Report on the Research at the Institute of Informatics of the University of Szeged

2003–2006

Szeged, 2007

A Short Introduction of the Institute

I. HISTORY AND MISSION

Systematic education in computer science was launched within the Mathematical Institute at the end of the 1950's by László Kalmár. The Institute of Informatics was founded as an independent unit in 1990. The head of the Institute: Prof. Zoltán Fülöp. The deputies of the head: Dr. Éva Gombás (student affairs) and Dr. Károly Dévényi (management)

The Institute consists of five departments and a research group:

- Department of Applied Informatics, head of the department: Dr. Tibor Csendes[1]
- Department of Computer Algorithms and Artificial Intelligence, head of the department: Prof. János Csirik
- Department of Foundations of Computer Science, head of the department: Prof. Zoltán Ésik
- Department of Image Processing and Computer Graphics, head of the department: Dr. Eörs Máté[2]
- Department of Software Engineering, head of the department: Dr. Tibor Gyimóthy
- Research Group on Artificial Intelligence of the Hungarian Academy of Sciences, head of the research group: Prof. János Csirik

The main activities of the institute are the education and research of modern informatics and computer science knowledge. Here we provide a sketch of our educational programs and research activities.

II. EDUCATION

The institute offers BSc, MSc, and PhD degrees. The curricula consist mainly of mandatory courses for undergraduates and a broad spectrum for specialization at graduate level. The curricula have already been adjusted to conform to the so-called Bologna project, embracing most of the topics of modern informatics and computer science.

The informatics/computer science and some of the engineering courses belong to the departments of the Institute of Informatics. The Institute of Mathematics and the Faculty of Economics and Business Administration are responsible for the mathematics and economics courses. The physics courses are taught by the Departments of Physics. In the Computer Engineer BSc program we cooperate with the Kecskemét College.

BSC PROGRAMS

Presently we have three programs at undergraduate level: Computer Economist, Computer Engineer, and Computer Program Designer.

[1] Dr. Balázs Imreh was the head between 2003-2005.

[2] Prof. Attila Kuba was the head between 2003-2006.

Computer Economist, BSc

The normal duration of the program is 7 semesters. The program produces experts who are well versed in the information society, and are able to understand and solve the problems arising in real business processes. They can manage the information technology supporting the business needs, such as to improve on the knowledge base and business intelligence of companies, model the cooperation of info communication processes and technologies, control those processes, identify problems, and develop applications (and also maintain and monitor their quality). Moreover the graduates are equipped by the theoretical basics to continue their studies at MSc level.

Computer Engineer, BSc

The normal duration of the program is 7 semesters. The goal of the program is to train computer experts with solid engineering skills. The graduates are expected to install and operate complex systems, especially in the information infrastructure area, and also to plan and develop the data and program system of such systems. This means skills both in hardware and advanced software technology, involving modeling, simulation, performance, reliability, configuration, trouble shooting, maintenance, and development of systems. They are also provided with appropriate basic knowledge to continue their studies at MSc level.

Computer Program Designer, BSc

The normal duration of the program is 6 semesters. The graduates are supposed to have high skills in planning and development of company information systems using modern software tools. Furthermore, they are trained in the planning, development and operation of decision support systems, expert systems, and multimedia systems. The graduates also receive firm basis in Computer Science knowledge in order to have suitable knowledge to continue their studies at MSc level.

GRADUATE PROGRAMS

Computer Program Designer, MSc

The normal duration of the program is 4 semesters. The goal of the training is to produce informatics/computer science experts who have firm theoretical basis, and they are able to expand their knowledge autonomously in a long run. They can work in teams or on their own, to develop, produce, apply, introduce, maintain, and to service information systems at high level. Furthermore, they possess the necessary cooperation and model making skill that are needed for solving of the informatics problems arising in their fields. They are also able to conduct research work, and to continue their studies at PhD level. There are six offered fields for specializations: Image Processing, Artificial Intelligence, Model Making for Informaticians, Operations Research, Computer Science, and Software Development.

PhD program in Computer Science

In addition of the above programs, a doctoral program in Computer Science is available since 1993. The aim of this program is to support graduate studies, leading to the degree of PhD in computer science, with an emphasis on theoretical aspects. The program is part of the Doctoral School in Mathematics and Computer Science of the Faculty of Science of the University of Szeged. It is composed of three subprograms: Theoretical Computer Science, Operations Research and Combinatorial Optimization, and Applications of Computer Science. The possible research topics include mostly come from those parts of computer science and related areas, which are being investigated at the Institute of Informatics. The normal duration of the program is 6 semesters. Students are required to take entrance examinations for the admittance. The State of Hungary usually supports up to 5-6 new fellowships every year that is offered to Hungarian citizens. Foreign students are not entitled for that fellowship, their tuition and other expenses have to be supported from other sources.

III. RESEARCH THEMES AND CO-OPERATIONS

The departments of the Institute conduct research in the following areas.

Department of Applied Informatics

Reliable computing, interval optimization, discrete optimization, PNS problems, extremal graph theory, combinatorial games, and history of mathematics.

Department of Image Processing and Computer Graphics

Image models based on random Markov fields, Parametric estimation of transformations, Higher order active contour models, Analysis of satellite pictures, Digital spatial models. Vectorization of scanned drawings, Computer-Aided surgery. Medical image analysis, Skeletonization by thinning, Image registration, and Discrete tomography.

Department of Foundations of Computer Science

Algebra and logics in computer science, Automata and formal languages. Tree-automata and tree-transducers. Term rewriting systems, and fixed points in computer science. Process algebras, Temporal logics. Structures in computer science: semirings and semi-modules, and categorical algebras.

Department of Computer Algorithms and Artificial Intelligence

Automata theory, Fuzzy theory, Bin packing, Meta heuristics, String matching, On-line algorithms, Machine Learning and Computational Learning Theory, Multi-Criteria Decision Making, Scheduling, Robotics, and Mechatronics.

Department of Software Engineering

Static and dynamic analysis of software systems. Slicing for imperative languages and logical programming. Reverse engineering. Open source software development. Linux file system and GCC compiler optimization. Embedded systems. Ad-Hoc networks. Process synthesis. Optimization problems arising in chemistry, biology and industry.

Research Group on Artificial Intelligence

Machine learning, Computational learning theory. Natural language procession, Language technology, Speech technology, Peer-to-peer algorithms and systems.

The members of the Institute of Informatics publish about 150 scientific papers in highly respected international journals/proceedings anually.

Partners

The Institute of Informatics has joint programs and research cooperation (e.g. CEEPUS, SOCRATES/ERASMUS) with the following higher education institutes from North-America, Europe, and Asia.

Canada: University of Waterloo, Canada, Queen's University, Canada.
USA: Boston University, MA, City University of New York, NY, Columbia University, New York, NY, The University of Iowa, Iowa City, IA, University of Illinois at Urbana-Champaign, IL, Stevens Institute of Technology, Hoboken NJ, AT&T Labs.
Austria: Technische Universität Wien, Medizinische Universität Graz, Technische Universität Graz.
Czech Republic: Charles University, Prague.
Denmark: University of Aalborg.
England: University College London, GB.
Finland: University of Turku, Lappeenranta University of Technology.
France: University of Bordeaux, INRIA, Sophia Antipolis, University of Paris 6 and 7.
Germany: Technische Universität Ilmenau, Technische Universität Dresden, Universität Hamburg, Technische Universität München, Universität Erlangen-Nürnberg, Universität Mannheim, Universität Karlsruhe, Universität Stuttgart.
Switzerland: University of Bern.
Italy: University of Rome La Sapienza.
Netherlands: Technical University of Eindhoven.
Serbia: University of Nis, University of Novi Sad, Institut Mihajlo Pupin, Belgrad.
Slovenia: University of Maribor.
Spain: Universidad de Almeria, Universidad de Tarragona.
China: Hong Kong University of Science & Technology.
Israel: Ben-Gurion University of the Negev, University of Haifa.
Japan: Kyoto Sangyo University, University of Aizu.

IV. OTHER ACTIVITIES

CONFERENCE ORGANIZATION

We have organized several conferences from the foundation of the Institute. In the last years the following conferences were organized.
16th International Symposium on Fundamentals of Computation Theory, Budapest, 2007.
13th International Conference on Discrete Geometry in Computer Imagery, 2006.
Logic and Combinatorics, Szeged, 2006.
Computer Science Logic 2006, Szeged, 2006.
Algebraic Theory of Automata and Logic, Szeged, 2006.

1. 2. 3. and 4. Hungarian Computer Linguistics Conference, Szeged, 2003, 2004, 2005, and 2006.
AFL 05 - 11th International Conference on Automata and Formal Languages, Dobogókő, 2005.
International Workshop on Soft Computing Applications, Szeged-Arad, 2005.
International Conference on Software Maintenance, 2005.
DLT'03 - Developments in Language Theory, Seventh International Conference, Szeged, 2003.
European Symposium on Algorithms, Budapest, 2003.
Conference of PhD Students in Computer Science, Szeged, 2004 and 2006.
Summer School on Image Processing, SSIP, Szeged, 2004, 2005, and 2006.
Veszprém Optimization Conference: Advanced Algorithms, Veszprém, 2004 and 2006.

Between the years 2000 and 2006 the people of the Institute served in program committees of more than 50 international conferences.

ACTA CYBERNETICA

A scientific journal, Acta Cybernetica has been published since 1969 by the Institute in English. The journal is available in about 150 university departments worldwide, its homepage is: `www.inf.u-szeged.hu/actacybernetica/starthu.xml`

OTHER SCIENTIFIC SERVICE

Several members of the faculty work as editors in international scientific journals; they play significant roles in major scientific organizations and serve in program committees of major conferences.

Some of those journals: Acta Cybernetica, Central European Journal of Operations Research, Grammars, IEEE Transactions on Image Processing, Informatica, Pure Mathematics and Application, Theoretical Computer Science, Theoretical Informatics and Applications, Optimization Letters, and Oriental J. of Mathematics.

Organizations in which the Institute is represented: European Association for Theoretical Computer Science, European Association for Computer Science Logic, Gesellschaft fr Angewandte Mathematik und Mechanik, International Federation of Information Processing, and Association for Computing Machinery.

V. RESOURCES

LIBRARIES

The Institute of Informatics has a library of which holds about 5000 Hungarian and English volumes and subscribes over 200 scientific journals. The recently renewed University Library also an invaluable resoure for both our faculty and our students. It offers not only numerous scientific books, journals but it serves as a place for study and host of conferences. The directories of all libraries at the University are connected together, and their shelfed items are searchable by browsers.

HARDWARE/SOFTWARE

The Institute provides computer access for about 3700 users. The students may use 220 workstation (Pentium4 based or IBM machines), in which both Mircosoft and Linux operation systems are available. All machines run by the Institute are linked to switches with speed 100Mbps, while those switches are hooked by optical cables (1Gbps) to the main switch to the University Computer Center. The Institute also operates the following servers: 2 Sunfire 280R, 1 IBM eServer, 1 Compaq Alphaserver DS20, 3 HP Proliant, 1 Sun Ultra Enterprise 2. (The servers are driven by Solaris 9, Linux, Windows 2000 Server or Windows 2003 Server.) A cluster, consisting of 4 HP Proliant server, has been working from the September of 2005. Its mass storage device is an MSA 500 disc array of capacity 1 TB.
`http://www.inf.u-szeged.hu/starten.xml`

Research by Departments

Department of Applied Informatics

I. COMPUTER-ASSISTED PROOFS FOR CHAOTIC AND STABILITY BEHAVIOUR IN DYNAMICAL SYSTEMS

INTRODUCTION

An important question is while studying approximations of the solutions of differential equations, whether the given problem has a stable solution or chaotic behaviour. We study verified computational methods to check regions the points of which fulfill the conditions of some behaviour.

In this case the verification means mathematical verification. In the computer part, hence rounding and other errors were considered. Instead of real numbers, we can also calculate with intervals. In case the bounds of the result interval are not computer representable, then they are rounded outward.

INVESTIGATION OF CHAOTIC REAGIONS FOR THE HÉNON MAP

The problem is usually solved by careful studying the given problem with much human interaction, followed by an estimation of the Lipschitz constant, bounding the rounding errors to be committed, and finally a number of grid points are checked one by one by a proper computer program [15]. Instead of that, we introduce a new – interval arithmetic based – automatized method.

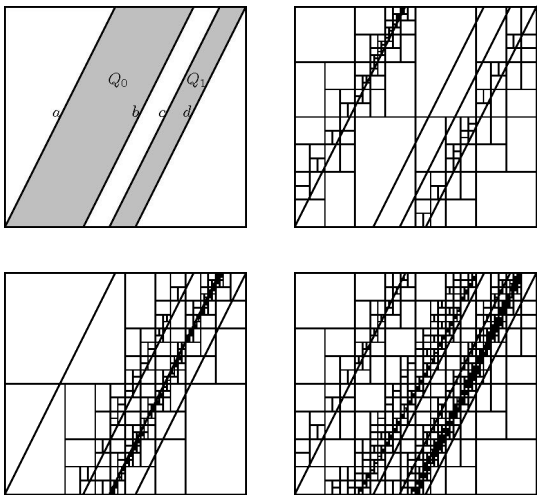

Figure 1. The parallelograms and the starting interval covered by the verified subintervals for which either the given condition holds, or they do not contain a point of the argument set.

To check the existence of chaotic reagions we have set up an adaptive subdivision algorithm based on interval arithmetic. First the algorithm determines the starting interval, that contains the region to be checked. Then the three inclusion relations are checked one after the other.

All of these proved to be valid – as expected. The amount of function evaluations (for the transformation, i.e. for the seventh iterate of the Hénon mapping $(\mathcal{H}(x_1, x_2) = (1 - Ax_1^2 + x_2, Bx_1))$ in each case) were 273, 523, and 1613, respectively. The algorithm stores those subintervals for which it was impossible to prove whether the given condition holds, these required further subdivision to achieve a conclusion (see Figure 1). The depth of the stack necessary for the checking was 11, 13, and 14, respectively. The CPU time used proved to be negligible, only a few seconds.

We have proven that this algorithm is capable to provide the positive answer after a finite number of steps, and also that the given answer is rigorous in the mathematical sense. Once we have a reliable computer procedure to check the conditions of chaotic behavior of a mapping it is straightforward to set up an optimization model that transforms the original chaos location problem to a global optimization problem.

The key question for the successful application of a global optimization algorithm was how to compose the penalty function. On the basis of earlier experiences collected with similar constrained problems, we have decided to add a nonnegative value proportional to how much the given condition was hurt, plus a fixed penalty term in case at least one of the constraints was not satisfied.

We have applied the global optimization model for the 5th iterate Hénon mapping. Note that the less the iteration number, the more difficult the related problem: no chaotic regions were reported for the iterates less than 7 till now. Table 1 presents the numerical results of the ten search runs.

LO	ZO	FE	PE	T
12	4	13,197	4,086	17
12	1	12,913	3,365	16
12	1	13,569	4,303	19
12	2	12,918	3,394	16
12	1	14,117	5,083	18
12	3	21,391	7,400	25
12	2	12,623	3,296	16
12	0	15,388	6,221	30
12	3	13,458	3,858	15
12	2	14,643	5,002	16

Table 1. Numerical results of the search runs (Here LO stands for the number of local optima found, ZO for the number of zero optimum values, FE for the number of function evaluations, PE for the number of penalty function evaluations, and finally T for the CPU time used in minutes.)

We applied successfully this method to locate several chaotic regions of Hénon map, and gave a lower bound for topological entropy. The topological entropy characterizes the mixing of points by the Hénon map. The numerical results are publised in [2–6, 11].

CHAOTIC BEHAVIOUR OF THE FORCED DAMPED PENDULUM

Recently, a few papers considered real dynamical problems and give a mathematical proof to chaotic behaviour [13]. In this research we investigated a forced damped pendulum as the mechanical model, i.e. we have a body on a weightless solid rod, forced to move on a vertical circle around the center point. The mass and the length of the pendulum are equal to 1. We have a not negligible friction depending on the speed of the pendulum with a friction factor of $b = 0.1$. An external periodic force is applied to the body, $\cos(t)$, where t is the time (it is independent of all other factors).

