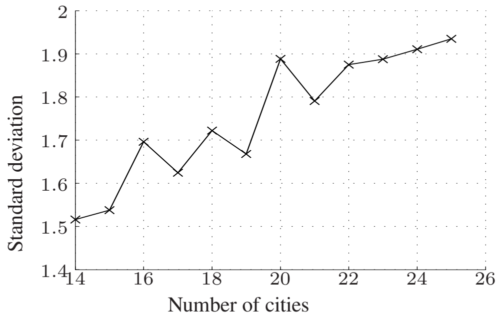

Fig. 5. Variation of standard deviation

of ants and evaporation coefficient led to decrease of standard deviation. Growing number of cities will increase the search space and, naturally, standard deviation will slowly increase.

Results and Conclusions

Ant colony optimization based image processing methods and technologies were suggested and investigated while receiving these important for the field of Electronics and Electrical Engineering results:

1. A new image pre-processing technique based on Max-Min Ant System is created, and is able to find solution 30% quicker for difficult problem than common Max-Min Ant System without starting position pheromone control.

2. A new image segmentation technique, based on multiple ant colonies competition, is created. It provides more than 60% better segmentation of overlapped protein spots in 2D electrophoresis gel image, than threshold function techniques.

3. Research result of ant colony optimization implementation in field programmable gate array are presented. Up to 1.9 times increase in performance was achieved solving traveling salesman problem by addition of floating point and 32 bits multiplier units, compared to MicroBlaze software processor without additional internal units.

4. Following recommendations are proposed:

    - For image preprocessing when Max-Min Ant System is used it is recommended to move 20% of all ants.

- For image segmentation based on multiple ant colonies competition it is recommended to stop segmentation based on population size fluctuations.
- For Ant System implemented in FPGA it is recommended to change parameters according to standard deviation of solutions.

List of Scientific Publications on the Topic of Dissertation

In the Reviewed Scientific Journals

Laptik, R.; Arminas, V; Navakauskas, D. 2009. Ant System Implementation using MicroBlaze: Some Preliminary Results on Efficiency Study, *Electronics and Electrical Engineering* 6(94): 27–30. ISSN 1392-1215 [Thomson ISI WEB of Science]

Laptik, R.; Navakauskas, D. 2009. MAX-MIN Ant System in Image Preprocessing, *Electronics and Electrical Engineering* 1(89): 21–24. ISSN 1392-1215 [Thomson ISI WEB of Science]

Laptik, R.; Navakauskas, D. 2007. Application of Ant Colony Optimization for Image Segmentation, *Electronics and Electrical Engineering* 8(80): 13–18. ISSN 1392-1215 [Thomson ISI WEB of Science]

Laptik, R.; Navakauskas, D. 2005. Application of Artificial Neural Networks for the Recognition of Car Number Plates, *Electronics and Electrical Engineering* 8(64): 27–30. ISSN 1392-1215 [Thomson ISI Master Journal List]

Laptik, R.; Navakauskas, D. 2005. Application of Artificial Neural Networks in Number Plate Recognition System, *Transport Systems Telematics* 59: 249–257. PL ISSN 0209-3324

In Other Scientific Works

Laptik, R.; Navakauskas, D. 2007. Ant Colony Optimization Application for Image Segmentation, in *Proceedings of the IC-SPETO Conference*, 151–152. ISBN 978-838594-029-6 [INSPEC]

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SKRUZDŽIŲ KOLONIJŲ TECHNOLOGIJOS VAIZDAMS APDOROTI

Tiriamoji problema

Terminas optimizavimas skruzdžių kolonijomis (OSK) apibendrina įvairius algoritmus, grindžiamus skruzdžių judėjimo gamtoje principais. OSK algoritmai yra metaeuristiniai ir priklauso spiečiaus sumanumo klasei. Pastebėta, kad gamtoje skruzdės geba rasti trumpiausią kelią tarp skruzdėlyno ir maisto. Skruzdžių elgsenos principai buvo panaudoti matematiniam skruzdžių kolonijos modeliui kurti.

OSK yra palyginti jauna optimizavimo algoritmų karta. Pirmas, atlikęs detalią analizę, pateikęs teorinį pagrindą bei veikiantį skruzdžių sistemos diskretaus optimizavimo algoritmo modelį, buvo italas Marco Dorigo, kuris 1992 metais apgynė pirmąją šios srities disertaciją (Dorigo 1992). Skruzdžių sistemos eksperimentiniai modelio tyrimai parodė, kad modelis tinkamas optimizavimo uždaviniams spręsti. Vieni plačiausiai žinomi ir spręsti OSK uždaviniai yra keliaujančio prekeivio (ang. *traveling salesman problem*) (Dorigo, Gambardella 1995, 1997a; Flood 1956) ir kvadratinio paskirstymo (ang. *quadratic assignment problem*) (Lawler 1963). Šiuo metu egzistuoja aštuonios pagrindinės skruzdžių sistemos atmainos, o kasmet pasiūlomos esančių atmainų modifikacijos.

