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Space and Time Efficient Image Information Processing: Paradigms and Prototypes

[1] Organization

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[2] Progress of the Research

This project is a continuation of the previous successful project conducted from May 2011 to March 2012. In the period of the current project 2012/05/23 - 2013/03/08 the team worked on several research tasks as outlined in project description. Apart from the electronic communication through e-mail, Skype, and phone, we exchanged research visits, had face-to-face meetings, and attended together conferences and workshops. In addition to the meetings and visits funded by the grant and listed at the end of the report, Prof. *Kamen Kanev* visited SUNY Fredonia hosted by Prof. *Reneta Barneva* and delivered two talks and Prof. *Valentin E. Brimkov* visited Université d'Auvergne hosted by Prof. *Rémy Malgouyres* and delivered a talk.

Several project members were also involved in the organization of the 15th International Workshop on Combinatorial Image Analysis, held in November 2012 in Austin, TX, USA. General Chair of the conference was Prof. *Valentin Brimkov*. Prof. *Reneta P. Barneva* was a Program and Publication Chair. Profs. *Kostadin Koroutchev* and *Valentin Brimkov* were members of the Steering Committee, Prof. *Rémy Malgouyres* was a member of the Program Committee, and Prof. *Reneta Barneva* served as Chair of the Organizing Committee. The proceedings of the workshop were published in Lecture Notes in Computer Science, Springer [1].

Another conference that gathered many project participants was the 15th International Conference on Humans and Computers held in Shizuoka, Japan, February 11-12, 2013. *Prof. Kanev* was

Program Chair and member of the International Advisory Committee; *Prof. Barneva* was invited speaker [2]. They as well as *Drs. Michael Vynnycky* and *Volodymyr Gnatyuk* participated with presentations [3,4,5].

A special issue of International Journal of Computer Mathematics (Taylor and Francis), edited by Profs. *Brimkov* and *Barneva,* is prepared for publication [6]. The issue contains eight papers devoted to various theoretical and practical issues such as topology preserving hexagonal thinning; combinatorial algorithm to construct 3D isothetic covers; isoperimetrically optimal polygons in the triangular grid with Jordan-type neighborhood on the boundary; ischemic heart disease detection using support vector machines; Jordan curve theorem with respect to a pretopology on Z^2; singularity analysis in digital signals through the evaluation of their unpredictable point manifold; approximability issues of guarding a set of segments; and recognition of concurrency relations between inaccurate lines.

The work on the project resulted in obtaining a series of results on space and time efficient computation based on different models. Details are given in the next section.

[3] Results

(3.1) Research results

Results in the following four directions were achieved:

A. Mathematical foundations of image information processing. The models and paradigms used for image representation are critical for the time- and space-efficiency of the information processing. In many cases, the models should also allow deriving some geometrical properties such as area, distances, angles, and derivatives of the geometrical objects. The work [7] deals with estimation of differentials of discrete signals which is almost mandatory in digital segmentation. A new fast method was presented based on convolutions by a mask with a logarithmic number of constant layers. It was compared to other multigrid convergent methods in the field such as the Binomial Convolution, the Digital Straight Segment Tangent Estimator, and the Taylor Polynomial Fitting. Our convolution method's main advantage is its complexity of O(2n.log2(m)), which makes it competitive to the convolution by Fast Fourier Transform (FFT) latest implementation. The precision of the first order derivative estimation, its resistance to noise, and its convergence rate were tested.

Another work [8] introduces a new method to compute conformal parameterizations using a recent definition of discrete conformity, and establishes a discrete version of Riemann mapping theorem. The algorithm can parameterize triangular, quadrangular, and digital meshes. It can also be adapted to preserve metric properties. The efficiency of the method is demonstrated through extensive experiments.

B. Space and time-efficient algorithms for PDE models. An algorithm for one-dimensional time-dependent Stefan problems was extended for the purpose of solving one-phase ablation-type moving boundary problems; in tandem with the Keller box finite-difference scheme, the so-called boundary immobilization method was used. An important component of the work was the use of variable transformations that must be built into the numerical algorithm in order to preserve second-order accuracy in both time and space. The analysis also determined that the ablation front initially moves as the time raised to the power 3/2; hence, it evolves considerably more slowly than the phase-change front in the classical Stefan problem with isothermal cooling [9].

Another work deals with the accuracy of a finite-difference method for parabolic PDEs with discontinuous boundary conditions. Although the numerical solution of parabolic partial differential equations (PDEs) is widely documented, the effect of discontinuous boundary conditions on numerical accuracy is not. This work employs the Keller box finite-difference method to study the effect of such discontinuities when solving the linear 1D

transient heat equation. It demonstrates that, without due care, this formally second-order accurate scheme loses accuracy, but that an analytical understanding of the behaviour of the solution helps to reformulate the problem in a way that restores accuracy [10].

