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## Extremely High Performance Algorithms and Models for Image Information Processing

### [1] Organization

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### [2] Progress of the Research

The participants had active scientific collaboration through electronic media and a face-to-face Workshop February 16-20, 2015 at which some of them met and reported the achieved

results, exchanged ideas about future joint work, and possibilities for cooperation between the institutions.

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

- Two project members were involved in the organization of the 16th International Workshop on Combinatorial Image Analysis, held in May 2014 in Brno, Czech Republic. Prof. Reneta P. Barneva was a Program and Publication Chair. Prof. Kostadin Koroutchev was a member of the Steering Committee.
- Profs. Barneva and Koroutchev are also playing key roles in the 17th International Workshop on Combinatorial Image Analysis, to be held in November 2015 in Kolkata, India. Prof. Reneta P. Barneva is a Program and Publication Chair and Prof. Kostadin Koroutchev is a member of the Steering Committee.
- A special issue of *Annals of Mathematics and Artificial Intelligence* (Springer), edited by Prof. Barneva has appeared online and soon will be published as hard copy as well. The papers are of very high quality and are directly related to the theme of the Research Cooperative Project: 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, Contextual Array Grammars and Array P Systems, and others.
- A special issue of *Discrete Applied Mathematics* (Elsevier) devoted to graph-theoretical problems has been approved and is a work in progress. Prof. Barneva serves as a

guest-editor. Several strong papers on characterization of absentee voxels, distance transformation on a triangular grid, transformations of digital spaces by contractions, and others related to the project theme have been submitted and are currently under review.

- Prof. Antoine Deza served as organizer of the Fields Industrial Optimization Seminar, Fields Institute, Toronto, in which speakers from McMaster University, Prosensus, Lehigh University, and Mitsubishi Electric Research Laboratories took part.
- Prof. Antoine Deza also served as organizer of the conference "Recent Advances in Linear Optimization" - RALO 2014, July 30-August 1, 2014, Ecole des Ponts ParisTech, Paris, France and 2014 CMS Winter Meeting "Recent Advances in Variational Analysis and Linear Optimization", December 5-8, 2014, Hamilton, Ontario.

### [3] Results

#### (3.1) Research results

Below is a brief explanation of the following results achieved:

A. Three-dimensional non-isothermal models for monolithic channels that seek to capture the local transport phenomena are computationally expensive. In this regard, we proposed a reduced model for a monolithic channel that reduces the computational cost, whilst preserving the 3D geometry and all of the essential physics – this is accomplished by exploiting the inherent slenderness of the monolith channel, coupled with scaling arguments, leading-order asymptotics and a fast space-marcher.

The model takes into account conservation of mass, momentum, species and energy coupled with chemical kinetics, and is demonstrated for a three-way reaction mechanism for treatment of automotive exhaust. The results of the reduced model are verified against those of the full model and experimentally validated. Overall, memory requirements and computing time are reduced by around 2–3 orders of magnitude as compared to the full set of equations [13].

B. The perspective 3-point problem, also known as pose estimation, has its origins in camera calibration and is of importance in many fields such as computer animation, automation, image analysis and robotics. One line of activity

involves formulating it mathematically in terms of finding the solution to a quartic equation. However, in general, the equation does not have a unique solution, and in some situations there are no solutions at all.

We proposed a new approach to the solution of the problem; this involves closer scrutiny of the coefficients of the polynomial, in order to understand how many solutions there will be for a given set of problem parameters. We found that, if the control points are equally spaced, there are four positive solutions to the problem at 25 % of all available spatial locations for the control-point combinations, and two positive solutions at the remaining 75 % [14].

C. We applied a recently derived numerical algorithm for one-dimensional time-dependent Stefan problems to the classical moving boundary problem that arises from the diffusion of oxygen in absorbing tissue. We used the so-called boundary immobilization method in tandem with the Keller box finite-difference scheme. Thus, we obtained new insights into three aspects of the problem: the numerical accuracy of the scheme used; the calculation of oxygen depletion time; and the behavior of the moving boundary as the oxygen is depleted [16].