The related second order differential equation is

$$x'' = \cos(t) - 0.1x' - \sin(x),$$

where x is the angle of the pendulum, and x' is the angle speed of the pendulum.

In the proof we will need certain quadrilaterals $\{Q_k\}_{k\in\mathbb{Z}}$ "long" in the unstable and "short" in the stable directions so that there are *"exceptional" orbits* of the Poincaré mapping P with the following properties:

- an exceptional orbit is contained in $\cup_{k\in\mathbb{Z}} Q_k$;
- an exceptional orbit visits the quadrilaterals consecutively: if $P^n(x_0, x_0') \in Q_k$ for some $k, n \in \mathbb{Z}$, then either $P^{n+1}(x_0, x_0') \in Q_{k-1}$ or $P^{n+1}(x_0, x_0') \in Q_k$ or $P^{n+1}(x_0, x_0') \in Q_{k+1}$.

In the main step of the proof of chaotic behaviour we will show that for an arbitrary consecutive order $\{Q_{i_k}\}_{k\in\mathbb{Z}}$ of quadrilaterals there is an exceptional orbit visiting the quadrilaterals in the prescribed order. To this end we have to know forward images $P(Q_k)$ and backward images $P^{-1}(Q_k)$ (see Figure 2).

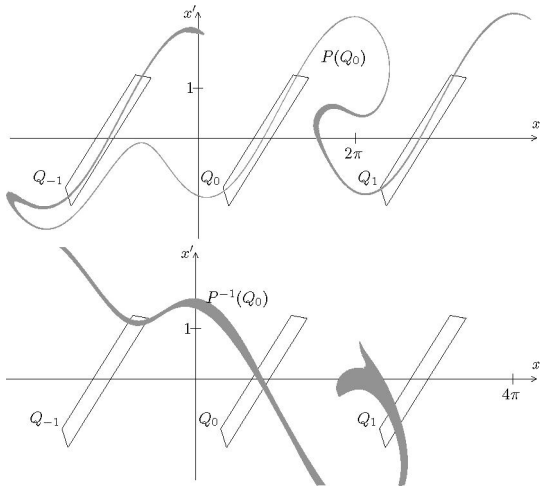

Figure 2. Forward and backward Poincare map in $t = \pm 2\pi$ time points of Q_0.

We applied the earlier mentioned subdivision method, which was able to prove the chaotic behaviour of the considered systems. The details of the proof was published in [7,8].

INVESTIGATION OF A DELAY DIFFERENTIAL EQUATION

E.M. Wright considered the delay differential equation

$$z'(t) = -\alpha z(t-1)(1 + z(t)),$$

where α is a positive number, and the initial function $\phi(s)$ is a constant, $c > -1$, i.e. $\phi(s) = c$ for $s \in [-1, 0]$.

To simplify the further calculations use the substitution $z(t) = e^{y(t)} - 1$. Then $z'(t) = e^{y(t)}y'(t)$ and $z(t-1) = e^{y(t-1)} - 1$. We obtain the delay differential equation

$$y'(t) = -\alpha(e^{y(t-1)} - 1),$$

where the initial function is $\phi(s) = c$, $s \in [-1, 0]$.

E.M. Wright conjectured in a paper [14] published in 1955 that all solutions of this delay differential equation converge to zero for a wide set of the parameter α. He gave a proof of the statement for α values between 0 and 1.5, and conjectured to be true for further α values below $\pi/2$.

We described and proved the correctness of a new, even more stronger bounding scheme that allows an efficient shrinking of the possible extreme values of a periodic solution. The present approach follow another line of thought, still it is a kind of extension of that of Wright.

We applied our Taylor series based algorithm to bound the trajectories. This method was publised in [1], and we illustrate the result in the case of $\alpha = 1.5$ on Figure 3.

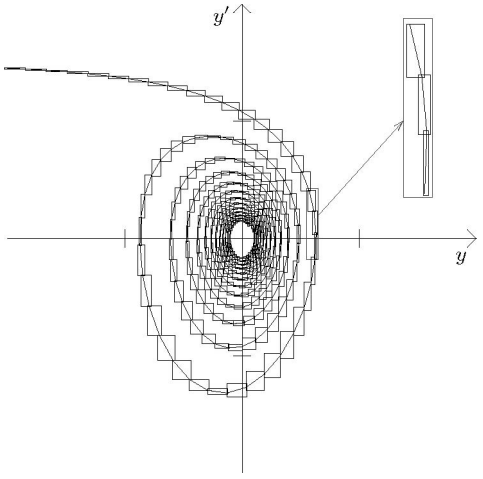

Figure 3. The bounded trajectory in y, y' coordinate systems.

After the theoretical investigations the remaining problem to be solved is to prove that for α values between 1.5 and $\pi/2$ no periodic solution exists with M and m absolute extreme values larger than 0.075.

We implemented a new parallel Branch and Bound algorithm, which is able to prove the remaining problem, so we prove Wright original conjecture. The computer part of the proof is published in [9,12].

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II. OPTIMIZATION OF COMPLEX TRANSPORTATION PROCEDURES

During the organization of the transportation procedures many optimization problems arise. The decision maker has to assign goods to different vehicles and the optimal paths in the road system has to be determined. The optimal path and also the cost of the path may depend on the type of the used vehicle. In [1] we suppose that two places are given the destination point and the termination point and some amount of good must be transported between these places. We have a practical packing problem that the goods are packed into three dimensional boxes, a box can be described by its size and its weight. Vehicles belonging to different types can be used for the transportation of the boxes.

We also consider [2, 3] the model where a vehicle has to visit the places but it can be used for internal transports. This means that in the case when a place i is visited before a place j then the vehicle can be used to transport some goods from i to j. The profit which can be achieved by such a transport is denoted by B_{ij}. Thus the goal is to find an ordering of the places which maximize the total profit which can be achieved by the internal transports according to the cost of travelling. We call this problem min-cost Hamiltonian path problem with internal transport, $HPPIT$ in short.

A BIN PACKING APPROACH OF A SHIPMENT CONSTRUCTION

Our optimization subproblem can be formulated as a generalized version of the three-dimensional bin packing problem. In box packing problem three dimensional boxes must be packed without overlapping into the minimal number of three dimensional unit cube. This problem was defined in previous papers and later many algorithm were developed for the solution of the problem. In our model there are different boxes which can be used for packing the items, thus our model is related to the variable sized bin packing problem, where the bins which can be used to pack the elements may have different size. The notion of bin packing and its multidimensional versions with variable sizes and heuristic algorithms to it were developed as we noted in references of [1]. The new model differs in two ways from the variable sized multidimensonal model. In this model there is a further restriction on the bins, each type of bins has a weight limit and the total weight of the boxes assigned to a bin (vehicle) cannot be more than the weight limit of the vehicle. Moreover in the new model we have a more general cost function, the cost of a bin depends on its type, but it can be an arbitrary value it is not the volume of the bin.

HAMILTON PATH PROBLEM WITH INTERNAL TRANSPORTS

Important combinatorial optimization problems require finding a permutation of vertices of a complete digraph that minimizes a certain cost function. The most familiar one is the min-cost Hamiltonian path problem - or its closed-path version, the Travelling Salesman Problem (TSP) -, when the cost of a permutation depends on consecutive node pairs only. Another problem is known as the Linear Ordering Problem (LOP) when we want to find a linear order of the nodes of a digraph such that the sum of the arc weights, which are consistent with this order,

is as large as possible. Now we consider a new optimization model using a mixed linear cost function from these two. Motivation of this common generalization of TSP and LOP is the above practical question. Thus the goal is to find an ordering of the places which maximize the total profit which can be achieved by the internal transports according to the cost of travelling. We call this problem min-cost Hamiltonian path problem with internal transport, $HPPIT$ in short. Heuristics on TSP or LOP can be modify to our problem and give new ones. The vehicle routing problem with inner transportation leads to the following mathematical model. Let G(V,A) be a directed complete graph, where $V = v_0, v_1, \ldots, v_n$ is the set of vertices, (v_0 is the depot, and the other vertices are the places which should be visited by the vehicle). Furthermore two (n+1)x(n+1) nonnegative matrices are given, B and D. B_{ij} is the possible profit which can be achieved by the inner transportation from v_i to v_j if v_i is visited before v_j ($B_{ii} = 0$ for each i). D_{ij} gives the cost of travelling from v_i to v_j ($D_{ii} = 0$ for each i).

In the HPPIT problem we would like to find a tour which visits each city exactly once and starts at the depot and returns there at the end of the tour. The objective is to maximize the total profit achieved by the inner transportation taking into account the cost of the tour. A feasible solution can be defined as a permutations p of the set $\{1, .., n\}$. The permutation describes the tour where the vehicle starts and ends at v_0 and visits the other vertices in the order $v_{p(1)}, v_{p(2)}, .., v_{p(n)}$. Then the objective function is given by the formula

$$z(p) = \sum_{0<i<j<n+1} B_{p(i),p(j)} + \sum_{i=1}^{n} (B_{0,p(i)} + B_{p(i),0}) - \sum_{0\leq i<n} D_{p(i),p(i+1)} - D_{p(n),0},$$

and the goal is to maximize this function. In the objective function the profit of the inner transportation from and to v_0 is independent on the order of the other vertices, thus it is a constant.

During the empirical analysis we investigated 14 heuristic algorithms.

ACKNOWLEDGEMENTS

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III. GRAPHS AND GAMES

EXTREMAL GRAPH THEORY

In [1] we considered the *interval number*, an important graph parameter. Partial characterization is given for the extremal cases of the degree formula, and we also give bounds on the interval number $i(G)$ if certain induced subgraphs are not present in G.

The paper [3] generalizes the classical theorem of Nash-Williams asserting that any planar graph can be covered by three forests. We show that additionally one of those forests has maximum degree at most 8. Similar results are obtained for outerplanar, series-parallel and $K_{3,2}$ minor-free graphs.

We investigate the edge-bandwidth of grid-type graph in [4]. Those are the $n \times n$ planar grid $P_n \oplus P_n$ and tori $C_n \oplus C_n$, the n-dimensional cube P_2^n, and the $K_n \oplus K_n$. In all cases asymptotically sharp bound on the edge-bandwidth are given.

POSITIONAL GAMES

In [2] we introduce the idea of the recycled version of games and prove some results on those. The main results are a logarithmic upper and lower bounds on the recycled line game, and a $\sqrt[3]{n}$ upper bound on the recycled Kaplansky game if the players use n marks.

The paper [5] solves some biased graph games. It extends the result of Székely and Beck on degree game, and the method has consequences for the balance games. We discuss the general diameter games on the complete graph on n vertices. It defies the heuristic intuition for the 1:1 case, but the acceleration of the game smooths out some of the irregularities.

The survey paper [6] gives a detailed introduction to Positional Games, while it contains some new results. These are as follows: the bandwidth games on $P_n \oplus P_n$, random proof for Chooser's win in some Picker-Chooser games, Erdős-Selfridge type of theorem for random hypergraph games, bounds on Chooser-Picker degree games etc.

ACKNOWLEDGEMENTS

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IV. NEW APPROACHES TO CIRCLE PACKING IN A SQUARE

The optimization problem of the densest packing of equal circles in a square arises from discrete geometry, it has become a well-studied problem in the past decades. The research in this topic on our part began nearly 10 years ago. During the 2003-06 period we have summarized our results in a book (with a CD) and some articles. In this time period P.G. Szabó finished his Ph.D. thesis about the circle packings [10].

INTRODUCTION

It is easy to understand what the densest circle packing is: to position a given number of equal circles in such a way that the circles fit fully in a square without overlapping. We gave some geometrical forms of the problem and we proved their equivalence. Since we studied the problem as a global optimization problem, we classified its mathematical models into the suitable problem classes of mathematical programming. An important experience of our research was to realize that those methods were efficient which strongly used the geometrical properties of the problem [11].

BOUNDS

First of all, we investigated how theoretical bounds can be determined for the optimum value. It was a natural idea to improve the lower bounds by applying computer and using global optimization technology. We checked the numerical results by interval arithmetic computations using the PROFIL/BIAS C++ library, so their reliability is now proved by computer. Based on E. Specht's modified billiard simulation method approximate circle packings up to 200 were given. We have investigated the problem of the existency of the structure of the circle packings based on the theory of Groebner bases, namely how the existency of a circle packing can be proved with a given structure [1–3, 12].

OPTIMAL PACKINGS

A new verified optimization method was presented for the circle packing problem. The developed algorithm is based on interval analysis. As one of the most efficient parts of the algorithm, an interval-based version of a previous elimination procedure is introduced. This method represents the remaining areas still of interest as polygons fully calculated in a reliable way. Currently the most promising strategy of finding optimal configurations is to partition the original problem into subproblems. Still as a result of the highly increasing number of subproblems, earlier computer-aided methods were not able to solve problem instances where the number of circles was greater than 27. M.Cs. Markót provided a carefully developed technique resolving this difficulty by eliminating large group of subproblems together. This elimination method played a key role in solving the previously open problem instances of packing 28, 29, and 30 circles [4, 6, 9].

REAPETED PATTERNS

Using the proven and the best known circle packings, we have investigated the structures of the packings, determined some pattern- and structure classes and included the special cases into them. The classification was based on a common algorithmical description of the structures and a number theoretical

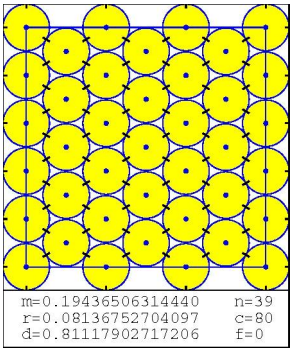

Figure 4. A grid circle packing for 39 circles.

relationship of the number of the circles. We studied separately a conjecture on an infinite circle packing sequence of the literature and we investigated the grid packing class too. Based on the pattern classes we have improved also the theoretical bounds. We gave sharp constant lower and upper bounds of the density [5].

MINIMAL POLYNOMIALS

We worked on the minimal polynomials of the packings. We have investigated the question whether a circle packing contains optimal substructures, how the minimal polynomial of the packing can be determined based on the general minimal polynomials of the substructures. This problem was solved by using the resultants. We demonstrated some examples, how the method can be used. The minimal polynomials were published and also the exact values for some cases until 100 circles. We studied separately the algebraic solution of the $P_{11}(m) = 0$ equation, where we guessed the suitable quadratical field based on the structure of the packing and we have found the exact value by a CAS (Computer Algebra System). We have also given a classification of the linear, quadratical and quartical packing classes and the connection is explained with the previous studied pattern classes [7].

Our summarized results are published in a book at Springer [13]. One especially important feature of the book is the inclusion of all the open source programming codes used on an enclosed CD. The wider scientific community has already been involved in checking the codes and has helped in having the computational proofs accepted. The main results we have summarized in a survey article, too [8].

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V. HISTORY OF MATHEMATICS AND INFORMATICS

During the period 2003-06, we worked on some books, book chapters and articles, based on our research on the history of mathematics and informatics. A big part of the research on the History of Mathematics is often an investigation of the correspondence and legacy of scientists. In the following topics, we have summarized, shortly, the studied scientific legacies.

FARKAS BOLYAI'S LEGACY

We found some interesting unknown mathematical notes of Farkas Bolyai (1775-1856) in his manuscripts on number theory from the second part of the 1850's years. These results joined to the work of E. Kiss (1929-2006) on János Bolyai's number theoretical gems. We found the proof of F. Bolyai for the Wilson's Theorem and its conversion, results on the conversion of Fermat's little Theorem, about the perfect numbers, etc. These collected results show a strong connection between the father and his son in their common last years too. We tried to give an answer for the following question: "How did János Bolyai know that 4 272 943 is a prime number?" E. Kiss refereed our investigations in his works (e.g. in the second edition of his Bolyai-book). Later, we have written a common paper with Kiss about the manuscripts of Bolyais on the Mathematical Analysis. The research was based on the Bolyai's collections in Marosvásárhely (Tirgu-Mures, Roumania) and Budapest (Hungary) [1–11].