Yet another work considers scientific and technical applications that require the solution of the steady 3D Navier Stokes equations in slender channels or ducts; often, this is carried out using commercially available software which is unable to make use of the fact that the equations can be parabolized to give a formulation that, in terms of RAM and CPU time and random access memory (RAM) usage, is orders of magnitude cheaper to compute. Here, a velocity-vorticity formulation in commercial finite-element solver is implemented to tackle the weakly compressible parabolized steady 3D Navier Stokes equations in a channel with a permeable wall - a situation that occurs in polymer electrolyte fuel cells. Benchmarks results indicate at least a 30-fold saving in CPU time and a 70-fold saving in RAM usage, as compared to full 3D computations, without any discernible loss in accuracy [11].

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

Specialized pervasive encoding is well suited for localization and automated navigation in various robotic and assistive applications where it is applied mostly to confined interiors. Such encoding could be embedded in manufacturing, storage, and other facilities where robot-assisted delivery and product handling is in place as well as in smart homes for elderly and disabled where automated transportation and specialized services are provided. Extending the scope of such pervasive encoding to natural human habitats requires development of methods and technologies for i) seamless and unobtrusive integration of pervasive encoding patterns in human environments and ii) efficient and reliable extraction, recognition, and analysis of such codes. The study [5] is a continuation of our previous research on Environmental Codes for Autonomous Position Determination based on interior design patterns mainly for mobile robots and reported elsewhere. In this work we have shifted the focus to human users and explore possibilities for environmental code processing with widely used mobile devices such as smart phones. We discussed the organization and development of a novel server-client environment integrating Windows, Mac, and iOS systems and specifically designed to facilitate experimental work with mobile devices. Environmental encoding pattern recognition and localization experiments are currently conducted on iPhones and other iOS based devices with plans to expand to other platforms in the near future.

Another aspect is the creation of encoding areas inside different objects by laser volumetric marking [3,12]. Unique capacities of focused, short laser pulses, to create different kinds of marks (local structure damages, micro-cracks, voids, pores, optically active nanoparticles, light-emitting centers, and other optical inhomogeneities) in the volume of materials, which are transparent for the selected laser wavelength are studied. 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 volumetric parameterized marking, encoding, and recording of digital information. Results obtained in experiments with different approaches and laser techniques for creation, monitoring, and measurement of such marks are reported.

D. Study on efficiency of brain computations

The hypothesis of a common information-processing principle exploited by the brains evolved through natural evolution has been explored. A model combining recent advances in cognitive psychology and evolutionary neuroscience has been proposed and analyzed. The macroscopic effects associated with the intelligence-like structures postulated by the model has been investigated and discussed from a statistical mechanics point of view. As a result of this analysis, some plausible explanations have been presented concerning the disparities and similarities

in cognitive capacities which are observed in nature across species. An interpretation on the efficiency of brain's computations, as well as the behavioral differences between different species, including humans and chimpanzees has been largely discussed [13].

E. Computational and geometric approach to colorful simplicial depth

In statistics, there are several measures of the depth of a point p in dimension d relative to a fixed set S of sample points. One key depth measure, introduced by Liu in 1990, is the simplicial depth, which is the number of simplices generated by points in S that contain p. A point of maximum simplicial depth can be viewed as a type of d-dimensional median. A colourful generalization of the simplicial depth was introduced and a new parity property was proved. The work exhibited extremal d-dimensional configurations with points of low colorful simplicial depth, and provided the first upper bound for the minimal colorful depth $\mu(d)$ of a core point p for any generic configuration S. The first improvement since Bárány's 1982 result of the lower bound for $\mu(d)$ was obtained. The lower bound has since been improved by Bárány and Matoušek who verified that $\mu(3)=10$, and Deza et al. which includes the current strongest bound of $\mu(d) \geq d(d+7)/2-8$ for $d\geq 5$ and verified that $\mu(4)=17$. The colorful feasibility problem is the equivalent generalization of the linear programming feasibility problem; i.e., to express p as a colorful convex combination of points in S. While the monochrome version is the traditional linear programming feasibility problem, and therefore efficiently solvable, it is still not known if a polynomial time algorithm for the colorful feasibility problem exists. The recent publications relevant to this line of research include [14,15,16]

