「様式３」

課題番号 ：P-15

Space and Time Extremely High Performance Algorithms and Models for Image Information Processing

[1] Organization

Project Leader: *Reneta P. Barneva* (Department of Computer Science, SUNY Fredonia, USA)

Representative at RIE: *Vygantas Mizeikis* (Research Institute of Electronics, Shizuoka University)

Participants:

Valentin E. Brimkov (Mathematics Department, Buffalo State College, State University of New York, USA)

Daniel D. Cunningham (Mathematics Department, Buffalo State College, State University of New York, USA)

Antoine Deza (Department of Computing and Software, Faculty of Engineering, McMaster University, Canada)

José Ramón Dorronsoro (Telecommunications and Computing Department, Escuela Politécnica Superior, Universidad Autónoma of Madrid (UAM) and Instituto de Ingeniería del Conocimiento (IIC), UAM, Spain)

Rémy Malgouyres (IUT Department of Informatics, Université d'Auvergne (Clermont 1), France)

Vygantas Mizeikis (Research Institute of Electronics, Shizuoka University, Japan)

Volodymyr Gnatyuk (V.E. Lashkaryov Institute of Semiconductor Physics, National Academy of Sciences of Ukraine)

Kostadin Koroutchev (Universidad Autónoma of Madrid, Spain)

Alberto Suarez (Universidad Autónoma of Madrid, Spain)

Akira Takahashi (Faculty of Informatics, Shizuoka University)

Sergey Gagarsky (Quantum Electronics and Biomedical Optics Department, State University of Information Technologies, Russia)

Michael Vynnycky (Department of Mathematics and Statistics, University of Limerick, Ireland)

Robert Olson (Department of Computer Science, SUNY Fredonia, USA)

Rossen Kostadinov (Faculty of Arts and Philosophy, Universidad Autonoma de Madrid, Spain)

Boris Brimkov (Department of Computational and Applied Mathematics, Rice University, USA)

Andrew David Speers (Department of Computer Science and Engineering, Faculty of Engineering, York University, Canada)

Carlos Asencio Pizarro (Departamento de Ingenieria Informatica, Escuela Politecnica Superior, Universidad Autonoma de Madrid, Spain)

Kamen Kanev (Graduate School of Informatics, Shizuoka University)

[2] Progress of the Research

The participants had active scientific collaboration through electronic media and a face-to-face Workshop January 27-31, 2014 at which some of them met. They reported the achieved results, exchanged ideas about future join work, and discussed possibilities for further cooperation between the institutions.

Apart from the specific results described in the next section, the team members were involved in the organization of several major international forums and in the publishing of a special issue of a reputable journal, both of them devoted to topics of the project.

- Several project members are also involved in the organization of the *16th International Workshop on Combinatorial Image Analysis*, to be held in May 2014 in Brno Czech Republic. Prof. Reneta P. Barneva is a Program and Publication Chair. Profs. Valentin Brimkov and Kostadin Koroutchev are members of the Steering Committee as the former is also an invited speaker. The proceedings of the workshop are submitted and will be published in Lecture Notes in Computer Science, Springer [1].
- Prof. Antoine Deza was the organizer of the *Retrospective Workshop on Discrete Geometry, Optimization, and Symmetry,* held at the Fields Institute, Toronto, Ontario, November 25-29, 2013. The workshop attracted participants from such prestigious universities as MIT, Stanford, Vanderbuilt, Tokyo University of Technology, University

College London, Universidad Nacional Autónoma de México, and others. The abstracts of the talks are available at [2].