LÁSZLÓ KALMÁR'S LEGACY

In 2005 László Kalmár's (1905-1976) correspondence with Hungarian mathematicians has been issued by us with notes, titled KALMÁRIUM. In 2006 we have continued this work for to publish the second part of this book, titled KALMÁRIUM II, and we wrote some other articles about the life and works of L. Kalmár. This research was based on the Kalmár's legacy at the University of Szeged [12–17].

MARCEL RIESZ'S LEGACY

Continuing our general research direction, we have examined Marcel Riesz's (1886-1969) legacy in the Swedish town of Lund. This research is a continuation of the work of L. Filep (1941-2004). By doing this, documents from Hungarian mathematical schools of international significance become available to the public and scholars, including important correspondence by Frigyes Riesz (1880-1956) and Marcel Riesz. We have concluded in earlier studies that these materials definitely contain items of mathematical and historical worth, which help us understand the history of mathematical problem solving in the twentieth century. This is of a great significance, because the Riesz brothers are famous in the world of mathematics. Their articles are still cited, but not much is publicly known about their life and times. Most know only a few scant details about their scientific correspondence. They also worked in foreign scientific academies and circles, so these are of international interest [18].

FURTHER RESEARCH

Some other research topics arised from different kind of requests.

PANNONIAN PHOENIX

Pannonian Phoenix, or The Hungarian Language Arisen From The Ashes – Our Earliest Printed Scientific Books from the 16th - 19th Centuries [19].

The National Széchényi Library and the Hungarian Academy of Sciences organized the 'Pannonian Phoenix' exhibition. We gave the analytic descriptions of the following mathematical books:

- Aritmetica, az az A szamvetesnec tvdomania, mell(y) az tvdos Gemma Frisivsnac szam-vetesboel magyar nyelure... forditattot. Debrecen, 1577.
- Tolvay Ferenc: Az Arithmetikanak; avagy A Számlálásnak öt Speciesinek rövid Magyar Regulákban foglaltatott Mestersége. Kolozsvár, 1698.

- Onadi János: Practici algorithmi erotemata methodica, az az olly cselekedö számok, mellyek könyü kérdések és feleletek által rövid utat mutatnak arra a tudományra, melyben akár mely féle adásnak s vételnek, osztálynak, vagy egyéb kereskedésben, csak a legg-kissebb summának-is bizonyos száma tanitattik. Kassa, 1693.
- Maróthi György: Arithmetica, vagy számvetésnek mestersége. Debrecen, 1743.
- Makó Pál: Bévezetés a számvetésre a' magyar és hozzá tartozandó tartományok' nemzeti iskoláinak számára. Buda, 1780.
- Dugonics András: A' tudákosságnak első könyve, mellyben foglaltatik a' betővetés (algebra). A' tudákosságnak másadik könyve, mellyben foglaltatik a föld-mérés (geometria). Pest, 1784.
- Bolyai Farkas: Az arithmetica eleje. Marosvásárhely, 1830.
- Brassai Sámuel: Euklides Elemei XV könyv. Pest, 1865.

JOHN VON NEUMANN

In the year of von Neumann (2003) we have written some papers about the life and works of John von Neumann (1903-1957) [20–23].

OTHER WORKS

There are some other works on Japanese History of Mathematics (Sangaku problems) [24], a forgotten Hungarian book on the 'upward' continued fractions [25], magic squares [26, 27], an old astronomical instrument "Jacob's Ladder" [28], and we edited the last unpublished work of L. Dávid (1881-1962) on the Cauchy-equation at János Bolyai's work [29, 30].

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Department of Computer Algorithms and Artificial Intelligence

I. AUTOMATA THEORY

We have continued to study complete systems of tree automata. In [5] we gave necessary and sufficient conditions under which a system of tree automata is isomorphically complete with respect to the α_i-products for the class of asynchronous tree automata.

Little is known about the general properties of tree languages recognized by deterministic root-to-frontier tree recognizers (DR tree languages). Therefore, we have started to study special classes of DR tree languages the counterparts of which are well-known in the theory of finite state recognizers (definite, nilpotent, monotone languages). Paper [3] contains our results concerning closedness of nilpotent DR tree languages under Boolean operations.

We say that a class **M** of finite monoids determines a class **K** of tree languages recognizable by tree recognizers if a tree language is in **K** if and only if its syntactic monoid is in **M**. Classes of monoids determining the classes of definite and nilpotent DR tree languages are given in [4].

Results of [4] show that the class of definite DR tree languages can be determined by the same class of monoids as the class of definite string languages. The same is true for the class of nilpotent DR tree languages. This was the observation which motivated us to give general conditions in [2] under which a class of tree languages with a given property can be determined by the same class of monoids as the class of string languages having the same property. The result has been applied to certain classes of tree languages.

CONNECTIONS OF RESEARCH TO EDUCATION

Tree automata and tree languages constitute different graduate and PhD courses. The open problems can serve as research subjects for PhD students. The textbook [1] gives a systematic treatment of finite state recognizers, string languages, tree recognizers and tree languages.

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II. ANALYSIS OF ALGORITHMS

BIN PACKING

In the classical bin packing, we are given a list L of items $(a_1, a_2, ..., a_n)$ each item $a_i \in (0, 1]$ and the goal is to find a packing of these items into a minimum number of unit-capacity bins. In [6] we present the theoretical results on the on-line Sum-of-Squares algorithm. SS is applicable to any instance of bin packing in which the bin capacity B and the item sizes $s(a)$ are integer (or can be scaled to be so), and runs in time $O(nB)$. It performs remarkably well from an average case point of view: For any discrete distribution in which the optimal expected waste is sublinear, SS also has sublinear expected waste. For any discrete distribution where the optimal expected waste is bounded, SS has expected waste at most $O(logn)$. We also discuss several interesting variants on SS, including a randomized $O(nB \log B)$-time online algorithm SS^* whose expected behavior is essentially optimal for all discrete distributions. Algorithm SS^* depends on a new linear-programming-based pseudopolynomial-time algorithm for solving the NP-hard problem of determining, given a discrete distribution F, just what is the growth rate for the optimal expected waste. In [5] it is proven that the asymptotic worst case bound of the SS algorithm is at most 2.777. In [1] a novel classification scheme is presented for bin packing problems. Classification of the papers and results in fields of research are helpful in placing new results in a historical context and in identifying open problems. The paper contains several examples on using the classification scheme for the known results on the area of bin packing.

SCHEDULING

In [9] the following scheduling problem is investigated. There are two sets of identical machines, the jobs have two processing times one for each set of machines. We consider two different objective functions, in the first model the goal is to minimize the maximum of the makespans on the sets, in the second model we minimize the sum of the makespans. We investigate the online and the offline versions. In the offline case an FPTAS is given for both objective functions. In the online case we characterize the competitive ratio of a load greedy algorithm which assigns every job to the set, where the job has smaller load. The competitive ratio of this algorithm tends to ∞ for both problems as the ratio m/k grows. We show that the post greedy algorithm has also unbounded competitive ratio as m/k grows. Finally we analyze a modified greedy algorithm and we show that it is constant competitive for arbitrary number of machines. Lower bound for the possible competitive ratios are also presented.

For most scheduling problems the set of machines is fixed initially and remains unchanged for the duration of the problem. Recently online scheduling problems have been investigated with the modification that initially the algorithm possesses no machines, but that at any point additional machines may be purchased. In all of these models the assumption that each machine has unit cost have been supposed. In [11] we consider the problem with general machine cost functions. Furthermore we also consider a more general version of the problem where the available machines have speed, the algorithm may purchase machines with speed 1 and machines with speed s. We defined and analyzed some algorithms for the solution of these problems and their special cases. Moreover some lower bounds on the possible competitive ratios are presented. In [15] we define and investigate a further scheduling model. In this new model the number of machines is not fixed; the algorithm has to purchase the used machines, moreover the jobs can be rejected. We show that the simple combinations of the algorithms used in the area of scheduling with rejections and the area of scheduling with machine cost are not constant - competitive. We present an exponential time 2.618-competitive algorithm called OPTCOPY.

STRING ALGORITHMS

In [13] the problem of finding the generalised median string is considered. The generalised median string is defined as a string that has the smallest sum of distances to the elements of a given set of strings. It is a valuable tool in representing a whole set of objects by a single prototype, and has interesting applications in pattern recognition. All algorithms for computing generalised median strings known from the literature are of static nature. That is, they require all elements of the underlying set of strings to be given when the algorithm is started. In this paper, we present a novel approach that is able to operate in a dynamic environment, where there is a steady arrival of new strings belonging to the considered set. Rather than computing the median from scratch upon arrival of each new string, the proposed algorithm needs only the median of the set computed before together with the new string to compute an updated median string of the new set. Our approach is experimentally compared to a greedy algorithm and the set median using both synthetic and real data.

SERVER PROBLEMS

We investigated some combinatorial optimization problems on routing servers. In [8] we consider a generalized online 2-server problem on the uniform space in which servers have different costs. Previous work focused on the case where the ratio between these costs was very large. We give results for varying ratios. For ratios below 2.2, we present a best possible algorithm which is trackless. We present a general lower bound for trackless algorithms depending on the cost ratio, proving that our algorithm is the best possible trackless algorithm up to a constant factor for any cost ratio. The results are extended for the case where we have two sets of servers with different costs. In [12] we recall the patching technique, which is a basic method in the area of developing heuristic algorithms for the traveling salesman problem and its generalization. We summarize some known applications and we present a new application of the technique for the p-TSP problem. We demonstrate the efficiency of this application by probabilistic and empirical analysis.

LEARNING ALGORITHMS

In [7] we investigate the problem of learning the order of criteria of lexicographic decision under various reasonable assumptions. Although the lexicographic decision is very simple, it is the most common and used decision model in everyday life. Even if the decision-makers use another model, they translate it (if it is possible) to lexicographic, because for the verbal communication only this approach is good. For learning the order of criteria we give a sample evaluation and an oracle based algorithm. In the worst case analysis of the sample evaluation algorithms we are dealing with the adversarial models. We show that if the distances of the samples are less than 4, then samples are not learnable, but 4-distance samples are polynomial learnable.

SURVEYS

We wrote surveys on several areas of the analysis of algorithms. An overview on the results concerning the area of median strings is given in [14]. A survey on the basic results competitive analysis of online algorithms is published in the book chapter [10]. The surveys [2], [3], [4] summarize some parts of the bin packing research field. In [2] the different versions of classical one dimensional bin packing and the basic results are presented. The paper [3] gives an overview on the area of variable sized bin packing and bin covering. In this models it is not supposed that the size of each bin is 1. In [4] the basic results on the performance guarantees for one dimensional bin packing are summarized.

ACKNOWLEDGEMENTS

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III. RESEARCH IN MULTICRITERIA DECISION MAKING AND FUZZY LOGIC

A COMMON PREFERENCE MODEL FOR VARIOUS DECISION MODELS

Decision-makers use aggregation procedures using value functions or preference relations. However, the aggregation procedure can not be independent from the value function or the preference relation. Conjoint measurement can handle both. The advantage of this model is that it gives a general modeling framework for the decision situation. But it does not tell us much about how we should make the decision-making. If a decision-maker is facing an aggregation problem he doesn't know which aggregation procedure is he going to use. To choose the MCDM method also seems to be a multicriteria decision problem. The conclusion is that a more general framework is needed.

We proposed a general multicriteria decision tool which contains the classical procedures (ELECTRE, PROMETHEE, TACTIC, MAUT, Lexicographic decision) as special cases. The so-called Bounded System is based on the class of nilpotent t-norms extended by hedges and mean and preference operators. With the Bounded System a heterogenous decision system can be built up i.e. on some criteria we can make a lexicographic decision, on some others we can use an outranking approach with veto threshold and maybe on the remaining criteria the utility approach. Our Bounded System is easy to understand and its parameters (weights, thresholds etc.) can also be easily assessed by a learning algorithm. [1]

THE GENERALIZED DOMBI OPERATOR

The multiplicative utility function is extensively used in the theory of multicriteria decision making. As its generalization a new fuzzy operator class, the Generalized Dombi operator was introduced, which unites well-known operators of fuzzy theory such as min/max, product/algebraic sum, Einstein, Hamacher, Dombi and drastic. Its formula is as follows.

$$o_\gamma^{(\alpha)}(\mathbf{x}) = \frac{1}{1+\left(\frac{1}{\gamma}\left(\prod_{i=1}^n\left(1+\gamma\left(\frac{1-x_i}{x_i}\right)^\alpha\right)-1\right)\right)^{1/\alpha}},$$

where $\mathbf{x} \in [0,1]^n$ and $\gamma, \alpha \in R$. Also, a new form of the Hamacher operator was given, which makes multi-argument calculations easier.

We also examined the De Morgan identity which connects the conjunctive and disjunctive operators by a negation. It is shown that in some special cases (min/max, drastic and Dombi) the new operator class forms a De Morgan triple with any rational involutive negation. [2]

REASONING WITH APPROXIMATED FUZZY INTERVALS

We have investigated the two fundamental approaches to approximate reasoning, the compositional rule of inference (CRI) and fuzzy truth value based reasoning. They are common in the sense that the so-called indetermination of the conclusion appears in both models. We have argued that this phenomenon is acceptable only in the logic view of reasoning, and so it should be avoided regarding the similarity based view. Sigmoid-like membership functions were introduced to avoid the indetermination of the conclusion. The generalized CRI reasoning scheme was investigated for all three representative t-norms. Only the Łukasiewicz t-norm based CRI scheme is not closed under sigmoid-like functions and from all three, the minimum is the best regarding computational complexity. The Membership Driven Inference (MDI) reasoning scheme was introduced by modifying the min-based CRI on sigmoid-like functions in order to get a simple yet powerful reasoning scheme. It was shown that it has a series of good properties, it fulfills the generalized modus ponens, the generalized modus tollens, the generalized chain rule, and more. Also, we have focused on the efficient computation of the MDI reasoning scheme. The class of squashing functions was introduced. This class of membership functions can arbitrarily approximate piecewise-linear memberships functions of fuzzy sets. Moreover, we have shown that by using squashing membership functions, the MDI reasoning scheme can be calculated on the parameters of the memberships instead of a pointwise computation. This efficient calculation of a rule's output can be applied to approximated trapezoidal and triangular fuzzy intervals, too, by an LR decomposition of them. [3,4]

ADVANCES IN TYPE-2 FUZZY LOGIC

Fuzzy logic in narrow sense is a generalization of classical two-valued logic, it considers a range of truth values, usually the unit interval. In recent years, research related to type-2 fuzzy logic has become even more active than ever. Type-2 fuzzy logic takes the generalization a step further by considering truth values that are themselves fuzzy. This means that every truth value (i.e. every element of $[0,1]$) has a fuzzy membership degree (which is again an element of $[0,1]$). This mapping from the unit interval to itself is the truth value, hence its name fuzzy truth value.

We have studied type-2 logical operations (such as conjunctions, disjunctions and implications) on non-interactive fuzzy truth values. Our investigations are intended to provide a theoretical background for type-2 approximate reasoning applications.

Regarding type-2 t-norms and t-conorms (i.e. conjunctions and disjunctions), sufficient conditions were given on the continuity of the resultant fuzzy truth values. We have shown easy-to-implement pointwise formulas for the type-2 conjunction and disjunction of fuzzy truth values with different monotonicity. As an important special case, we considered the extended Łukasiewicz operations on interactive linear fuzzy truth values. It was shown that the computationally complex convolutions of the extended Łukasiewicz operations are equivalent to simple operations on the parameters on the linear fuzzy truth values. We have given necessary and sufficient conditions when these operations preserve continuity and linearity. These results can be directly applied to type-2 fuzzy systems and also to approximate reasoning systems based on fuzzy truth values.