(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., Aggarwal, J.K., (Eds.) Computational Image Analysis, *Springer Verlag*, LNCS 7655, Heidelberg-Berlin, 2012.
2. Barneva, R.P., Space and time efficient algorithms in imaging sciences, The 15th International Conference on Humans and Computers (HC-2012), Electronic Abstracts Collection (Hamamatsu sessions), Paper No ID18, pp. 33. [11-12 February 2013, Aizu-Wakamatsu & Hamamatsu, Japan; Düsseldorf, Germany].
3. Gnatyuk, V.A., Kanev, K., Mizeikis, V., Aoki, T., Gagarsky, S.V., Poperenko, L.V., Volumetric marking with laser-induced parameterized centers, The 15th International Conference on Humans and Computers (HC-2012), Electronic Abstracts Collection (Hamamatsu sessions), Paper No ID12, pp. 20-21. [11-12 February 2013, Aizu-Wakamatsu & Hamamatsu, Japan; Düsseldorf, Germany].
4. Vynnycky, M., Kanev, K., The P3P Problem revisited, The 15th International Conference on Humans and Computers (HC-2012), Electronic Abstracts Collection (Hamamatsu sessions), Paper No ID08, pp. 13. [11-12 February 2013, Aizu-Wakamatsu & Hamamatsu, Japan; Düsseldorf, Germany].
5. Inoue, T., Mochiduki, S., Kanev, K., Barneva, R.P., Environmental Encoding Pattern Recognition and Localization with Mobile Devices, The 15th International Conference on Humans and Computers (HC-2012), Electronic Abstracts Collection (Hamamatsu sessions), Paper No ID17, pp. 31. [11-12 February 2013, Aizu-Wakamatsu & Hamamatsu, Japan; Düsseldorf, Germany].
6. Brimkov, V.E., Barneva, R.P. (Eds.), *International Journal on Computer Mathematics* (Taylor and Francis), http://www.tandfonline.com/action/showAxaArticles?journalCode=gcom20, to appear in printed version in 2013.
7. Gonzalez, D., Malgouyres, R., Esbelin, H.-A.,Samir, C., Fast level-wise convolution, Combinatorial Image

Analysis, Barneva, R.P., Brimkov, V.E., Aggarwal, J.K., (Eds.), *Springer Verlag*, LNCS 7655, Heidelberg-Berlin, 2012, pp. 223-233.

8. Cartade, C., Mercat, C., Malgouyres, R., Samir, C., Mesh parameterization with generalized discrete conformal maps, Journal of Mathematical Imaging and Vision, Springer, 2013, DOI 10.1007/s10851-012-0362-y
9. Mitchell, S. L., Vynnycky, M., An accurate finite difference method for ablation-type Stefan problems, *J. Comp. Appl. Math*. 236 (2012) 4181-4192.
10. Vynnycky, M., Mitchell, S. L., On the accuracy of a finite-difference method for parabolic PDEs with discontinuous boundary conditions, *Num. Heat Trans. B* (2012) submitted.
11. Vynnycky, M., Sharma, A. K., Birgersson, E., A finite-element method for the weakly compressible parabolized 3D Navier Stokes equations in a channel with a permeable wall, *Comput. Fluids* (2012) submitted
12. Gnatyuk, V.A., Kanev, K., Mizeikis, V., Aoki, T., Gagarsky, S.V., Poperenko, L.V., Laser marking and recording of digital information, Proceedings of The 11th International Conference on Global Research and Education in Engineers and Better Life: Inter-Academia-2012, (August, 2012) pp.189-200.
13. Chinea, A., Korutcheva, E., Intelligence and embodiment: A statistical mechanics approach, Journal on Neural Networks, DOI: 10.1016/j.neunet.2013.01.007, Reference: NN 3127.
14. Deza, A., Meunier, F., Sarrabezolles, P., A Combinatorial approach to colourful simplicial depth. AdvOL-Report 2012/4, McMaster University (2012) submitted.
15. Deza, A., Stephen, T., Xie, F., A note on lower bounds for colourful simplicial depth, *Symmetry* 5 (2013) 47 - 53.
16. Meunier, F., Deza, A., A further generalization of the colourful Carathéodory theorem. Discrete Geometry and Optimization, *Fields Institute Communications Series* 69 (to appear).

Travelling report

Name:	Reneta Barneva
Affiliation:	State University of New York at Fredonia, USA
Period of time:	February 9, 2013 – February 18, 2013
Destination:	Research Institute of Electronics, Shizuoka University, Japan
Purpose:	Participation in the 15th International Conference Human and Computers. Giving a talk "Space and Time Efficient Algorithms in Imaging Sciences." Discussing various tasks of the collaborative project research.
Name of receiver:	Prof. Kamen Kanev

Name:	Michael Vynnicky
Affiliation:	Department of Mathematics and Statistics, University of Limerick, Ireland
Period of time:	February 9, 2013 – February 19, 2013
Destination:	Research Institute of Electronics, Shizuoka University, Japan
Purpose:	Participation in the 15th International Conference Human and Computers. Giving a talk "The P3P Problem Revisited." Discussing various tasks of the collaborative project research.
Name of receiver:	Prof. Kamen Kanev