- Prof. Antoine Deza was the organizer of the *Second Industry-Academic Workshop on Optimization in Finance and Risk Management*, attracting experts from different areas. It was also held at the Fields Institute, Toronto, Ontario, in September 23-24, 2013. Some of the industrial participants were from top institutions as IBM, Goldman Sachs Asset Management, Bank of Montreal, Royal Bank of Canada, Scotiabank, and others [3].
- Prof. Kamen Kanev was a PC Chair of the 16th International Conference on Humans and Computers held at Shizuoka University and jointly organized with the iCAST2013 and UMEDIA2013 conferences and the International Symposium on Spatial Media (ISSM'13-'14).
- Dr. Volodymyr Gnatyuk was a member of the International Committee of The 14th International Young Scientists Conference "Optics and High Technology Material Science" (SPO 2014), held at the Faculty of Physics of Taras Shevchenko National University of Kyiv, Ukraine, October 24-27, 2013.
- Dr. Volodymyr Gnatyuk presented the project-related results at The 12th International Conference on Global Research and Education: Inter-Academia-2013, held at the University of Sofia, Bulgaria, September 23-27, 2013.
- Dr. Volodymyr Gnatyuk reported the review of the laser marking and encoding results at the Cooperative Research Workshop "Imaging Devices and Digital Imaging of Semantic Surfaces in Active Knowledge Management", held at RIE, Shizuoka University, Hamamatsu, Japan, November 15, 2013.
- A special issue of *Annals of Mathematics and Artificial Intelligence (Springer)*, edited by Profs. Barneva and Brimkov, is being prepared for publication [4]. The issue is still a work in progress, but is expected to appear soon. All accepted papers are of very high quality and some of them are directly related to the theme of the Cooperative Research Project (for example, the papers "Efficient Segmentation with the Convex Local-Global Fuzzy Gaussian Distribution Active Contour for Medical Applications," "Cellular Topology and Topological Coordinate Systems on the Hexagonal and on the Triangular Grids," "Convenient Adjacencies for Structuring the Digital Plane," "On 2D Constrained Discrete Rigid Transformations," and "Contextual Array Grammars and Array P Systems."

[3] Results

(3.1) Research results

The ***twelve significant results*** obtained in the framework of the Cooperative Research Project can be grouped into the following ***six*** major themes:

Time- and space-efficiency of embedded software of graphical intelligent peripherals.

1) In [5] the authors discuss the design and development of an improved CLUSPI method for augmented computer vision and positioning of autonomous agents in indoor settings. The method employs environmental patterns posted on walls, ceilings, floors, and other surrounding surfaces that are accessible for digital imaging. Such patterns are blended into the environment as decorative elements where the encoding and decoding is based on orientation and clustering of artistic figures. As part of this work a specialized client-server system for multi-platform experiments with various environmental codes and imaging devices have been implemented. Conducted experiments indicate robust and reliable code extraction with extremely high recognition rates in most practical setups.

2) and 3) Works [6, 7] present the design and implementation of time- and space- efficient algorithms for the purposes of CLUSPI application on large surfaces. Various laser-assisted technological approaches and methods suitable for optical recording of digital information by creation of micromarks (data bits, pixels, and other information carriers) in the bulk of materials, transparent for a selected laser wavelength are evaluated and discussed. A marking center refers to a local area with optical properties different from the ones of the bulk obtained in result of actions of short laser pulses tightly focused in the volume of a transparent dielectric. Depending on the characteristics of laser pulses (wavelength and duration), selected materials (such as glass, plastic, organic medium, etc.) and irradiation conditions, a resulting laser-induced mark can be a point microcrack or void (pore), parameterized centers with different sizes

and orientations, colored or light emitting centers, as well as any other local inhomogeneity caused by thermal breakdown, optical excitation, chemical reaction or burning of material. Laser-induced marks with varying appearance (or data pixels) can serve as multi-bit information carriers that open a wide range of new possibilities for marking, encoding, and recording of digital information and creation of images.

Mathematical models of high performance time and space algorithms for image information processing.

4) Differentials estimation of discrete signals is almost mandatory in digital segmentation. A previous work by team members, introduced fast level-wise convolution (LWC) with time-complexity $O(n \log m)$. The research was continued, as convergence proofs were devised for two LWC compatible kernel families [8]. The first one is the pseudo-binomial family, and the second one is the pseudo-Gaussian family. The proposed method was experimentally compared to the Digital Straight Segment tangent estimator. Tests are done on different digitized objects at different discretization step using the DGtal library.

5) A major problem in computer graphics, image processing, numerical analysis and other applied areas is constructing a relevant object discretization. In a recent work, a project team member investigated an approach for constructing a connected discretization of a subset A of the n-dimensional Euclidean space by taking the integer points within an offset of A of a certain radius. The minimal value of the offset radius which guarantees connectedness of the discretization was determined, provided that set A is path-connected. In [9] these results have been essentially strengthened by proving that the same results hold when A is connected, but not necessarily path-connected. Moreover, it is demonstrated that similar facts hold about Hausdorff discretization, thus generalizing known results of other researchers.