Our investigations on implications have shown that type-2 S-implications have similar properties on the lattice of convex normal fuzzy truth values like type-1 S-implications on the unit interval. Residual implications (i.e. residuals of conjunctive operations) are fundamental in fuzzy logic. Type-2 residual implications are approached from two distinct views: as extended residual implications of t-norms, and as general residuated structures. Extended type-2 implications are compared to type-2 S-implications, and it turned out that regarding the lattice of convex normal fuzzy truth values the latter seem more adequate for approximate reasoning purposes. [5–7]

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Department of Foundations of Computer Science

THEORETICAL COMPUTER SCIENCE

The research performed in the Department of Foundations of Computer Science lies in the intersection of algebra, logic and computer science. The main themes are automata and formal languages, tree automata and term rewriting, weighted tree automata, logics on words and trees, finite model theory, fixed point operators in computer science, and axiomatic questions.

I. ALGEBRA & LOGIC IN COMPUTER SCIENCE

SEMIRINGS AND SEMIMODULES

In [12], we introduced inductive *-semirings as a generalization of Kozen's Kleene algebras, We proved that inductive *-semirings are iteration semirings and they are closed under several algebraic constructions. In [10, 14, 15] we studied semiring-semimodule pairs equipped with a *- and $^\omega$-operation. We established several algebraic properties of these structures and studied several subclasses where the *- and $^\omega$-operations are defined using a partial order, a completely additive structure and/or an infinite product. We used these algebraic structures to give an abstract treatment of Büchi-automata and weighted Büchi-automata on infinite words. In [13], we applied these structures to context-free languages over ω-words. In [16], we defined algebraically complete semirings as an extension of inductive *-semirings. One of the most fundamental nontrivial normal form theorems for context-free languages is the Greibach normal form theorem. We established Greibach's normal form theorem in all algebraically complete semirings.

CATEGORICAL ALGEBRAS

In [3], we generalized the notion of partially ordered algebras to categorical algebras. An important result in partially ordered algebras that has many applications in Computer Science is that each ordered algebra can be completed into a continuous ordered algebra preserving all valid inequalities. We extended this result to categorical algebras and discussed several applications in Computer Science.

REGULAR WORDS

Regular words were introduced by Courcelle in the late 70's. His motivation came from recursive program schemes. They were subsequently studied by Thomas and Heilbrunner. Courcelle raised several important problems regarding the equational axiomatization of regular words and the decidability of the equational theory. Courcelle's questions for axiomatization were completely solved in [1, 2]. We also gave a P-time algorithm to decide the equational theory. This greatly improves an earlier algorithm of Thomas with no explicit upper bound for its complexity.

AXIOMATIC THEORY OF AUTOMATA

In [11], we gave an introduction to the axiomatic theory of automata and languages developed earlier by Conway, Bloom, Ésik and Kuich.

LOGIC ON WORDS

Linear temporal logic has the same expressive power as aperiodic automata. In order to be able to express modular counting and other properties of words, Wolper introduced Extended Linear Temporal Logic. In [7], we bridged Wolper's logic and the Krohn-Rhodes decomposition theory of finite automata and gave an algebraic characterization of Wolper's logic.

LOGIC ON TREES

Temporal logics can be classified into linear time and branching time logics. The latter logics can be viewed as logics on trees. Important branching time logics are CTL (Computational Tree Logic) and CTL*. In both logics, one can define only regular properties. However, it is an open problem to give a decidable characterization of those regular properties (given by a finite tree automaton) definable in these logics. An algebraic approach to deal with this and related problems in formal logic has been developed in the papers [4–6, 8, 9] using pseudovarieties of finite algebras and the cascade product (wreath product). The method developed in these papers reduces the characterization of the expressive power to the membership problem in pseudovarieties of finite algebras.

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II. AUTOMATA AND FORMAL LANGUAGES

WEIGHTED TREE AUTOMATA

In [1], we proved a general Kleene theorem applicable to weighted tree automata and formal power series over trees, finite or infinite. In [5] we gave a survey of results on weighted tree automata and tree transducers. In [4], we studied fuzzy subsets of algebras including algebras of trees and established a triple equivalence between equational, rational and recognizable fuzzy sets.

In [2] we showed that the cost-finiteness of tree automata with costs over finitely factorizing and monotonic semirings is decidable. We showed that it is also decidable whether a tree automaton with costs over a finitely factorizing, monotonic, and naturally ordered semiring is bounded with respect to the natural order.

In [18], we compared the classes of tree series which are recognizable by (a) multilinear mappings over some finite dimensional K-vector space, where K is a field, (b) K-Σ-tree automata, where K is a commutative semiring, (c) weighted tree automata over K, where K is a semiring, (d) finite, polynomial tree automata over K, where K is a commutative and continuous semiring, (e) polynomially-weighted tree automata, where K is a semiring, and (f) weighted tree automata over M-monoids.

TREE SERIES TRANSDUCERS

The first definition of the semantics of a tree series transducer, called algebraic semantics, is based on a tree series substitution that does not take into account the number of the occurrences of the substitution variables. In [16] we introduced tree series transducers of which the semantics takes into account that number. We compared the computation power of the two models.

In [17] we defined a tree series transducer model with an operational style semantics and called this model weighted tree transducer. We showed that tree series transducers with algebraic semantics and weighted tree transducers are semantically equivalent.

In [11] we generalized the famous tree transducer hierarchy of J. Engelfriet for tree series transducers over commutative, idempotent and positive semirings.

ALGEBRAIC PROPERTIES OF REGULAR TREE LANGUAGES

In [3], we showed that regular tree languages can be axiomatized by a few simple equations and the least fixed point rule. This extends a result of Kozen from words to trees. In [8], we introduced a new algebraic framework for the study of varieties of tree languages in relation to logic.

MULTI BOTTOM-UP TREE TRANSDUCERS

In [12] we defined deterministic multi bottom-up tree transducers and showed that they are semantically equivalent with deterministic top-down tree transducers with regular look-ahead. Then in [13] we compared the computation power of linear deterministic multi bottom-up tree transducers and eight well-known classes of deterministic bottom-up and deterministic top-down tree transducers.

SHAPE PRESERVING TREE TRANSDUCERS

Shape-preserving tree transducers generalize length-preserving sequential machines. In [10] we showed that shape-preserving top-down tree transducers are equivalent to finite-state relabelings. Moreover, we proved that it is decidable if a top-down tree transducer is shape preserving. In [20] it was proved that shape-preserving bottom-up tree transducers are also equivalent to finite-state relabelings. The decidability of the shape-preserving property for bottom-up tree transducers was proved in [21].

PEBBLE TREE TRANSDUCERS

In [14, 15], we investigated pebble tree transducers and macro pebble tree transducers. We showed that the circularity problem and the strong circularity problem for pebble tree transducers is decidable and that the weak circularity problem for pebble macro tree transducers is decidable. Moreover, we proved several decomposition results for macro pebble tree transducers.

In [22], n-pebble tree-walking automata with alternation were defined. It was shown that tree languages recognized by these devices are exactly the regular tree languages. Then it was shown that the deterministic and noncircular pebble alternating tree-walking automata are strictly less powerful than their nondeterministic counterparts.

STORAGE-TO-TREE TRANSDUCERS

In [19] it was shown that the class of tree transformations induced by regular storage-to-tree transducers with positive look-ahead is equal to the composition of the class of transformations induced by regular storage-to-tree transducers with the class of linear homomorphisms. It was also proved that the classes of transformations induced by both IO and OI context-free-storage-to-tree transducers are closed under positive look-ahead and composition with linear homomorphisms.

TREE AUTOMATA AND TERM REWRITE SYSTEMS

In [27] several characterizations and decidability results were obtained for ground tree transformations and congruence relations induced by tree automata.

TERM REWRITE SYSTEMS PRESERVING RECOGNIZABILITY

Salomaa showed that linear monadic term rewrite systems effectively preserve recognizability. We [31] showed that there are finitely many descendants of any recognizable tree language L for all linear monadic term rewrite systems, and we gave these descendants through finitely many linear monadic term rewrite systems. We [29] showed that right-linear half-monadic term rewrite systems effectively preserve recognizability. Using this property, we [29] showed that termination and convergence are decidable properties for right-linear half-monadic term rewrite systems.

GROUND TERM REWRITING

We [28] showed that for any given finitely generated congruences ρ and τ over the term algebra, it is decidable if the intersection of ρ and τ is a finitely generated congruence. If the answer is yes, then we can effectively construct a finite relation U over ground terms such that the congruence closure of U is equal to the intersection of ρ and τ.

We [30] showed that for a given left-linear right-ground term rewrite system R it is decidable if there is a ground term rewrite system S such that the restriction of the rewriting relation of R to ground terms is equal to the rewriting relation of S. If the answer is yes, then one can effectively construct such a ground term rewrite system S.

HIGHER DIMENSIONAL AUTOMATA

In [6], we defined parenthesizing automata, that operates on higher dimensional words (i.e., on elements of free algebras with several independent associative operations). We have extended several basic results of the classical theory of automata to parenthesizing automata including the equivalence to algebraic recognizability and monadic-second order definability. In [7], we described infinite higher dimensional words in algebraic frameworks and gave graph-theoretic descriptions of them. Based on these results parenthesizing Büchi-automata was defined with generalization of the above mentioned classical results [24, 25]. In [23], it was shown that the classes of languages that can be accepted by parenthesizing automata with at most i pairs of parentheses form a strict hierarchy, for $i \geq 0$. The aim of [26] is to relate parenthesizing automata to the work of Hashiguchi, Ichihara and Jimbo on binoid languages.

OTHER

In [9] we gave a short introduction to tree transducers for those who just would like to get an insight into the field.

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OTHER ACTIVITIES

I. EDITED BOOKS

In the period 2003–3006, the members of the Department of Foundations of Computer Science edited or co-edited the following books and special journal issues.

1. AFL 05, Special Issue of Acta Cybernetica, Volume 17, Number 4, 2006.
2. Automata and Formal Languages, Special Issue of Theoretical Computer Science, Volume 366, Number 3, 2006.
3. Recent Advances in Formal Languages and Applications, Studies in Computational Intelligence 25, Springer-Verlag, 2006.
4. Computer Science Logic, Proceedings of CSL 2006, LNCS 4207, Springer-Verlag, 2006.
5. Automata and Formal Languages, Proceedings of the 11th International Conference, AFL 2005, Dobogókő, May 17–20, 2005.
6. Process Algebra, Special Issue of Theoretical Computer Science, Volume 335, Number 2-3, 2005.
7. Proceedings of the 4th Conference for PhD Students, CSCS 2004, Special Issue of Acta Cybernetica, Volume 17, Number 2, 2005.
8. Developments in Language Theory, DLT 2003, Special Issue of Theoretical Computer Science, Volume 327, Number 3, 2004.
9. Fixed Points in Computer Science 03, Warsaw, Special Issue of Theoretical Informatics and Applications, Volume 38, Number 4, 2004.
10. Fixed Points in Computer Science 02, Copenhagen, Special Issue of Theoretical Informatics and Applications, Volume 37, 271–391, 2003.
11. Process algebra: Open problems and future directions, PA'03, Bologna, Italy, July 21–25, 2003, BRICS Notes Series NS-03-3, 2003.
12. Developments in Language Theory, Proceedings of the 7th International Conference, DLT 2003, LNCS 2710, Springer, 2003.
13. Proceedings of the 3rd Conference for PhD Students, CSCS 2002, Special Issue of Acta Cybernetica, Volume 16, Number 2, 2003.

II. ORGANIZED CONFERENCES

In the period 2003–3006 the Department of Foundations of Computer Science has organized the following conferences and workshops:

1. Computer Science Logic, CSL 2006, Szeged, Hungary, September 25–29, 2006.
2. Logic and Combinatorics, Satellite Workshop of CSL 2006, Szeged, Hungary, September 23–24, 2006.
3. Algebraic Theory of Automata and Logic, Satellite Workshop of CSL 2006, Szeged, Hungary, September 30 and October 1, 2006.
4. Automata and Formal Languages, 11th International Conference, AFL 2005, Dobogókő, Hungary, May 17–20, 2005.
5. Developments in Language Theory, 7th International Conference, DLT 2003, Szeged, Hungary, July 7–11, 2003.

Department of Image Processing and Computer Graphics

I. MEDICAL AND NEUTRON TOMOGRAPHY APPLICATIONS OF AN AUTOMATIC REGISTRATION METHOD

Registration is a fundamental task in image processing. Its purpose is to find a geometrical transformation that relates the points of an image to their corresponding points of another image. Many registration algorithms have been proposed in the past decade. Automatic methods become more and more popular due to their convenient usability and with the computing power of today's computers the running time is acceptable for many applications. We have developed a fast, fully automatic algorithm that is capable of solving linear registration of 2D and 3D images of different sources. For medical images, we joined the Retrospective Registration Evaluation Project conducted by Vanderbilt University, USA. We also applied the method to register 2D neutron tomography images with success. The evaluations show that our method has the potential to produce satisfactory results, but visual inspection is necessary to guard against large errors.

II. REGISTRATION METHOD

First we describe the fully automatic, iterative registration method that is capable of finding linear transformations to align images from the same or different modalities (i.e., taken by the same or different imaging devices).

We follow the notations of [4]. Let X denote the object to be imaged, and let A and B be 3D images of X taken by the same or different imaging devices. The images usually have different fields of view, thus the domains Ω_A and Ω_B will be different. $A(x_A)$ and $B(x_B)$ are referred to as the intensity values at spatial positions x_A and x_B, respectively. Intensity values represent some kind of measurement of the material in spatial positions of X, such as attenuation of X-ray beams in case of Computed Tomography (CT), changes in states of protons under changing the magnetic field properties in Magnetic Resonance Imaging (MRI), or distribution of nuclear tracers in case of Positron Emission Tomography (PET) and Single Photon Emission Computed Tomography (SPECT).

As the images A and B represent the same object X, there is a relation between the spatial locations in A and B: position $x \in X$ is mapped to x_A in image A, and to x_B in image B. The registration process involves recovering the spatial transformation T which maps x_B to x_A over the entire domain of interest, which can be the entire domain of image A or the overlapping portion of the domains.

The medical images are discrete, they sample the object at a finite number of points. Sample spacing can be different for different images. These grid positions and the corresponding sample values together are referred to as voxels.

For any given T, the intersection of discrete domains Ω_A and Ω_B might be the empty set, when no sample points will exactly overlap. To overcome this, we have to resample image intensities of image B in Ω_A. The simplest resampling method is to select the intensity value of the closest grid position of Ω_B.

Linear or more complex interpolation methods (cubic spline, B-Spline, Sinc) can also be used. Let $\mathcal{T}$ denote the transformation that maps both the position and the associated intensity value at that position, and B^T the resampled image B.

The selection of the similarity measure is probably the most crucial part of a registration algorithm. We need a function which optimally has one global optimum at perfect alignment, has no local optimums, and is "smooth enough" to find this optimum fast. Practically it is very hard, or even impossible to find such a similarity measure, especially when the images are taken by different imaging devices. Many similarity measures were proposed in the past decade. We chose the measures based on the mutual information of the images proposed by Collignon et al. [3] and Viola and Wells [11,12], and on the normalized mutual information of the images proposed by Studholme et al [8].

Both measures utilize the entropy of image A,

$$H(A) = -\sum_a p_A^T(a) \cdot \log p_A^T(a),$$

the entropy of image B,

$$H(B) = -\sum_b p_B^T(b) \cdot \log p_B^T(b),$$

and the joint entropy of images A and B,

$$H(A,B) = -\sum_a \sum_b p_{AB}^T(a,b) \cdot \log p_{AB}^T(a,b),$$

where p_A and p_B are the histograms, and p_{AB} is the co-occurrence matrix of the intensity values of images A and B.

Mutual information is computed as

$$MI(A,B) = H(A) + H(B) - H(A,B),$$

and the normalized mutual information as

$$NMI(A,B) = \frac{H(A) + H(B)}{H(A,B)}.$$

We found that when mutual information is calculated over the overlapping domain $\Omega_{A,B}^T$, the failure rate is high [8]. We decided to use the whole Ω_A instead, in case of this measure, which solved the problem.