D. We consider a mathematical problem constituting a two-phase moving boundary problem, for which usually asymptotic methods are employed for analysis. Non-dimensionalization yields a model with eighteen dimensionless parameters, but asystematic separation of time scales leads to a reduced model consisting of just a second-order differential equation with two initial conditions. The results of this asymptotic model are compared with those of earlier experimental and theoretical work and it is demonstrated that the current model would be a computationally efficient tool for this kind of problems [17].

E. An important application of imaging is in Internet advertising. It has witnessed growth of 15% in 2012, reaching \$36.6 billion in the United States. Guaranteed display advertising campaigns are typically for brand awareness where the industry practice is for ad networks to maximize representativeness, which is accomplished by displaying ads of each campaign as proportionally as possible to all targeted viewer types. Quadratic optimization programs for this problem have recently been developed. We pursue the quadratic objective function approach motivated in part by

the availability of advanced and efficient solvers. We introduce the model and formulate the joint chance constrained optimization program to solve the ad network's problem, discussing how lower and upper bounds can be found through sample approximations. We also present a convex approximation program, which can be used to find lower and upper bounds under different Internet viewer distribution assumptions [2].

F. An important question in image recognition is counting the types of squares in a string. In relation to this, we consider the problem of bounding the number of distinct squares in a string. Fraenkel and Simpson showed in 1998 that a string of length  $n$  contains at most  $2n$  distinct squares. Ilie presented in 2007 an asymptotic upper bound of  $2n - \Theta(\log n)$ . We show that a string of length  $n$  contains at most  $\lfloor 11n/6 \rfloor$  distinct squares. This new upper bound is obtained by investigating the combinatorial structure of double squares and showing that a string of length  $n$  contains at most  $\lfloor 5n/6 \rfloor$  particular double squares. In addition, the established structural properties provide a novel proof of Fraenkel and Simpson's result.

G. In relation to the design and implementation of time- and space- efficient algorithms for the purposes of CLUSPI application on large surfaces, laser-based technological approaches and methods suitable for volumetric optical recording of digital information and creation of images are considered. They are based on formation of different kinds of micromarks in the bulk of materials, transparent for a selected laser wavelength. The techniques are evaluated and discussed. Along with the analysis of formation of laser-induced parameterized centers with different geometries in glass, some emphasis is put on laser-induced creation of dark marks in organic materials, particularly in polystyrene containing light-absorbing inclusions.

Parameterized marks with varying appearance or data pixels can serve as multi-bit information carriers. The dominant mechanisms of laser radiation absorption and induced formation of marks in different transparent materials are discussed [4, 5].

H. Unlike traditional approaches, which are based on continuous models requiring float arithmetic computations and rounding, "combinatorial" (or "discrete") approaches are based on studying combinatorial properties of discrete structures. They provide models and algorithms, which often

appear to be more efficient and accurate than those based on continuous models. Some recent combinatorial approaches aim at constructing a self-contained digital topology and geometry, which might be of interest and importance not only for image analysis, but also as independent mathematical disciplines. The approach is used in binary image reconstruction from a small number of projections and morphological skeleton, to define the properties of support vectors of separating hyperplanes, for offline handwritten signature verification and others [1].

### (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., Combinatorial and discrete geometric problems in image analysis, *Annals of Mathematics and Artificial Intelligence* (Springer), December 2014, DOI 10.1007/s10472-014-9442-6.
- (2) Deza, A., Huang, K., Metel, M., Chance constrained optimization for targeted Internet advertising. *Omega - International Journal of Management Science* (Elsevier) 53 (2015) 90 - 96.
- (3) Deza, A., Franek, F., Thierry, A., How many double squares can a string contain? *Discrete Applied Mathematics* 180 (2015) 52 - 69.
- (4) Gnatyuk, V.A., Vlasenko, O.I., Levytskyi, S.N., Zelenska, K.S., Poperenko, L.V., Gagarsky, S.V., Laser marking in transparent materials and mechanisms of laser-induced defect formation, *The 16th Italian National Conference on Photonic Technologies (FOTONICA-2014), Abstracts, 2014, Abstract No P.1.35., May 2014, Naples, Italy.*
- (5) Gnatyuk, V.A., Vlasenko, O.I., Levytskyi, S.N., Zelenska, K.S., Poperenko, L.V., Gagarsky, S.V., Aoki, T., Laser marking in