Efficient algorithms for solving problems on maps.

Given a finite set of straight-line segments S in the plane, one considers the problem of finding a minimum in size set V of points on the segments, such that each segment of S contains at least one point in V. This problem was called guarding a set of segments (GSS). GSS is a special case of the set cover problem where the given family of subsets can be taken as a set of intersections of the straight line segments in S. Requiring that the given subsets can be interpreted geometrically this way is a major restriction on the input, yet it has been shown that the problem is still strongly NP-complete. GSS is relevant to any physical structure that can be modelled by a finite set of straight-line segments. Examples could be a network of streets in a city, tunnels in a mine, corridors in a building or pipes in a factory. One looks for a minimum number of locations at which to place ‘guards’ in a way that any point of the structure can be ‘seen’ by at least one guard (assuming guards have infinite visibility range in all directions, but cannot see around corners). An equivalent problem is to find a minimum number of locations to place ‘terminals’ so that any point of the network has a direct access to at least one ‘terminal’ at all times.

6) In previous work by a project team member the GSS approximability was studied both theoretically and experimentally. These investigations were continued as part of the project. In [10] further results were obtained that shed more light on GSS approximability. In particular, conditions were found under which GSS defined on drawings of arbitrary (not necessarily planar) graphs admits good approximation. As a consequence, other more general results about GSS approximability were obtained. Thus it was shown that GSS on a segment set with almost tree (1) structure is $(2 - \varepsilon)$-approximable for $0 < \varepsilon \leq 1$, and that GSS on a random graph drawing is almost surely 2-approximable.

Computational and geometric approach to colorful simplicial depth – a problem without a known polynomial time algorithm.

7) The research activities around the colorful simplicial depth and the colorful linear programming feasibility problem resulted in a series of recent advances. A significant lower bound improvement by team was made in [11] by employing a purely combinatorial approach.

More specifically, the colorful simplicial depth conjecture states that any point in the convex hull of each of $d + 1$ sets, or colours, of $d+1$ points in general position in $\mathbf{R}^d$ is contained in at least $d^2 +1$ simplices with one vertex from each set. In [11] the conjecture was verified in dimension 4 and the known lower bounds were strengthened in higher dimensions. These results are obtained using a combinatorial generalization of colorful point configurations called octahedral systems. New properties of octahedral systems were obtained, generalizing earlier results on colorful point configurations and exhibiting an octahedral system which cannot arise from a colorful point configuration. The number of octahedral systems is also given.

Space-efficient algorithms for graph problems related to image processing

8) The shortest path problem is fundamental to many areas of image processing. In [12], approaches were presented that allow solving the problem in environments where computation space is scarce. Two constant-work-space algorithms are proposed for solving the shortest path problem for cactus graphs and clique-cactus graphs of arbitrary size. Both algorithms perform in polynomial time. Moreover, an in-place algorithm for finding the shortest path in cactus graphs is presented, which performs in polynomial time of lower degree.

As an image can easily be modeled by its adjacency graph, graph theory and algorithms on graphs are widely used in imaging sciences. In [13] and [14] we study the problem of finding the maximal cliques of the intersection graphs of certain polygons. Intersection graphs appear applicable to numerous research domains, in particular computer imagery. A major application is found in representation and visualization of relations among objects in a scene. This includes data visualization for the purposes of software engineering, drawing Euler diagrams, visualization of overlapping clusters on graphs, video database queries; in graph-based recognition and visualization of grid patterns in street networks, solid intersection, and contingency tables. Moreover, intersection graph-based discrete models of continuous n-dimensional spaces have been developed to solve problems of surface graphics. Algorithms for maximal clique computation are applicable to computer graphics and image analysis. Thus, maximal clique computation has been applied to image segmentation and to deformable object model learning in image analysis. Maximal clique computation on certain intersection graphs is also relevant to problems of computer vision and computer graphics, as well as to visualization in natural sciences. For samples of the above-mentioned applications see [14] and the references therein.