To speed up the registration process and to avoid falling into a local optimum, we use the Gaussian multiresolution pyramid representation of the images [1]. The search starts at the coarsest level. When an optimum is found, the result is propagated to the next, finer level. We use Powell's direction set, iterative, nonlinear optimization algorithm to find the optimum of the similarity measure [7]. Further optimizations of the algorithm can be found in [9].

III. EVALUATION OF MR–CT AND MR–PET REGISTRATION

It is necessary to measure the quality of alignment to be able to decide whether a registration algorithm is suitable for solving a given registration problem. The alignment need not be perfect, but the error must be below a certain (application dependent) threshold. The similarity measure cannot be used to judge this, since it is not guaranteed that it reaches its global optimum at perfect alignment. An other method, visual inspection is generally applicable. Although visual inspection is always necessary since the automatic methods occassionally might fall into a nonglobal optimum producing a bad result without any warnings, a more accurate evulation procedure based on some kind of measurements is necessary. An overview of such procedures can be found in [4].

To evaluate our registration method, we joined the Retrospective Registration Evaluation Project of Vanderbilt University, USA in 1999 [13]. The objective of that project was to perform blinded evaluation of retrospective image registration techniques using a prospective, marker-based registration method as a gold standard. A gold standard is a system whose accuracy is known to be high. A fiducial marker system can serve as an excellent gold standard for rigid registration, since some of these systems can provide submillimetric accuracy. The primary disadvantage is the high invasiveness i.e., bone-implanted markers [6]. In order to ensure blindness, all retrospective registrations were performed by participants who had no knowledge of the gold-standard until after their results had been submitted.

The evaluation followed these steps. Image volumes of three modalities: X-ray computed tomography (CT), magnetic resonance (MR), and positron emission tomography (PET) were obtained from patients undergoing neurosurgery at Vanderbilt University Medical Center, on whom bone-implanted markers were mounted. These volumes had all traces of the markers removed and were provided to project collaborators outside Vanderbilt, who then performed registration on the volumes. The investigators communicated their results to Vanderbilt, where the accuracy of each registration was evaluated.

Two registration tasks were evaluated: CT to MR and PET to MR, and these tasks were broken into subtasks according to the type of MR and to whether or not the MR image was corrected (rectified) for geometrical distortion. The image data set of nine patients were used, seven of which contained both CT and MR, and seven with both PET and MR.

The results of the project were published in [13] and [14]. Since we joined the project later, our results were not included in those papers, thus we compared our results against those evaluated earlier [9].

Before the evaluation of our results, we visually inspected the quality of registration. Using the NMI method, all registration results were visually acceptable. In case of mutual information, for the CT to MR task, all 41 results were visually acceptable. In case of PET to MR, for five image pairs the results of registration was visually misregistered. The other 30 results were visually acceptable. In spite of these clear misregistrations, all results were submitted for evaluation to Vanderbilt University. Figure 5 show the result of a MR–CT registration problem.

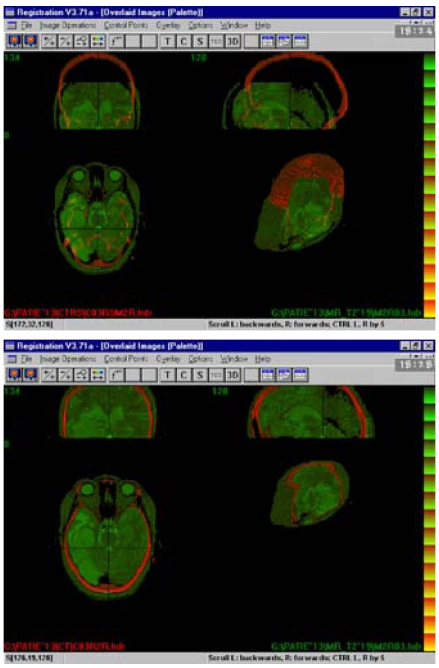

Figure 5. Fusion of the CT to MR registration problem for Patinet #5, before (top) and after (bottom) registration. CT data is shown in red, MR data in green color.

The results show that in case of CT to MR registration task, both of our methods produce acceptable results. Our MI method ranks high, the NMI method produces average results. For PET to MR problems, the MI method tends to fail (five failures out of 35 cases), and produces average results. The NMI method gives stable results and ranks high among the competing algorithms. The running time was about 30-120 seconds on a 800 Mhz Pentium-III PC. More detailed results of the evaluation of our methods can be found at
`http://www.vuse.vanderbilt.edu/~image`.

IV. APPLICATION OF AUTOMATIC REGISTRATION IN SEGMENTING ORGANS OF THE PELVIC REGION

In a cooperation with General Electric Medical Systems Hungary, the algorithm had been modified to solve pelvic CT–CT registration problems of different patients. When segmenting organs of the pelvic region, transforming (or registering) CT studies of different patients to a common reference frame can be used in two preprocessing tasks:

- Generating a probability atlas, or a deformable organ model (model creation),
- and in the clinical application, establishing the voxel-to-voxel correspondence between the study to be segmented and the probability atlas or model (initial organ placement).

In these cases precise alignment of all anatomical structures is not crucial, the focus is on proper alignment of the pubic bone area and fast execution.

Studies are registered against a previously selected suitable reference study. The modified algorithm consists of two steps. First, a global nine degree of freedom transformation (three rotation, three scale, and three translation) is to be found. Then this is locally refined in the pubic bone area, modifying six of the parameters (three rotation and three translation). The

local neighbourhood of the pubic bone area is selected manually for the reference study only, as a preprocessing step.

It has been shown that after the refinement step, prostate regions are significantly ($P < 0.05$ using Student t-test) closer to each other [10]. The study database was provided by General Electric Medical Systems and consisted of 26 CT images with expert segmented "gold-standard" prostate and bladder regions. The failure rate was low (three out of 26), even though many of the studies were distorted by artificial metallic objects or not satisfying the assumed protocol. The running time is 20–40 seconds using a 3 Ghz Pentium IV desktop PC. It is possible to make it even faster by removing the unnecessary image regions (the border around the patient) of the reference study.

V. APPLICATION OF IMAGE REGISTRATION IN NEUTRON TOMOGRAPHY

We could use the registration algorithm in an interesting, non-medical problem [2, 5]. Using neutron radiography, the inner regions of object made from metal, copper, or aluminum can be inspected, which is more useable than using conventional X-ray techniques due to their much lower contast properties. Similarly to X-ray, a neutron ray is passing through the inspected object while it is attenuated more or less according to the object properties. An imaging plate is placed at the back of the inspected object which detects the intensity of the passed ray. By rotating the object around its axis, a set of 2D projections is generated. Using discrete or conventional tomography algorithms, a 3D model of the object can be obtained.

The imaging process consists of the following steps. The object is placed on a table which can be rotated around by a given angle after the 2D image is taken. At the back of the object a rail track is situated, in which the casing of the imaging plate can be moved. After an image is taken, the casing is removed, the imaging plate is taken out of the casing and the image data is read. After deleting the contents of the imaging plate, it is put back into the casing and moved to the back of the object using the rail track.

The way the images are taken introduces geometric differences between the consecutive projections. It means that the same projection directions from the source might pass the imaging plate at different pixel locations. Such geometric differences can degrade the result of the reconstruction. The task of the image registration algorithm is to recover these geometric differences.

If we take a closer look at the way the images are taken, we can conclude that placing the casing in and out cannot produce significant errors. The rail track provides one way motion only, and an immobile bumper stops the casing precisely enough. The main source of error is the moving of the imaging plate in and out from the casing. To track these movings, external markers attached to the casing are applied, the projections of which are visible in the top, bottom, left and right hand side of the images. Since the imaging plate moves with respect to these markers, we can expect that when the markers are aligned, the image data is suitable for reconstruction.

It is assumed that a rigid-body transformation (translation along the axes and rotation about the center of the image) can align the images. The registration algorithm utilizes the normalized version of mutual information as pixel similarity measure. One of the projection images is selected as the reference image and the others are registered against it one by one. Although the algorithm is fully automatic, a preprocessing step is necessary. The center region of the images, where the projection of the object is visible must be masked out and the similarity measure is evaluated only outside of it. This mask selection is necessary only for the reference image. The result of the preprocessing step is shown in Figure 6.

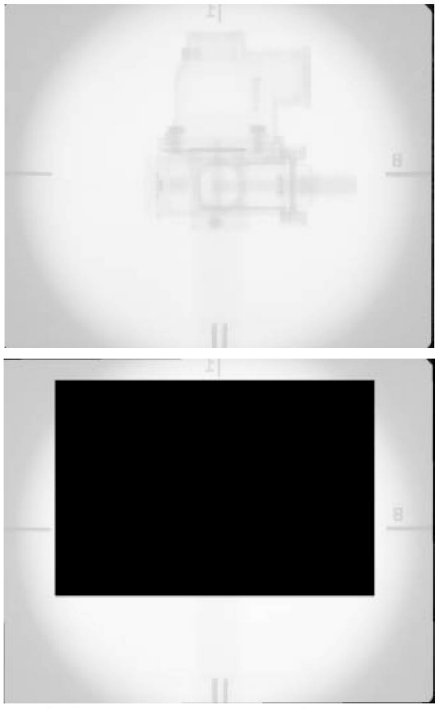

Figure 6. A 2D projection image of a gas pressure regulator (top) and the manually selected masked region (bottom).

The running time is around 90–120 seconds for images of size 5000×4000 pixels. Visual inspection confirmed that the registration provided acceptable results, the markers align reasonably well and the result can be used for tomographic reconstruction. We can expect further improvements in precision if the markers were attached to the rail track instead of the casing.

VI. CONCLUSIONS

In this paper we summarized our experiments using an automatic, voxel-similarity based registration method for medical and non-medical problems. We can conclude that voxel-similarity measures, in our case the ones based on mutual information, can be successfully applied to align multimodal medical images and neutron tomography images also. Although the registration itself is fully automatic, in some cases manual selection of masked out regions is required as a preprocessing step. Especially when aligning neutron tomography images using external markers, other solutions could also be considered by detecting those markers and aligning the extracted geometric features. Such an approach could work without any preprocessing steps and could be much faster than the approach we used. The problem of such an approach is that it requires special programming and it would require much

more development time. When the running time is not crucial, our automatic approach is able to solve the problem without any severe modifications.

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VII. DISCRETE TOMOGRAPHY

Discrete Tomography (DT) deals with the reconstruction of discrete valued functions from their line integrals along certain directions called projections. The function itself usually represents a two-dimensional cross-section of an object consisting of a small number of homogeneous materials, while the projections can be regarded as the results of some imaging methods (like, e.g., X-ray, gamma, or neutron imaging). Typical applications arise in non-destructing testing of industrial parts, investigating of crystalline or macromolecule structures with electron microscopy or examining the shape of blood vessels and heart chambers in human body with angiography. In all of these applications there is a strong reason that restricts the number of available projections to at most about 10 (often only 2 or 4). This usually yields ambiguous reconstruction, i.e., the result image of a classical reconstruction method can be quite dissimilar to the original one. Another problem is that the reconstruction problem is in most cases NP-hard. Therefore, in DT more sophisticated methods are needed that can guarantee accurate and fast reconstruction despite the fact that there are a few available projections. Such methods can be developed by exploit the prior knowledge that the image to be reconstructed can contain only a small number of different intensity values.

RECONSTRUCTION WITH GEOMETRICAL PRIORS

One way to reduce ambiguity and to avoid intractability is to suppose that one wants to reconstruct a binary image (also called discrete set) that belongs to a certain class of images having some geometrical properties (connectedness, convexity, etc.). The main challenge here is to find geometrical properties that drastically reduces the number of possible solutions of the same reconstruction problem but still keeps the reconstruction process tractable.

Although a former result shows that the reconstruction in the class of horizontally and vertically convex (shortly, *hv*-convex) discrete sets from two projections is NP-hard we have shown that it is possible to reconstruct all the solutions of the same reconstruction task with a quite fast algorithm in polynomial-time if we have the additional information that the set to be reconstructed is also 8-connected and consists of several components [5].

For so called Q-convex sets a fast operation is also presented that can speed up the reconstruction of such kind of sets [6]. Moreover we also investigated how the knowledge that the Q-convex set is not 8-connected can facilitate the reconstruction.

We also generalised a uniqueness result of directed horizontally or vertically convex polyominoes and showed that this result also holds if the polyomino is diagonally convex. Additionally, a negative result is also given showing that for any other direction of convexity there can be exponentially many line-convex polyominoes with the same horizontal and vertical projections [3].

The general task of reconstructing a discrete set from four projections is NP-hard, too. In [4] we introduced the class of decomposable discrete sets and developed a polynomial-time reconstruction algorithm for this class using four projections. We also analysed the possibility to adapt the developed technique for the reconstruction problems in the classes of Q-convexes and hv-convexes.

EMISSION DISCRETE TOMOGRAPHY

Recently, a new field of DT called *Emission Discrete Tomography* (EDT) has been studied. In this model the function to be reconstructed represents an object having some radiation surrounded by a homogeneous material having certain absorption. Thus, the projections are depending not only the emission but the absorption, too. Uniqueness and non-uniqueness theorems for EDT was proved in [10] and [14]. Moreover, in [9] the surprising result was published that in the EDT model the reconstruction of hv-convex discrete sets from two projection can be done in polynomial time, at least for a certain absorption coefficient.

RECONSTRUCTION WITH OPTIMIZATION

The reconstruction process can also be formulated as an optimization task where the aim is to find the global minimum of the objective functional

$$\Phi(f) = \sum_{\vartheta} ||[\mathcal{R}f](\vartheta) - P_{\vartheta}||^2 + \gamma||f - f_0||^2$$

where P_{ϑ} denotes the input projection of angle ϑ, f is the image function that approximates the solution, $[\mathcal{R}f](\vartheta)$ denotes the projection of the image f taken at angle ϑ, $||.||$ is the Euclidean norm, and $\gamma \geq 0$ is a regularizing parameter. f_0 is a prototype function that has the same domain and range as f, and is similar to the expected reconstruction result. Such a model has the advantage that due to the second term on the right hand side prior information of the image to be reconstructed can be incorporated. Moreover, it also can handle incorrect measurements of projections. The regularazing parameter γ stands for controlling whether prior information or the projections are more reliable in a certain reconstruction task.

Such kind of optimization problems can be solved, e.g., by a simulated annealing (SA) approach. A lot of work has been done at our department in this field, mostly concentrating on applications of neutron and X-ray tomography [1,2,8,12,13]. The same technique was applied to solve some reconstruction problems in the case of so-called fan-beam projections [15,16].

However, SA is not the only method by which the above optimization problem can be solved. Very recently, SA was compared to a dc-programming method from the viewpoint of reconstruction efficiency. It turned out that (for the images used in that comparison) there is no significant difference of accuracy and running time between the two methods [18].

DIRECT FRAMEWORK

DIscrete REConstruction Techniques (DIRECT) is a toolkit for testing and comparing 2D/3D reconstruction methods of discrete tomography. The toolkit involves generating projections of discrete objects, running reconstruction methods, and visualization of result. Most of the reconstruction techniques developed at our department are built-in into this framework which is updated from time to time. The DIRECT toolkit can be reached at

`http://www.inf.u-szeged.hu/~direct/`

with a full access for registered users.

CONFERENCES ORGANIZED

The Workshop on Discrete Tomography and Its Applications was held in June 2005 in New York City with the co-organization of Attila Kuba. This small conference attracted more than 60 participants from 10 countries including all the authors of the present paper. The conference proceedings was published electronically [17] and includes 38 contributions from which 9 were written by our collegues as a sole or coauthor. Furthermore, based on some of the talks a book was edited entitled Advances in Discrete Tomography and Its Applications that will be published in March 2007 [7], in which 6 from the 15 chapters are written by the members of our group, solely or partially. Further informations on the conference are available at

`http://www.dig.cs.gc.cuny.edu/`

The 13th Conference on Discrete Geometry for Computer Imagery was held in Szeged in October 2006. As part of the conference program one session was devoted to the topic of DT. Some of the authors of this paper has also publications in the conference proceedings [11]. The homepage of the conference can be found at

`http://www.inf.u-szeged.hu/dgci`

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VIII. HIGHER-ORDER ACTIVE CONTOURS AND ITS APPLICATION TO TREE CROWN DETECTION

OBJECTIVES, GOALS

The aim of our work is to introduce prior shape knowledge into existing image segmentation models. To accomplish we extended the recently introduced higher-order active contour framework for region and image modeling by introducing a model for a 'gas of circles', the ensemble of regions in the image domain consisting of an unknown number of circles, with approximately fixed radius and short range of interactions. We applied the developed models of current interest in remote sensing image processing: the extraction of tree crowns. Forestry services are interested in various quantities associated with forests and plantations, such as the density of trees, the mean crown area and diameter, etc.