Optimizavimas skruzdžių kolonija, kaip metaeuristika yra bendras taisyklių rinkinys, kuris nenusako, kaip taikyti jas vaizdams apdoroti. Taip pat nėra žinoma, kuriuos vaizdų apdorojimo būdus tikslinga pagrįsti OSK. Dar pilnai neištirtas OSK našumas juos įgyvendinant šiuolaikiniuose įrenginiuose, grįstuose lauku programuojamomis loginėmis matricomis (LPLM).

Darbo aktualumas

Vaizdo pirminis apdorojimas – neišvengiamas procesas, reikalingas rengiant vaizdą tolimesnei analizei. Įprasti vaizdų apdorojimo metodai tinka, kai vaizdo apdorojimo operatorių seka yra aiški ir tinka plačiam ratui panašių vaizdų. Tokią vaizdo apdorojimo seką parenka programuotojas. Kartais reikalinga vaizdui apdoroti operacijų seka nėra aiški ir jos parinkimas ilgai trunka. Dažnai keičiant seką, taikant ją prie skirtingų vaizdų, laiko sąnaudos smarkiai išauga.

Evoliucinių skaičiavimų metodai, tokie kaip genetiniai algoritmai ir genetinis programavimas yra taikomi vaizdams apdoroti, tačiau spiečiaus sumanumu grįstų metodų atšaka yra palyginus nauja ir nepakankamai ištirta. OSK – vienas iš spiečiaus sumanumu grįstų metodų, kuris gali būti taikomas vaizdų apdorojime, tačiau jo taikymo galimybės vaizdams nėra pakankamai ištirtos.

Taip pat mažai ištirti OSK metodų įgyvendinimo būdai įterptinėse sistemose, kurios vis dažniau naudoja lauku programuojamas logines matricas (LPLM) pasižyminčias perprogramavimo lankstumu.

OSK taikymas galėtų palengvinti pirminį vaizdų apdorojimą, automatizuojant vaizdų apdorojimo operatorių sekų parinkimą. OSK naudojimas vaizdų segmentavime galbūt leistų atlikti tikslesnį objektų atskyrimą. OSK įgyvendinimas LPLM galimai paspartintų optimizavimo uždavinių vykdymą įterptinėse sistemose.

Tyrimų objektas

Tyrimų objektas yra vaizdų apdorojimo skruzdžių kolonijomis technologijos ir su jomis susieti dalykai: optimizavimo skruzdžių kolonijomis algoritmai, vaizdų apdorojimo metodai ir jų įgyvendinimas lauku programuojamomis loginėmis matricomis.

Darbo tikslas

Darbo tikslas yra pasiūlyti ir ištirti optimizavimu skruzdžių kolonijomis grįstus vaizdų apdorojimo būdus ir priemones.

Darbo uždaviniai

1. Atlikti analitinę optimizavimo skruzdžių kolonijomis technologijų literatūros apžvalgą, pagrindžiant konkrečių vaizdų apdorojimo būdų ir skruzdžių kolonijų atmainų parinkimą tolimesniems tyrimams.
2. Remiantis optimizavimo skruzdžių kolonijomis metaeuristika, pasiūlyti ir ištirti originalias vaizdų apdorojimo metodikas.
3. Ištirti galimybę įgyvendinti optimizavimą skruzdžių kolonijomis įterptine sistema, grindžiama lauku programuojama logine matrica.

Tyrimų metodika

Darbe taikomos optimizavimo skruzdžių kolonijomis, vaizdų pirminio apdorojimo ir segmentavimo teorijos. Kompiuterinis modeliavimas atliekamas taikant MATLAB™ programą. Algoritmai įgyvendinami C programavimo kalba, taikoma specializuota LPLM įranga ir jos programavimo priemonės: Xilinx EDK su MicroBlaze programiniu procesoriumi.