9) We presented results which extended and generalize ones related to studies on max-tolerance, semi-square, and convex polygon intersection graphs. We considered the maximal clique problem defined on intersection graphs of convex polygons, quasi-homothetic trapezoids, and homothetic triangles, the latter being equivalent to the max clique problem defined on max-tolerance graphs. For the case of quasi-homothetic trapezoid graph studied in [13], we showed that the number of maximal cliques in such graphs is $\Theta(n^3)$ which improved the previously known $\Theta(n^4)$ bound. We also presented a space-efficient in-place algorithm for finding the maximum clique on such graphs. We reported experimental results of a computer implementation of our algorithm on randomly generated sets of polygons of the considered type. The experiments confirmed the expected cubic regression for the number of maximal cliques in semi-square graphs, which has been proved only for an artificially constructed class of instances. Other experiments showed that the well-known Lovasz theta function approximates very well the clique number for the considered classes of graphs.

10) In [14] we studied the maximal clique problem on intersection graphs of convex polygons. We presented results which refine or improve some of the results recently proposed by others. Thus, it was shown therein that an intersection graph of n convex polygons whose sides are parallel to k different directions has no more than n^{2k} maximal cliques. We proved that the number of maximal cliques does not exceed n^k. Moreover, we showed that this bound is tight for any fixed k. We also discussed algorithmic aspects.

Other research problems and results

In addition to the basic project tasks considered above, team members carried out research on other important problems related to the general project theme.

Combinatorics on words with applications to pattern matching problems

The characterization and detection of repetitive structures arises in a variety of applications in imaging sciences. In fact, studying repetitions, periodicities, and other similar regularities play a central role in various facets of computer science and subtend properties that are either interesting and deep from the standpoint of combinatorics, or susceptible to exploitation in tasks of automated inference and data compression, or both. In strings, the notions of a *repetition* or *square* (i.e., two consecutive occurrences of a same primitive word), is intermingled with the dawn of language theory and combinatorics on strings.

In the framework of the Cooperative Research Project, the following two problems have been considered.

11) Fraenkel and Simpson conjectured in 1998 that the number of distinct squares in a string is at most its length. Kolpakov and Kucherov conjectured in 1999 that the number of runs in a string is also at most its length. Since then, both conjectures attracted the attention of many researchers and many results have been presented, including asymptotic lower bounds for both, asymptotic upper bounds for runs, and universal upper bounds for distinct squares in terms of the length. In [15], a project team member proposed a parametrized approach for estimating the maximal number of squares and runs in a string. The approach provides a computationally efficient framework allowing to confirm and extend earlier experimental results by other researchers.

12) Recently, efforts have been made at generalizing clever string searching techniques, notions and results to structures of higher dimensions, particularly two-dimensional arrays, where texts and patterns can be considered as “bit-map” images, represented by matrices of pixels and stored in a database. This is naturally driven by various applications to *pattern recognition*, low level *image processing*, *computer vision* and, more recently, *multimedia*.

Combinatorial pattern matching problems have been studied in the framework of diverse computation models and settings. Numerous algorithms exist (mostly for problems on strings), including optimal sequential algorithms, online algorithms, algorithms that solve a problem in real time, or ones that use only constant auxiliary space in addition to the input. In [16] we introduce the reader to parallel computation approach for pattern matching problems. We discuss the basic steps of a parallel algorithm design, illustrating them by author's results on the problem of detecting all two-dimensional repetitions in a two-dimensional array.

(3.2) Future work

The obtained theoretical results laid out a basis for solving various practical problems. The team is considering extending the work for new models and algorithms. Of special interest are the results for mobile devices.

In the framework of the research meetings and visit exchange, ways to deepen the collaboration were outlined.

[4] Publications

(1) Barneva, R.P., Brimkov, V.E., Slapal, J, (Eds.) Computational Image Analysis, *Springer Verlag*, LNCS, Vol. 8466, Heidelberg-Berlin, 2014.

(2) http://www.fields.utoronto.ca/programs/scientific/13-14/discretegeom/Abstracts.html

(3) http://www.fields.utoronto.ca/video-archive/event/192/2013.