To include more complex prior knowledge, longer-range interactions are needed. There is a large body of work that does this implicitly, via a template region or regions to which the segmented region R is compared. However, such energies effectively limit R to a bounded subset of region space close to the template(s), which excludes, *inter alia*, cases like tree crown extraction in which R has an unknown number of connected components. 'Higher-order active contours' (HOACs) provide a complementary approach. HOACs generalize classical active contours to include multiple integrals over the contour. Thus HOAC energies explicitly model long-range interactions between boundary points without using a template. This allows the inclusion of complex prior knowledge while permitting the region to have an arbitrary number of connected components, which furthermore may interact amongst themselves. The approach is very general: classical energies are linear functionals on the space of regions; HOACs include all polynomial functionals.

In [2,3,6], a HOAC energy was used for tree crown extraction. In this 'gas of circles' model, collections of mutually repelling circles of given radius r_0 are local minima of the geometric energy. The model has many potential applications in varied domains, but it suffers from a drawback: such local minima can trap the gradient descent algorithm used to minimize the energy, thus producing phantom circles even with no supporting data. The model as such is not at fault: an algorithm capable of finding the global minimum would not produce phantom circles. This suggests two approaches to tackling the difficulty. One is to find a better algorithm. The other is to compromise with the existing algorithm by changing the model to avoid the creation of local minima, while keeping intact the prior knowledge contained in the model. We solved the problem of phantom circles in [2, 3, 6]'s model by calculating, via a Taylor expansion of the energy, parameter values that make the circles into inflection points rather than minima. In addition, we find that this constraint halves the number of model parameters, and severely constrains one of the two that remain, while improving the empirical success of the model [4, 5].

THE 'GAS OF CIRCLES' MODEL

HOAC energies generalize classical active contour energies by including multiple integrals over the contour. The simplest such generalizations are quadratic

energies, which contains double integrals. There are several forms that such multiple integrals can take, depending on whether or not they take into account contour direction at the interacting points. The Euclidean invariant version of one of these forms is

$$E_g(\gamma) = \lambda L(\gamma) + \alpha A(\gamma) - \frac{\beta}{2}\int\int \tau(p)\cdot\tau(p')\Psi(|p,p'|)dpdp',$$

where γ is the contour, parameterized by p; L is the length of the contour; A is the area; $|p,p'| = |\gamma(p) - \gamma(p')|$; $\tau = \dot{\gamma}$ is the (unnormalized) tangent vector to the contour; and Ψ is an interaction function that determines the geometric content of the model. With an appropriate choice of interaction function Ψ, the quadratic term creates a repulsion between antiparallel tangent vectors. This has two effects. First, for particular ranges of α, β, and d_{min} ($\lambda = 1$ wlog), circular structures, with a radius r_0 dependent on the parameter values, are stable to perturbations of their boundary. Second, such circles repel one another if they approach closer than $2d_{min}$. Regions consisting of collections of circles of radius r_0 separated by distances greater than $2d_{min}$ are thus local energy minima. We [2, 3, 6] called this the 'gas of circles' model.

Via a stability analysis, we [2,3,6] found the ranges of parameter values rendering circles of a given radius stable as functions of the desired radius. Stability, however, created its own problems, as circles sometimes formed in places where there was no supportive data. To overcome this problem, in [4,5], the criterion that circles of a given radius be local energy minima was replaced by the criterion that they be points of inflexion. As well as curing the problem of 'phantom' circles, this revised criterion allowed the fixing of the parameters α, β, and d_{min} as functions of the desired circle radius, leaving only the overall strength of the prior term, λ, unknown. For energy-based models, parameter adjustment is a problem, so this is a welcome advance.

To illustrate the behaviour of the prior model, figure 7 shows the result of gradient descent starting from the region on the left. Note that there is no data term. The parameter values in these experiments render the circles involved stable. With the parameter values calculated in [4,5], they would disappear.

Figure 8 illustrates results using the published models.

A MULTI-SPECTRAL DATA MODEL

In the above models we also described a likelihood model. This described the behaviour of only one band of the three available bands in the CIR images which we are using provided by the French Forest Inventory (IFN). The model was Gaussian, with the values at different pixels independent, and with different means and variances for tree crowns and the background. While successful, this model, even with the strong region prior, was not capable of extracting accurately the borders of all trees. Some trees were simply too similar to the background. The purpose of [1], is to replace the likelihood model in [2–6] by one that makes use of all three bands in the CIR images. We studied the improvement or otherwise of the extraction results produced by modelling the three bands as independent or as correlated. As we shown, even at the level of maximum likelihood, the inclusion of 'colour' information, and in particular, interband correlations, can greatly improve the results, and in conjunction with the region prior, the full model is considerably better than that based on one band alone. The results can be seen on figure 9.

COLLABORATION

This work is a joint research between ARIANA research group of INRIA Sophia Antipolis, France and Institute of Informatics, University of Szeged; based on a bidirectional Ph.D. work. The project started in 2004.

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IX. PARAMETRIC ESTIMATIONS OF 2D AFFINE TRANSFORMATIONS ON BINARY IMAGES

We consider the problem of planar object registration on binary images. The purpose is to find an unknown transformation between a given known object (template) and a distorted observation of the template. We only consider affine transformations (translation, scaling, rotation and shearing). The direct approach

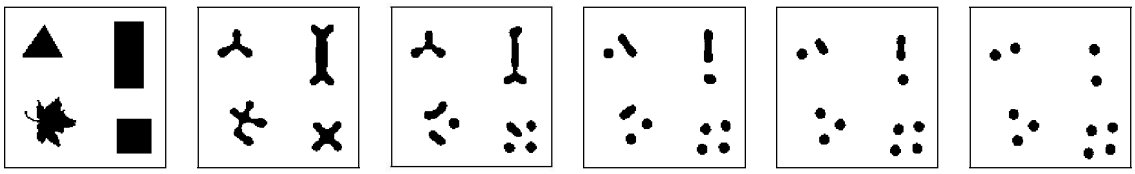


Figure 7. Sequences of curve evolution using E_g itself, from left to right: from the initialization to stable state.

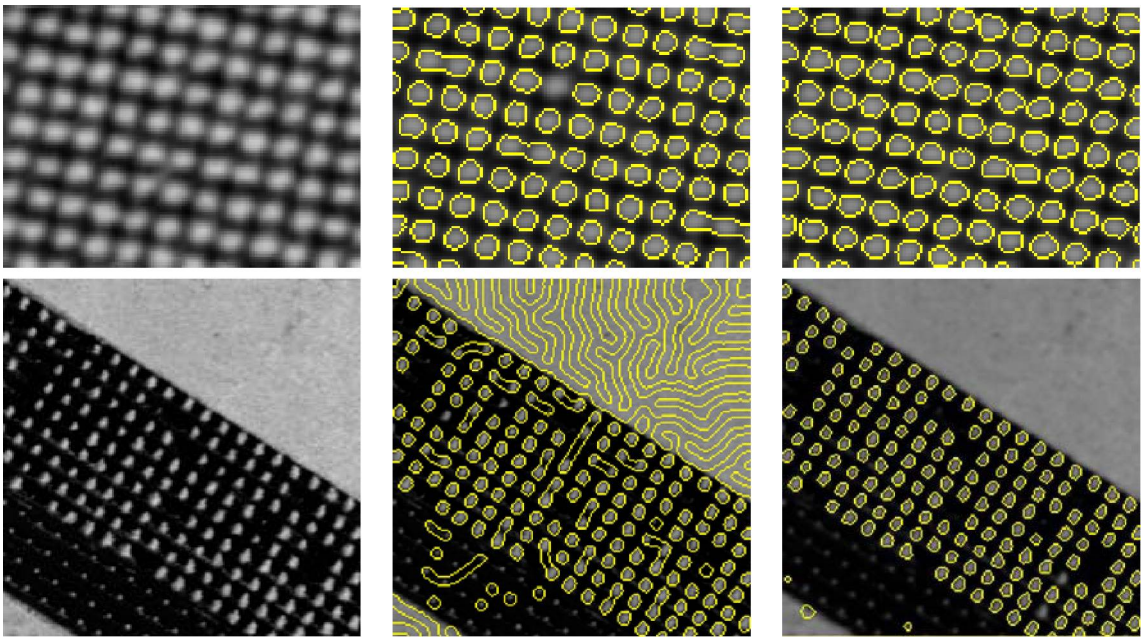


Figure 8. Results on real aerial images, first column: original, second: results with [2, 3, 6] model, last column: results using [4, 5]. IFN ©

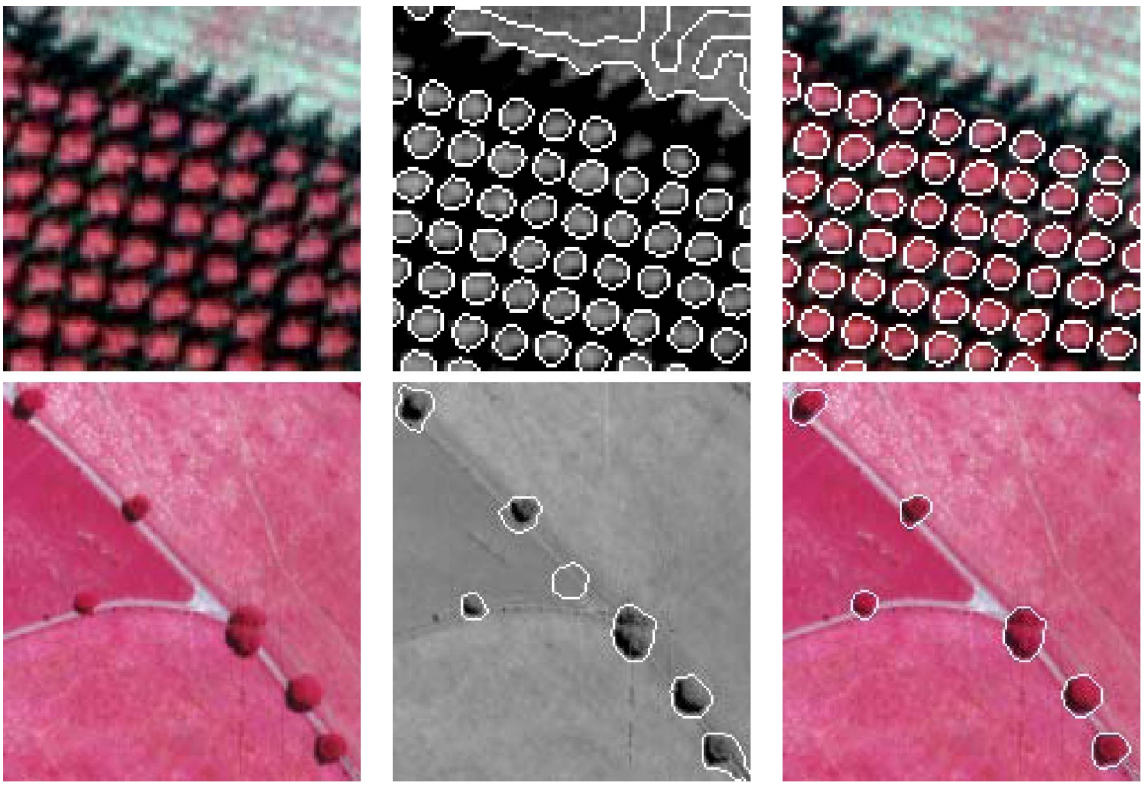


Figure 9. Results on real CIR aerial images, first column: original images, second: results using only the infrared channel, last column: results using [1] model. IFN ©

is to apply each of the allowed affine deformations to the template and search for the one that matches the observation. While the object is known, the tremendous number of possible transformations makes this approach unfeasible. Therefore classical registration algorithms reformulate the task as a non-linear optimization problem. Our approach adopts a novel idea where the exact transformation is obtained as a solution of a set of polynomial equations. These equations are constructed in a simple way using some basic geometric information of the binary image. Another advantage of the proposed solution is that it is fast, unique and exact regardless of the magnitude of transformation.

INTRODUCTION

Image registration is a crucial step in almost all image processing tasks [1,8] where images of different views or sensors of an object need to be compared or combined. In a general setting, one is looking for a transformation which aligns two images such that one image (called the *observation*) becomes similar to the second one (called the *template*). Due to the large number of possible transformations, there is a huge variability of the object signature. In fact, each *observation* is an element of the orbit of the transformations applied to the *template*. Hence the problem is inherently *ill-defined* unless this variability is taken into account. Recently, a novel approach has been proposed by Hagege and Francos [4–6] which provides an accurate and computationally simple solution to the problem avoiding both the correspondence problem as well as the need for optimization. The fundamental novelty is that it reformulates the original problem as an *equivalent linear parameter estimation* one having a *unique* and *exact* solution.

ESTIMATION OF 2D AFFINE TRANSFORMATIONS

The parametric estimation of two-dimensional affine transformations between two gray-level images has been addressed by Hagege and Francos in [6]: The *observation* and *template* is regarded as two bounded, Lebesgue measurable two-dimensional functions g and h (both mapping $\mathbb{R}^2 \rightarrow \mathbb{R}$) such that $h(\mathbf{x}) = g(\boldsymbol{A}\mathbf{x})$, where $\boldsymbol{A}$ is the unknown affine transformation that we want to recover. The proposed solution yields to a system of linear equations employing only zero and first order constraints while higher order moments are avoided. In this project, we have addressed an important special case: the registration of *binary* images.