Darbo mokslinis naujumas ir jo reikšmė

1. Sukurta nauja vaizdų pirminio apdorojimo, grįsta max-min skruzdžių sistema, metodika. Šios metodikos taikymas leidžia automatizuoti pirminį vaizdų apdorojimą.
2. Sukurta nauja vaizdų segmentavimo, grįsta daugelio skruzdžių kolonijų varžymusi, metodika. Šios metodikos taikymas lemia tikslesnį susiliejusių baltymų pėdsakų segmentavimą.
3. Gauti našumo įvertinimo rezultatai, įgyvendinant skruzdžių sistemą lauku programuojamoje loginėje matricoje. Parodyta kaip optimizavimą skruzdžių kolonijomis našiai įgyvendinti įterptinėse sistemose.

Darbo rezultatų praktinė reikšmė

Sukurtą vaizdų pirminio apdorojimo max-min skruzdžių sistemą galima taikyti kaip universalią priemonę, leidžiančią parinkti vaizdo apdorojimo operatorių seką duotam vaizdo apdorojimo uždaviniui spręsti. Vaizdų pirminis apdorojimas tampa daug patogesnis, nes sistema automatiškai, atsižvelgiant į pirminį ir galutinį vaizdus, parenka vaizdų apdorojimo operatorių seką.

Vaizdų segmentavimo OSK metodika lemia tikslesnį nespalvotų vaizdų segmentavimą, todėl galima būti sėkmingai taikoma: apsaugos video sistemose (naktį filmuotiems vaizdams), medicinoje (rentgeno, ultragarso ir pan. vaizdams), biochemijoje (vienmatės ar dvimatės elektroforezės gelių vaizdams).

OSK įgyvendinimo LPLM rezultatai taikyti sėkmingai užbaigtame Valstybinio mokslo ir studijų fondo remtame mokslininkų grupių projekte „Skruzdžių kolonijų optimizavimo įgyvendinimas lauku programuojamomis loginėmis matricomis“ (registracijos Nr. T-08127, sutarties Nr. T-112/08). Parodyta, kad OSK galima įgyvendinti LPLM įrenginiuose, kuriant šiuolaikinius, nedidelių gabaritų, tačiau našius prietaisus.

Ginamieji teiginiai

1. Sukurta nauja vaizdų pirminio apdorojimo, grįsta max-min skruzdžių sistema, metodika, esant sudėtingiems sprendimams, apie 30 % greičiau randa sprendinį nei bendrinė max-min skruzdžių sistema be pradinės skruzdžių padėties valdymo.
2. Sukurta nauja vaizdų segmentavimo, grįsta daugelio skruzdžių kolonijų varžymusi, metodika leidžia gauti virš 60 % geresnius baltymų pėdsakų segmentavimo rezultatus nei taikant slenksčio funkcija dvimatės elektroforezės gelių vaizdams su susiliejusiais baltymų pėdsakais.
3. Įgyvendinant skruzdžių sistemą lauku programuojamoje loginėje matricoje galima pasiekti 1,9 karto didesnį veikimo greitį, naudojant slankaus kablelio modulį ir 32 bitų daugiklį, lyginant su įprastu MicroBlaze procesoriumi be papildomų modulių.

Darbo rezultatų aprobavimas

Darbo rezultatai pateikti 6 straipsniuose, 5 iš kurių yra paskelbti recenzuojamose mokslo žurnaluose. Taip pat rezultatai paviešinti 10 mokslinių konferencijų:

- 13-toje tarptautinėje konferencijoje „Elektronika“, 2009, Kaunas, Vilnius, Lietuva;
- 1-oje tarptautinėje konferencijoje „Bio-Inspired Signal and Image Processing“, 2008, Varšuva, Lenkija;
- 12-toje tarptautinėje konferencijoje „Elektronika“, 2008, Kaunas, Vilnius, Lietuva;

- XI-toje Lietuvos jaunųjų mokslininkų konferencijoje „Mokslas – Lietuvos ateitis“, Elektronika ir Elektrotechnika, 2008, Vilnius, Lietuva;
- 11-toje tarptautinėje konferencijoje „Elektronika“, 2007, Kaunas, Vilnius, Lietuva;
- Tarptautinėje konferencijoje „International Conference on Fundamentals of Electrotechnics and Circuit Theory“, 2007, Gliwice, Ustron, Lenkija;
- X-toje Lietuvos jaunųjų mokslininkų konferencijoje „Mokslas – Lietuvos ateitis“, Elektronika ir Elektrotechnika, 2007, Vilnius, Lietuva;
- 10-toje tarptautinėje konferencijoje „Elektronika“, 2006, Kaunas, Vilnius, Lietuva;
- IX-toje Lietuvos jaunųjų mokslininkų konferencijoje „Mokslas – Lietuvos ateitis“, Elektronika ir Elektrotechnika, 2006, Vilnius, Lietuva;
- 5-toje tarptautinėje konferencijoje „Transport Systems Telematics“, 2005, Gliwice, Ustron, Lenkija.