(4) Brimkov, V.E., Barneva, R.P. (Eds.), *Annals of Mathematics and Artificial Intelligence* (Springer), to appear in 2014.

(5) Barneva, R., Kanev, K., Mochiduki, Sh., Position Encoding and Localization with Environmental Patterns, *Western New York Image Processing Workshop*, Rochester Institute of Technology, November 2013, pp. 43-46.

(6) Zelenska, K.S., Zelensky, S.E., Poperenko, L.V., Rozouvan, S.G., Kanev, K., Mizeikis, V., Gnatyuk, V.A., Thermal mechanisms of laser marking in transparent polymers with light-absorbing microparticles, *Journal of Physics: Conference Series*, to appear.

(7) Gnatyuk, V.A., Vlasenko, O.I., Levytskyi, S.N., Kanev, K., Mizeikis, V., Aoki, T., Gagarsky, S.V., Poperenko, L.V., Zelenska, K.S., Statsenko, A.O., Features of laser-induced damage and creation of marking centers in digital material processing, *Journal of Physics: Conference Series*, to appear.

(8) Gonzalez, D., Malgouyres, R., Esbelin, H.-A., Samir, Ch., Convergence of Level-Wise Convolution Differential Estimators, *Proc. Discrete Geometry for Computer Imagery*, 2013, pp. 335-346.

(9) Brimkov, V., On Connectedness of Discretized Objects, G. Bebis et al. (Eds.): ISVC 2013, Part I, *LNCS (Springer)* 8033, pp. 246–254, 2013.

(10) Brimkov, V.E., Approximability issues of guarding a set of segments, *International Journal of Computer Mathematics*, Taylor & Francis, pp. 1653-1667 (2013).

(11) Deza, A., Meunier, F., Sarrabezolles, P., A combinatorial approach to colourful simplicial depth. *SIAM Journal on Discrete Mathematics* 28 (2014) 306 - 322.

(12) Brimkov, B., Memory Efficient Shortest Path Algorithms for Cactus Graphs, G. Bebis et al. (Eds.): ISVC 2013, Part I, *LNCS* (Springer) 8033, pp. 476–485, 2013.

(13) Brimkov, V.E., S. Kafer, M. Szczepankiewicz, J. Terhaar, Maximal cliques in intersection

graphs of quasi-homothetic trapezoids, *Proc.MCURCSM'13*, Ohio, paper No 10, 10 pp. (2013).

(14) Brimkov, V.E., S. Kafer, M. Szczepankiewicz, J. Terhaar, On Intersection Graphs of Convex Polygons, Proc. 16th International Workshop on Combinatorial Image Analysis, *Lecture Notes in Computer Science*, to appear.

(15) Deza, A., Franek, F, A *d*-step approach to the maximum number of distinct squares and runs in strings. Discrete Applied Mathematics 163 (2014) 268–274.

(16) Brimkov, V.E., Parallel algorithms for combinatorial pattern matching, *16th International Workshop on Combinatorial Image Analysis*, *Lecture Notes in Computer Science*, to appear.

「様式３」

Travelling report

Name:	Reneta Barneva
Affiliation:	State University of New York at Fredonia, USA
Period of time:	January 23, 2014 – February 1, 2014
Destination:	Research Institute of Electronics, Shizuoka University, Japan
Purpose:	Participation in the Planning and Coordination Meeting of the 2013-14 Cooperative Research Project and the related workshop, Research Institute of Electronics, Shizuoka University, Hamamatsu. Giving a talk “Digital Geometry Algorithms and Models for Advanced Imaging Devices” and moderating a round table discussion about the possibilities of institutional cooperation.
Name of receiver:	Prof. Kamen Kanev

Name:	Valentin Brimkov
Affiliation:	State University of New York at Fredonia, USA
Period of time:	January 23, 2014 – February 1, 2014
Destination:	Research Institute of Electronics, Shizuoka University, Japan
Purpose:	Participation in the Planning and Coordination Meeting of the 2013-14 Cooperative Research Project and the related workshop, Research Institute of Electronics, Shizuoka University, Hamamatsu. Giving a talk entitled “Complexity and Approximability Issues in Image Analysis.”
Name of receiver:	Prof. Kamen Kanev