Binary images do not contain radiometric information hence they can be represented by the characteristic function $\quad : \mathbb{R}^2 \rightarrow \{0,1\}$, where 0 and 1 correspond to the background and foreground respectively. Let us denote the *template* by $\quad_t$ and the *observation* by $\quad_o$. We will also use the following notations:

$$\mathbf{x} = [x_1, x_2]^T \text{ and } \mathbf{y} = [y_1, y_2]^T, \text{ where } \mathbf{x}, \mathbf{y} \in \mathbb{R}^2$$

$$\boldsymbol{A} = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \text{ and } \boldsymbol{A}^{-1} = \begin{pmatrix} q_{11} & q_{12} \\ q_{21} & q_{22} \end{pmatrix}$$

$$\mathbf{y} = \boldsymbol{A}\mathbf{x}, \quad \mathbf{x} = \boldsymbol{A}^{-1}\mathbf{y} \tag{1}$$

If $\boldsymbol{A}$ is the transformation which aligns the *observation* and *template*, then the following equality holds:

$$_t(\mathbf{x}) = \quad _o(\boldsymbol{A}\mathbf{x}) \tag{2}$$

Now we will construct a solution for $\boldsymbol{A}$. Note that it is also possible to solve for $\boldsymbol{A}^{-1}$ since $\boldsymbol{A}$ must be invertible. The first step is to find the determinant of $\boldsymbol{A}$, *i.e.* the measure of the transformation. A simple approach is to integrate $\quad_t(\mathbf{x})$ by substitution using Eq. (2). Note that we always use Lebesgue integrals. The Jacobian $|\boldsymbol{A}|$ can then be evaluated through the identity relation

$$\int_{\mathbb{R}^2} \quad _t(\mathbf{x}) = \int_{\mathbb{R}^2} \quad _o(\boldsymbol{A}\mathbf{x}) = |\boldsymbol{A}^{-1}| \int_{\mathbb{R}^2} \quad _o(\mathbf{y}) \tag{3}$$

$$|\boldsymbol{A}| = \frac{\int_{\mathbb{R}^2} \quad _o(\mathbf{y})}{\int_{\mathbb{R}^2} \quad _t(\mathbf{x})} \tag{4}$$

The equality in Eq. (2) remains valid if we multiply by the same non-zero constant or take the integral of both sides. Hence for $k = 1, 2$, we have

$$\int_{\mathbb{R}^2} x_k \quad _t(\mathbf{x}) = |\boldsymbol{A}^{-1}| \sum_{i=1}^{2} q_{ki} \int_{\mathbb{R}^2} y_i \quad _o(\mathbf{y}) \tag{5}$$

Since the characteristic functions take only values from $\{0,1\}$, we can further simplify the above integrals:

$$\int_{\mathbb{R}^2} \quad (\mathbf{x}) = \int_{\mathcal{F}} 1 \tag{6}$$

where the domain $\mathcal{F}$ consists of the foreground regions: $\mathcal{F} = \{\mathbf{x} \in \mathbb{R}^2 | \quad (\mathbf{x}) = 1\}$. Therefore evaluating the integrals in Eq. (6) yields the *area* of the foreground regions. From this point of view, the measure of the transformation $|\boldsymbol{A}|$ corresponds to the ratio of the *observation* and *template* objects' area. In the remaining part of this paper, we will always integrate over the respective domain $\mathcal{F}$ unless otherwise noted. Therefore we obtain from Eq. (19) and Eq. (6)

$$q_{k1} \int y_1 + q_{k2} \int y_2 - |\boldsymbol{A}| \int x_k = 0, \quad k = 1, 2 \tag{7}$$

Let us notice that these equations are based on the first order moments of the object on the *observation* and *template*. Similarly, we can obtain another two equations by matching the second order moments of the object:

$$q_{k1}^2 \int y_1^2 + 2q_{k1}q_{k2} \int y_1 y_2 + q_{k2}^2 \int y_2^2 - |\boldsymbol{A}| \int x_k^2 = 0 \tag{8}$$

where $k = 1, 2$. The system (7),(8) provides 4 equations which is enough to solve for the four unknowns. We may get up to two possible solutions for each unknown q_{ki} due to the quadratic polynomial equations in Eq. (8). Out of these potential solutions, we have to chose the transformation whose elements are real and the determinant equals the Jacobian $|\boldsymbol{A}^{-1}|$ computed in Eq. (4). The sign ambiguity of the determinant can be easily eliminated: A negative Jacobian would mean that the transformation is not orientation-preserving (*i.e.* flipping of coordinates is allowed). In practice, however, physical constraints will usually prevent such a transformation hence we can assume that $|\boldsymbol{A}|$ is always positive. The *uniqueness* of the solution is then guaranteed as long as the observation and template is not affine symmetric (see [4] for the proof).

Let us now examine the existence of the solution. For that purpose, rewrite Eq. (7) and Eq. (8) for a fixed k in the following simplified form, where we omit the k index and replace the coefficients of the unknowns by $a, b, \ldots, g$:

$$\begin{aligned} aq_1 + bq_2 - c &= 0 \\ dq_1^2 + eq_1q_2 + fq_2^2 - g &= 0 \end{aligned} \tag{9}$$

We will show that an algebraic solution of the system exists if the *resultant* [2] has a real solution: Assuming $a \neq 0$, let us rewrite the system Eq. (9) in terms of q_1:

$$\begin{aligned} aq_1 + (bq_2 - c) &= 0 \\ dq_1^2 + (eq_2)q_1 + (fq_2^2 - g) &= 0 \end{aligned} \quad (10)$$

Since $d > 0$, a sufficient condition for the existence of common roots of the system Eq. (9) is that the resultant of the system must have real roots:

$$(a^2f + b^2d - abe)q_2^2 + (ace - 2bcd)q_2 + (c^2d - a^2g) = 0 \quad (11)$$

Obviously, the above quadratic polynomial has real roots if its discriminant D is non-negative:

$$D = (ace - 2bcd)^2 - 4(a^2f + b^2d - abe)(c^2d - a^2g) \geq 0$$

Note that D can always be computed hence our algorithm can always tell whether a solution exists or not.

ESTIMATION IN THE PRESENCE OF TRANSLATION

In the following we extend the presented solution and show how to obtain the parameters when the transformation also includes an unknown translation [4]:

$$\mathbf{y} = \boldsymbol{A}\mathbf{x} + \mathbf{c}, \quad \mathbf{x} = \boldsymbol{A}^{-1}\mathbf{y} - \boldsymbol{A}^{-1}\mathbf{c}, \text{ and}$$

$$_t(\mathbf{x}) = \ _o(\boldsymbol{A}\mathbf{x} + \mathbf{c}) \quad (12)$$

where $\mathbf{c}$ is a two-dimensional real vector representing the translation along the two axis. We can put all parameters in a single matrix by using homogeneous coordinates. More specifically let $-\boldsymbol{A}^{-1}\mathbf{c} = [q_{10}, q_{20}]^T$ and $\tilde{\mathbf{y}} = [1, y_1, y_2]^T$. Eq. (12) becomes

$$\mathbf{x} = \boldsymbol{T}\tilde{\mathbf{y}} \text{ with } \boldsymbol{T} = \begin{pmatrix} q_{10} & q_{11} & q_{12} \\ q_{20} & q_{21} & q_{22} \end{pmatrix} \quad (13)$$

The *first* column of $\boldsymbol{T}$ contains the translational parameters. The Jacobian of the transformation can be computed by Eq. (4) since the translation has no effect on the measure of the transformation. Furthermore, $_o(\mathbf{y}) \equiv \ _o(\tilde{\mathbf{y}})$ by definition, hence Eq. (19) and Eq. (7) can be rewritten as follows:

$$\int x_k \ _t(\mathbf{x}) = \int \boldsymbol{T}_k\tilde{\mathbf{y}} \ _o(\boldsymbol{A}\mathbf{x} + \mathbf{c})$$

$$q_{k0}\int 1 + q_{k1}\int y_1 + q_{k2}\int y_2 = |\boldsymbol{A}|\int x_k, \quad k = 1, 2 \quad (14)$$

The second order moment equations can be similarly rewritten. In the translational case, however, we have two more variables, therefore we have to add two more equations. This is achieved by matching the third order moments.

Now the system of equations contains six polynomial equations up to order three. Therefore we may get up to six possible values for each unknown q_{ki}. Out of these solutions, we can select the right one by following the procedure described in the previous section (*i.e.* drop the complex roots and select the transformation whose determinant matches the Jacobian computed by Eq. (4)).

NUMERICAL IMPLEMENTATION

In the previous section, we have constructed a system of polynomial equations and shown how to obtain an exact solution. These equations are defined in the continuum while in practice we are working on digital (*i.e.* discrete) images. This means that an integral over the domain $\mathcal{F}$ can only be *approximated* by a discrete sum over the foreground pixels introducing an inherent, although negligible error into our computation. A more important issue is the numerical error caused by unnormalized image coordinates. This can be especially severe in our case since we are working with squares and third powers of the coordinates. A standard technique to minimize this error is to transform the whole image into $[-1, 1] \times [-1, 1]$ (see Fig. 10): Fist we apply $\boldsymbol{H}$ to the template image T and $\boldsymbol{G}$ to the observed image O. Then the normalized images O' and T' are registrated.

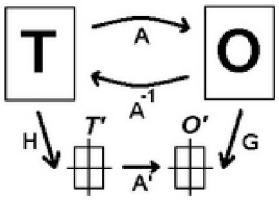


Figure 10. Normalization of the template T and observation O. The origin is translated to the center of the image and then it is scaled into $[-1, 1] \times [-1, 1]$.

Of course, we have to take into account the effect of normalization in our calculations since it affects the measures. Therefore the Jacobian of the transformation is computed as

$$|\boldsymbol{A}'| = \frac{|\boldsymbol{G}| \int \ _o(\mathbf{y})}{|\boldsymbol{H}| \int \ _t(\mathbf{x})} = \frac{|\boldsymbol{G}|}{|\boldsymbol{H}|}|\boldsymbol{A}| \quad (15)$$

where $\boldsymbol{A}'$ is the transformation aligning the *normalized* images. Furthermore, the left and right hand sides of equations has to be multiplied by $|\boldsymbol{G}|$ and $|\boldsymbol{H}|$ respectively. Finally, the transformation aligning the original, unnormalized images is obtained as

$$\boldsymbol{A} = \boldsymbol{G}^{-1}\boldsymbol{A}'\boldsymbol{H} \quad (16)$$

EXPERIMENTS

The proposed algorithm has been tested on synthetic as well as on real images. In Fig. 11, we have applied a known affine transformation $\boldsymbol{A}$ to the template and measured the error of the estimated transformation matrix $\widehat{\boldsymbol{A}}$ as $\boldsymbol{A}^{-1}\widehat{\boldsymbol{A}} - \boldsymbol{I}$:

$$\boldsymbol{A} = \begin{pmatrix} 4 & 2 & 100 \\ 1 & 3 & 50 \end{pmatrix}$$

$$\widehat{\boldsymbol{A}} = \begin{pmatrix} 4.0007 & 1.9983 & 95.0785 \\ 0.9843 & 2.9997 & 50.9082 \end{pmatrix}$$

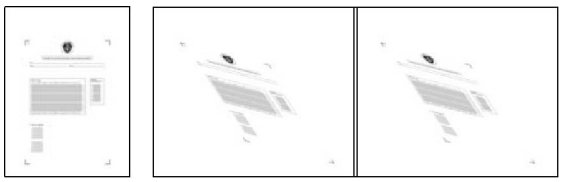
$$\boldsymbol{A}^{-1}\widehat{\boldsymbol{A}} - \boldsymbol{I} = \begin{pmatrix} 0.0034 & -0.0004 & -1.6581 \\ -0.0063 & 0.0001 & 0.8554 \end{pmatrix}$$

The small errors are mainly caused by the discretization and rounding when we applied $\boldsymbol{A}$ to the template. Due to these errors, there is no perfect mapping between the template and observation. Nevertheless, the alignment of the images is almost perfect in spite of the relatively large size ($\approx 2000 \times 3000$) and fine details of the foreground object (see Fig. 11). We had similar findings on real images, where a printed template has been scanned and registrated. Registration error

is typically below 5% independently of the strength of the transformation.

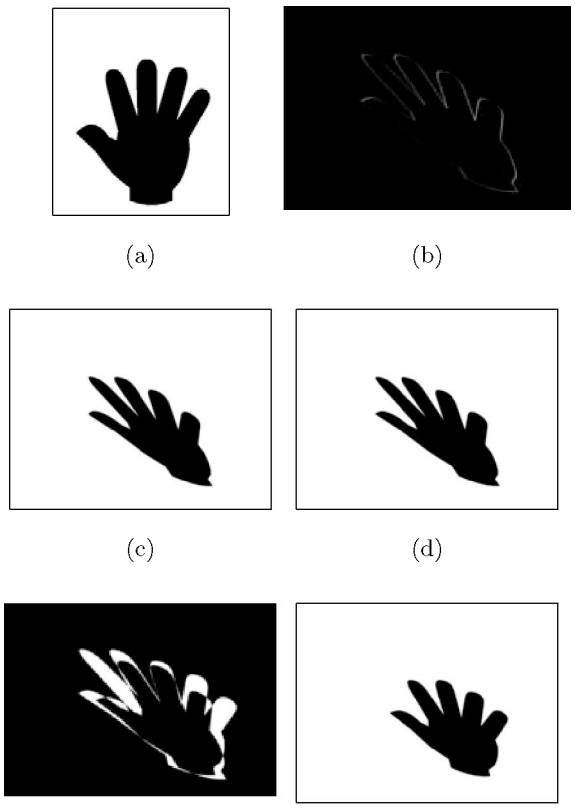
In Fig. 12, we can see a comparison between our method and the one proposed by Thevenaz *et al.* [7]. Our algorithm performs clearly better.

Finally we remark that the CPU time of our Matlab implementation has been around 1 sec. on images of size $\approx 3000 \times 4000$.



(a) (b) (c)

Figure 11. Synthetic example: (a) template (b) observation (c) registrated image



(a) (b)

(c) (d)

(e) (f)

Figure 12. Result of registrations: (a) template (337×400) (b) difference image of our method, error = 1.69% (c) the result of our method (d) observation (2248×1587) (e) difference image with [7], error = 29.52% (f) result of registration [7]

CONCLUSION

We have presented a novel approach for binary image registration. The fundamental difference compared to classical image registration algorithms is that our model works without any landmark, feature detection or optimization. It uses all the information available in the input images, but there is no need for an established correspondence between them.

COLLABORATION

This work is a joint research between the Department of Electrical and Computer Engineering, Ben-Gurion University of the Negev, Israel and Institute of Informatics, University of Szeged.

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MARKOV RANDOM FIELDS AND MCMC SAMPLING IN IMAGE SEGMENTATION

Markov Random Field (MRF) modeling and Markov Chain Monte Carlo (MCMC) sampling methods are successfully used in different areas of image processing [20]. Herein, we will consider two topics: The first one is dealing with automatic segmentation of color images in a probabilistic framework. In particular, we address the problem of automatic identification of Gaussian mixture components either with known [9] or unknown [6, 7] number of components. The second one deals with a multilayer MRF model applied to the segmentation of color video objects [8, 10].

SEGMENTETION OF COLOR IMAGES VIA REVERSIBLE JUMP MCMC SAMPLING

The simplest statistical model for an image consists of the probabilities of pixel classes. The knowledge of the dependencies between nearby pixels can be modeled by a MRF. Such models are quite powerful even if it is not easy to determine the values of

the parameters which specify a MRF. If each pixel class is represented by a different model then the observed image may be viewed as a sample from a realization of an underlying label field. Unsupervised segmentation can therefore be treated as an *incomplete data problem* where the color values are observed, the label field is missing and the associated class model parameters, *including the number of classes*, need to be estimated. Such problems are often solved using MCMC procedures. Although the general theory and methodology of these algorithms are fairly standard, they have their limitations in case of problems with parameters of varying dimension. Recently, a novel method, called Reversible Jump MCMC (RJMCMC), has been proposed by Green [4]. This method makes it possible to construct reversible Markov chain samplers that jump between parameter subspaces of different dimensionality.

Due to the difficulty of estimating the number of pixel classes (or clusters), unsupervised algorithms often assume that this parameter is *known a priori* [10]. When the number of pixel classes is also being estimated, the unsupervised segmentation problem may be treated as a *model selection problem* over a combined model space. Our approach [6, 7] consists of building a Bayesian color image model using a first order MRF. The observed image is represented by a mixture of multivariate Gaussian distributions while inter-pixel interaction favors similar labels at neighboring sites. In a Bayesian framework, we are interested in the *posterior distribution* of the unknowns given the observed image. Herein, the unknowns comprise the hidden label field configuration, the Gaussian mixture parameters, the MRF hyperparameter, and the number of mixture components (or classes). Then a RJMCMC algorithm is used to sample from the whole posterior distribution in order to obtain a MAP estimate via simulated annealing.

The novelty of our approach is two-fold: first, we extend the ideas in [1, 19] and propose a RJMCMC method for identifying multi-variate Gaussian mixtures. Second, we apply it to unsupervised color image segmentation. RJMCMC allows us the direct sampling of the whole posterior distribution defined over the combined model space thus reducing the optimization process to a single simulated annealing run. Another advantage is that no coarse segmentation neither exhaustive search over a parameter subspace is required.