- transparent materials and mechanisms of laser-induced defect formation (laser-induced marks as information carriers in digital encoding), 2014 Fotonica AEIT Italian Conference on Photonics Technologies. Proceedings of the 16th Italian National Conference on Photonic Technologies FOTONICA-2014, May 2014, DOI:10.1109/Fotonica.2014.6843885.
- (6) Vynnycky, M. & O'Brien, M. A., The slow, steady ascent of a hot solid sphere in a Newtonian fluid with strongly temperature-dependent viscosity, *Appl. Math. Comput.* 231 (2014) 231-253.
  - (7) Sharma, A. K., Vynnycky, M., Ling, C. Y., Birgersson, E. & Han, M., The quasi-steady state of all-vanadium redox flow batteries: a scale analysis, *Electrochimica Acta* 147 (2014) 657- 662.
  - (8) Adley, C. C., Cooker, M. J., Fay, G. L., Hewitt, I., Lacey, A. A., Mellgren, N., Robinson, M. & Vynnycky, M., A mathematical model of the rainwater flows in a green roof, *Mathematics-in-Industry Case Studies Journal* 6 (2014) 1-21.
  - (9) Vynnycky, M. & Mitchell, S. L., On the numerical solution of a Stefan problem with finite extinction time, *J. Comp. Appl. Math.* 276 (2015) 98-109.
  - (10) Vynnycky, M. & Kimura, S., Can natural convection alone explain the Mpemba effect?, *Int. J. Heat Mass Tran.* 80 (2015) 243-255.
  - (11) Fowler, A. C., Rust, A. C. & Vynnycky, M., The formation of vesicular cylinders in pahoehoe lava flows, *Geophys. Astrophys. Fluid Dyn.* 109 (2015) 39-61.
  - (12) Sharma, A. K., Ling, C. Y., Birgersson, E., Vynnycky, M. & Han, M., Verified reduction of dimensionality for an all-vanadium redox flow battery model, *J. Power Sources* 279 (2015) 345-350.
  - (13) Sharma, A. K., Birgersson, E. & Vynnycky, M., Towards computationally-efficient modeling of transport phenomena in three-dimensional monolithic channels, *Appl. Math. Comput.* 254 (2015) 392-407.
  - (14) Vynnycky, M. & Kanev, K., Mathematical analysis of the multisolution phenomenon in the P3P problem, *J. Math. Imaging Vis.* 51 (2015) 326-337.
  - (15) Vynnycky, M. & Gordon, A. D., Non-isothermal hydrophobicity-dependent two-phase flow in the porous cathode gas diffusion layer of a polymer electrolyte fuel cell, accepted for publication in *J. Engng Maths* (2014). DOI: 10.1007/s10665-014-9748-8
  - (16) Mitchell, S. L. & Vynnycky, M., The oxygen diffusion problem: analysis and numerical solution, accepted for publication in *Appl. Math. Mod.* (2014). DOI:10.1016/j.apm.2014.10.068.
  - (17) Vynnycky, M., An asymptotic model for the primary drying stage of vial lyophilization, accepted for publication in *J. Engng Maths* (2015). DOI: 10.1007/s10665-015-9789-7.
  - (18) Vynnycky, M., Zambrano, M. & Cuminato, J. A., On the avoidance of ripple marks on cast metal surfaces, accepted for publication in *Int. J. Heat Mass Tran.* (2015).DOI:10.1016/j.ijheatmasstransfer.2015.02.063
  - (19) Stewart, I. W., Vynnycky, M., McKee, S. & Tomé, M. F., Pressure-driven flow in smectic A liquid crystals, submitted to *SIAM J. Appl. Math.* (2014).
  - (20) Vynnycky, M. & Saleem, S., On the resolution of thermal gradients in a model for the continuous casting of binary alloys, submitted to *Appl. Math. Comput.* (2014).
  - (21) Tomé, M. F., Bertoco, J., Oishi, C. M., Araujo, M. S., Cruz, D., Pinho, F. T. & Vynnycky, M., A finite difference technique for solving the K-BKZ constitutive equation for two dimensional moving free surface flows, submitted to *J. Comp. Phys.* (2014).
  - (22) Florio, B. J., Vynnycky, M., Mitchell, S. L. and O'Brien, S. B. G., Mould-taper asymptotics and air-gap formation in continuous casting, submitted to *Appl. Math. Comput.* (2015).

## **Travelling report**

None