Disertacijos struktūra

Disertaciją sudaro: įvadas, keturi skyriai, bendrosios išvados, literatūros sąrašas su atskirai pateiktomis autoriaus publikacijomis ir priedais.

Pirmame skyriuje atliekama evoliucinių technologijų vaizdams apdoroti analitinė apžvalga. Nagrinėjama OSK vieta evoliuciniuose skaičiavimuose, evoliucinių technologijų raida ir klasifikacija, tinkamumas vaizdams apdoroti, įgyvendinamumas bei formuluojami disertacijos uždaviniai.

Antrame skyriuje nagrinėjama vaizdų pirminio apdorojimo problema, naudojant max-min skruzdžių sistemą. Pateikiamos max-min skruzdžių sistemos modifikacijos, taikant ją vaizdams apdoroti, siūlomi patobulinimai, skirti pagreitinti sistemos veikimą, atliekami pasiūlytų patobulinimų eksperimentiniai tyrimai.

Trečiame skyriuje nagrinėjama vaizdų segmentavimo problema, taikant OSK. Pasiūloma ir detalizuojama daugelio skruzdžių kolonijų varžymosi grįsta metodika, tinkanti vaizdams segmentuoti. Atliekami siūlomos metodikos eksperimentiniai tyrimai.

Ketvirtame skyriuje nagrinėjama OSK įgyvendinimo LPLM įrenginyje problema. Išanalizuojamos įgyvendinimo galimybės, įgyvendinamas pseudo atsitiktinių skaičių generatorius bei skruzdžių sistema. Atliekamas įgyvendintos skruzdžių sistemos našumo eksperimentinis tyrimas, įvertinama įvairių modulių įtaka vykdomų skaičiavimų greičiui. Eksperimentiniams tyrimams, naudojamas keliaujančio prekeivio uždavinys, sprendžiamas perrinkimo metodu ir skruzdžių sistema.

Disertacijos pabaigoje apibendrinami darbo rezultatai ir pateikiamos bendrosios išvados. Priede pateikiamas disertacijoje naudotų sąvokų žodynas.

Bendrosios išvados

Disertacijoje pasiūlyti ir ištirti optimizavimu skruzdžių kolonijomis grįsti vaizdų apdorojimo būdai ir priemonės bei gauti šie Elektros ir elektronikos inžinerijos mokslo krypčiai svarbūs rezultatai:

1. Sukurta nauja vaizdų pirminio apdorojimo, paremto max-min skruzdžių sistema, metodika, kuri, esant sudėtingiems sprendiniams, randa sprendinį 30 % greičiau nei bendrinė max-min skruzdžių sistema be pradinio skruzdžių padėties valdymo.
2. Sukurta nauja vaizdų segmentavimo, paremto daugelio skruzdžių kolonijų varžymusi, metodika leidžianti gauti daugiau nei 60 % tikslesnius susiliejusių baltymų pėdsakų dvimatės elektroforezės gelių vaizduose segmentavimo rezultatus nei taikant slenksčio funkciją.
3. Atlikti skruzdžių sistemos įgyvendinimo lauku programuojamoje loginėje matricoje tyrimai, lyginant su įprastu MicroBlaze procesoriumi be papildomų modulių, leido pasiekti 1,9 karto didesnę veikimo spartą, sprendžiant keliaujančio prekeivio užduotį, naudojant slankaus kablelio modulį ir 32 bitų daugiklį.
4. Parengtos šios rekomendacijos:
   - Vaizdų pirminio apdorojimo metodikoje, naudojant max-min skruzdžių sistemą, rekomenduojama pradinį skruzdžių dėstymą atlikti perkeliant 20 % skruzdžių.
   - Vaizdų segmentavimo, paremto daugeliu skruzdžių kolonijų varžymusi, metodikoje rekomenduojama segmentavimo procesą stabdyti remiantis skruzdžių populiacijos dydžio svyravimais.
   - Įgyvendintos daugialusčiame LPLM įrenginyje su MicroBlaze programiniu procesoriumi skruzdžių sistemos parametrus rekomenduojama keisti remiantis skruzdžių sistemos sprendinio standartiniu kvadratiniu nuokrypiu.

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ANT COLONY TECHNOLOGIES
FOR IMAGE PROCESSING

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SKRUZDŽIŲ KOLONIJŲ TECHNOLOGIJOS
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