The model assumes that the real world scene consists of a set of regions whose observed color changes slowly, but across the boundary between them, they change abruptly. What we want to infer is a *labeling* ω consisting of a simplified, abstract version of the input image: regions has a constant value (called a *label* in our context) and the discontinuities between them form a curve - the contour. Such a labeling ω specifies a *segmentation*. Taking the probabilistic approach, one usually wants to come up with a *probability measure* on the set Ω of all possible segmentations of the input image and then select the one with the highest probability. Note that Ω is finite, although huge. A widely accepted standard, also motivated by the human visual system [13,17], is to construct this probability measure in a Bayesian framework. First, we have to quantify how well any occurrence of ω fits $\mathcal{F}$. This is expressed by the probability distribution $P(\mathcal{F}|\omega)$ - the *imaging model*. Second, we define a set of properties that any segmentation ω must posses regardless the image data. These are described by $P(\omega)$, the *prior*, which tells us how well any occurrence ω satisfies these properties. For that purpose, ω_s is modeled as a discrete random variable taking values in the set of labels $\Lambda = \{1, 2, \ldots, L\}$. The set of these labels $\omega = \{\omega_s, s \in \mathcal{S}\}$ is a random field, called the *label process*. Furthermore, the observed color features are supposed to be a realization $\mathcal{F}$ from another random field, which is a function of the label process ω. Basically, the *image process* $\mathcal{F}$ represents the manifestation of the underlying label process. The multivariate Normal density is typically an appropriate model for such classification problems where the feature vectors $\mathbf{f}_s$ for a given class λ are mildly corrupted versions of a single mean vector μ_λ. Applying these ideas, the *image process* $\mathcal{F}$ can be formalized as follows: $P(\mathbf{f}_s \mid \omega_s)$ follows a three-variate Gaussian distribution $N(\mu, \mathbf{\Sigma})$, each pixel class $\lambda \in \Lambda = \{1, 2, \ldots, L\}$ is represented by its mean vector μ_λ and covariance matrix $\mathbf{\Sigma}_\lambda$. As for the *label process* ω, a MRF model is adopted [10,11] over a nearest neighborhood system. The prior $P(\omega)$ will represent the simple fact that segmentations should be locally homogeneous. Factoring the above distributions and applying the Bayes theorem gives us the *posterior* distribution $P(\omega|\mathcal{F}) \propto P(\mathcal{F}|\omega)P(\omega)$. Note that the constant factor $1/P(\mathcal{F})$ has been dropped as we are only interested in $\widehat{\omega}$ which *maximizes* the posterior, i.e. the Maximum A Posteriori (MAP) estimate of the hidden field ω:

$$\widehat{\omega} = \arg\max_{\omega \in \Omega} P(\mathcal{F} \mid \omega) P(\omega),$$

The models of the above distributions depend also on certain parameters. Since neither these parameters nor ω is known, both has to be inferred from the only observable entity $\mathcal{F}$. This is known in statistics as the *incomplete data* problem and a fairly standard tool to solve it is *Expectation Maximization* [10,11]. However, our problem becomes much harder when the number of labels L is unknown. When this parameter is also being estimated, the unsupervised segmentation problem may be treated as a *model selection* problem over a combined model space. From this point of view, L becomes a *model indicator* and the observation $\mathcal{F}$ is regarded as a three-variate Normal *mixture* with L components corresponding to clusters of pixels which are homogeneous in color.

The goal of our analysis is inference about the number L of Gaussian mixture components (each one corresponds to a label), the component parameters $\Theta = \{\Theta_\lambda = (\mu_\lambda, \Sigma_\lambda) \mid \lambda \in \Lambda\}$, the component weights p_λ summing to 1, the inter-pixel interaction strength β, and the segmentation ω. A broadly used tool to sample from the posterior distribution is the Metropolis-Hastings method [5]. Classical methods, however, can not be used due to the changing dimensionality of the parameter space. To overcome this limitation, a promising approach, called Reversible Jump MCMC (RJMCMC), has been proposed in [4]. When we have multiple parameter subspaces of different dimensionality, it is necessary to devise different *move types* between the subspaces [4]. These will be combined in a so called *hybrid sampler*. For the color image segmentation model, the following move types are needed:

1. sampling the labels ω (i.e. re-segment the image);
2. sampling Gaussian parameters $\Theta = \{(\mu_\lambda, \Sigma_\lambda)\}$;

3. sampling the mixture weights $p_\lambda(\lambda \in \Lambda)$;
4. sampling the MRF hyperparameter β;
5. sampling the number of classes L (splitting one mixture component into two, or combining two into one).

The only randomness in scanning these move types is the random choice between splitting and merging in move (5). One iteration of the hybrid sampler, also called a *sweep*, consists of a complete pass over these moves. The first four move types are conventional in the sense that they do not alter the dimension of the parameter space. Hereafter, we will focus on move (5), which requires the use of the reversible jump mechanism. This move type involves changing L by 1 and making necessary corresponding changes to ω, Θ and p.

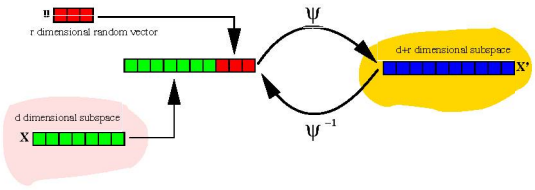


Figure 13. ψ is a *diffeomorphism* which transforms back and forth between parameter subspaces of different dimensionality. *Dimension matching* can be implemented by generating a random vector u such that the dimensions of (X, u) and X' are equal.

The *split proposal* begins by randomly choosing a class λ with a uniform probability $P^{split}_{select}(\lambda) = 1/L$. Then L is increased by 1 and λ is split into λ_1 and λ_2. In doing so, a new set of parameters need to be generated. Altering L changes the dimensionality of the variables Θ and p. Thus we shall define a deterministic function ψ as a function of these Gaussian mixture parameters:

$$(\Theta^+, p^+) = \psi(\Theta, p, u) \tag{17}$$

where the superscript $+$ denotes parameter vectors after incrementing L. u is a set of random variables having as many elements as the degree of freedom of joint variation of the current parameters (Θ, p) and the proposal (Θ^+, p^+). Note that this definition satisfies the *dimension matching* constraint [4] (see Fig. 13), which guarantees that one can jump back and forth between different parameter sub-spaces. This is needed to ensure the convergence of simulated annealing towards a global optimum. The new parameters of λ_1 and λ_2 are assigned by matching the 0^{th}, 1^{th}, 2^{th} moments of the component being split to those of a combination of the two new components [6, 7]:

$$p_\lambda = p^+_{\lambda_1} + p^+_{\lambda_2} \tag{18}$$

$$p_\lambda \mu_\lambda = p^+_{\lambda_1}\mu^+_{\lambda_1} + p^+_{\lambda_2}\mu^+_{\lambda_2} \tag{19}$$

$$p_\lambda(\mu_\lambda \mu_\lambda^T + \mathbf{\Sigma}_\lambda) = p^+_{\lambda_1}(\mu^+_{\lambda_1}\mu^{+T}_{\lambda_1} + \mathbf{\Sigma}^+_{\lambda_1}) + p^+_{\lambda_2}(\mu^+_{\lambda_2}\mu^{+T}_{\lambda_2} + \mathbf{\Sigma}^+_{\lambda_2}) \tag{20}$$

There are 10 degrees of freedom in splitting λ since covariance matrices are symmetric. Therefore, we need to generate a random variable $u1$, a random vector $\mathbf{u2}$ and a symmetric random matrix $\boldsymbol{u3}$. We can now define the diffeomorphism ψ which transforms the old parameters (Θ, p) to the new (Θ^+, p^+) using the above moment equations and the random numbers $u1$, $\mathbf{u2}$, and $\boldsymbol{u3}$:

$$p^+_{\lambda_1} = p_\lambda u1 \tag{21}$$

$$p^+_{\lambda_2} = p_\lambda(1 - u1) \tag{22}$$

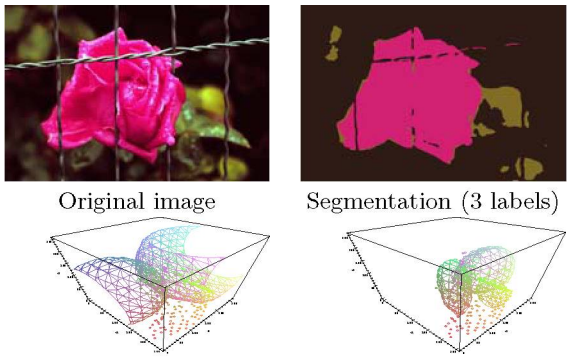
$$\mu^+_{\lambda_1,i} = \mu_{\lambda,i} + u2_i\sqrt{\Sigma_{\lambda,i,i}\frac{1-u1}{u1}} \tag{23}$$

$$\mu^+_{\lambda_2,i} = \mu_{\lambda,i} - u2_i\sqrt{\Sigma_{\lambda,i,i}\frac{u1}{1-u1}} \tag{24}$$

$$\Sigma^+_{\lambda_1,i,j} = \begin{cases} u3_{i,i}\left(1-{u2_i}^2\right)\Sigma_{\lambda,i,i}\dfrac{1}{u1} & \text{if } i=j \\ u3_{i,j}\Sigma_{\lambda,i,j}\sqrt{\left(1-{u2_i}^2\right)} & \\ \quad\times\sqrt{\left(1-{u2_j}^2\right)u3_{i,i}u3_{j,j}} & \text{if } i\neq j \end{cases} \tag{25}$$

$$\Sigma^+_{\lambda_2,i,j} = \begin{cases} \left(1-u3_{i,i}\right)\left(1-{u2_i}^2\right) & \\ \quad\times\Sigma_{\lambda,i,i}\dfrac{1}{u1} & \text{if } i=j \\ \left(1-u3_{i,j}\right)\Sigma_{\lambda,i,j} & \\ \quad\times\sqrt{\left(1-{u2_i}^2\right)\left(1-{u2_j}^2\right)} & \\ \quad\times\sqrt{\left(1-u3_{i,i}\right)\left(1-u3_{j,j}\right)} & \text{if } i\neq j \end{cases} \tag{26}$$

The random variables u are chosen from the interval $(0, 1]$. In order to favor splitting a class into roughly equal portions, beta(1.1, 1.1) distributions are used. To guarantee numerical stability in inverting $\mathbf{\Sigma}^+_{\lambda_1}$ and $\mathbf{\Sigma}^+_{\lambda_2}$, one can use some regularization like in [2], or one can use the well-known Wishart distribution [15]. However, we did not experience such problems, mainly because the obtained covariance matrices are also reestimated from the image data in subsequent move types. Therefore as long as our input image can be described by a mixture of Gaussians, we can expect that the estimated covariance matrices are correct. The next step is the reallocation of those sites $s \in \mathcal{S}_\lambda$ where $\omega_s = \lambda$. This reallocation is based on the new parameters and has to be completed in such a way as to ensure the resulting labeling ω^+ is drawn from the posterior distribution with $\Theta = \Theta^+$, $p = p^+$ and $L = L + 1$.



Original image — Segmentation (3 labels)

Initial Gaussians — Final (3 classes)

Figure 14. Segmentation of image *rose41*.

Table 2. F-measure and CPU time comparison

Method	F-measure	CPU time
Human segmentation	0.79	—
RJMCMC	0.57	15 min
JSEG	0.56	2 min

Merging of a pair (λ_1, λ_2) is basically the inverse of the split operation.

Finally, the split or merge proposal is accepted with a probability relative to the probability ratio of

the current and the proposed states. The segmentation and parameter estimation is then obtained as a MAP estimation implemented via simulated annealing:

Algorithm 1 (RJMCMC Segmentation)

① *Set* $k = 0$. *Initialize* $\widehat{\beta}^0$, $\widehat{L}^0$, $\widehat{p}^0$, $\widehat{\Theta}^0$, *and the initial temperature* T_0.

② *A sample* $(\widehat{\omega}^k, \widehat{L}^k, \widehat{p}^k, \widehat{\beta}^k, \widehat{\Theta}^k)$ *is drawn from the posterior distribution using the* hybrid sampler *outlined earlier. Each sub-chain is sampled via the corresponding move-type while all the other parameter values are set to their current estimate.*

③ *Goto Step* ② *with* $k = k+1$ *and* T_{k+1} *until* $k < \mathcal{K}$.

As usual, an exponential annealing schedule ($T_{k+1} = 0.98T_k$, $T_0 = 6.0$) was chosen so that the algorithm would converge after a reasonable number of iterations. In our experiments, the algorithm was stopped after 200 iterations ($T_{200} \approx 0.1$).

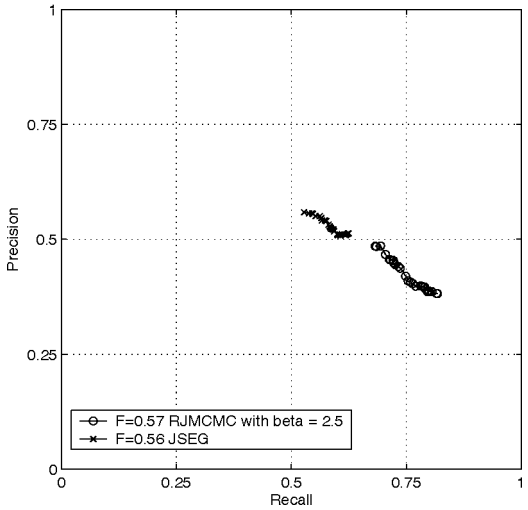


Figure 16. Precision-recall curve for JSEG and RJMCMC.

EXPERIMENTAL RESULT

The proposed algorithm has been tested on a variety of real color images and results have also been compared to those produced by JSEG [3], a recent unsupervised color image segmentation algorithm. In Fig. 15, we show a couple of results obtained on the Berkeley Segmentation Dataset [16], and in Fig. 16, we plot the corresponding precision-recall curves. Note that RJMCMC has a slightly higher *F-measure* (see Table 2) which ranks it over JSEG. However, it is fair to say that both method perform equally well but behave differently: while JSEG tends to smooth out fine details (hence it has a higher precision but lower recall value), RJMCMC prefers to keep fine details at the price of producing more edges (i.e. its recall values are higher at a lower precision value).

MULTILAYER MRF MODELIZATION

The human visual system is not treating different features sequentially. Instead, as pointed out by Kersten *etal.* [13], multiple cues are perceived simultaneously and then they are integrated by our visual system in order to explain the observations. Therefore different image features has to be handled in a parallel fashion. In this project, we attempt to develop such a model in a Markovian framework based on our earlier work on color-texture segmentation [12]. We propose a new MRF image segmentation model which aims at combining color and motion features for video object segmentation. The model has a multi-layer structure: Each feature has its own layer, called *feature layer*, where an MRF model is defined using only the corresponding feature. A special layer is assigned to the combined MRF model. This layer interacts with each feature layer and provides the segmentation based on the combination of different features. Unlike previous methods, our approach doesn't assume motion boundaries being part of spatial ones. The uniqueness of the proposed method is the ability to detect boundaries that are visible only in the motion feature as well as those visible only in the color one.

We use perceptually uniform CIE-L*u*v* color values; and optical flow data obtained via the algorithm proposed in [18]. We have chosen this method because it provides smooth optic flow fields necessary for our MRF model. Our model consists of 3 layers. At each layer, we use a first order neighborhood system and extra inter-layer cliques (Fig. 17). The image features are represented by multi-variate Gaussian distributions. For example, on the color layer, the observed image $\mathcal{F}^c = \{\mathbf{f}_s^c | s \in \mathcal{S}^c\}$ consists of three spectral component values (L*u*v*) at each pixel s denoted by the vector $\mathbf{f}_s^c$. We assume that $P(\mathbf{f}_s^c \mid \omega_s)$ follows a Gaussian distribution, the classes $\lambda \in \Lambda^c = \{1, 2, \ldots, L^c\}$ are represented by the mean vectors ${\mu^c}_\lambda$ and the covariance matrices ${\mathbf{\Sigma}^c}_\lambda$. The class label assigned to a site s on the color layer is denoted by ψ_s. The energy function $U(\psi, \mathcal{F}^c)$ of the so defined MRF layer has the following form:

$$\sum_{s \in \mathcal{S}^c} \mathcal{G}^c(\mathbf{f}_s^c, \psi_s) + \beta \sum_{\{s,r\} \in \mathcal{C}} \delta(\psi_s, \psi_r) + \sum_{s \in \mathcal{S}^c} V^c(\psi_s, \eta_s^c)$$

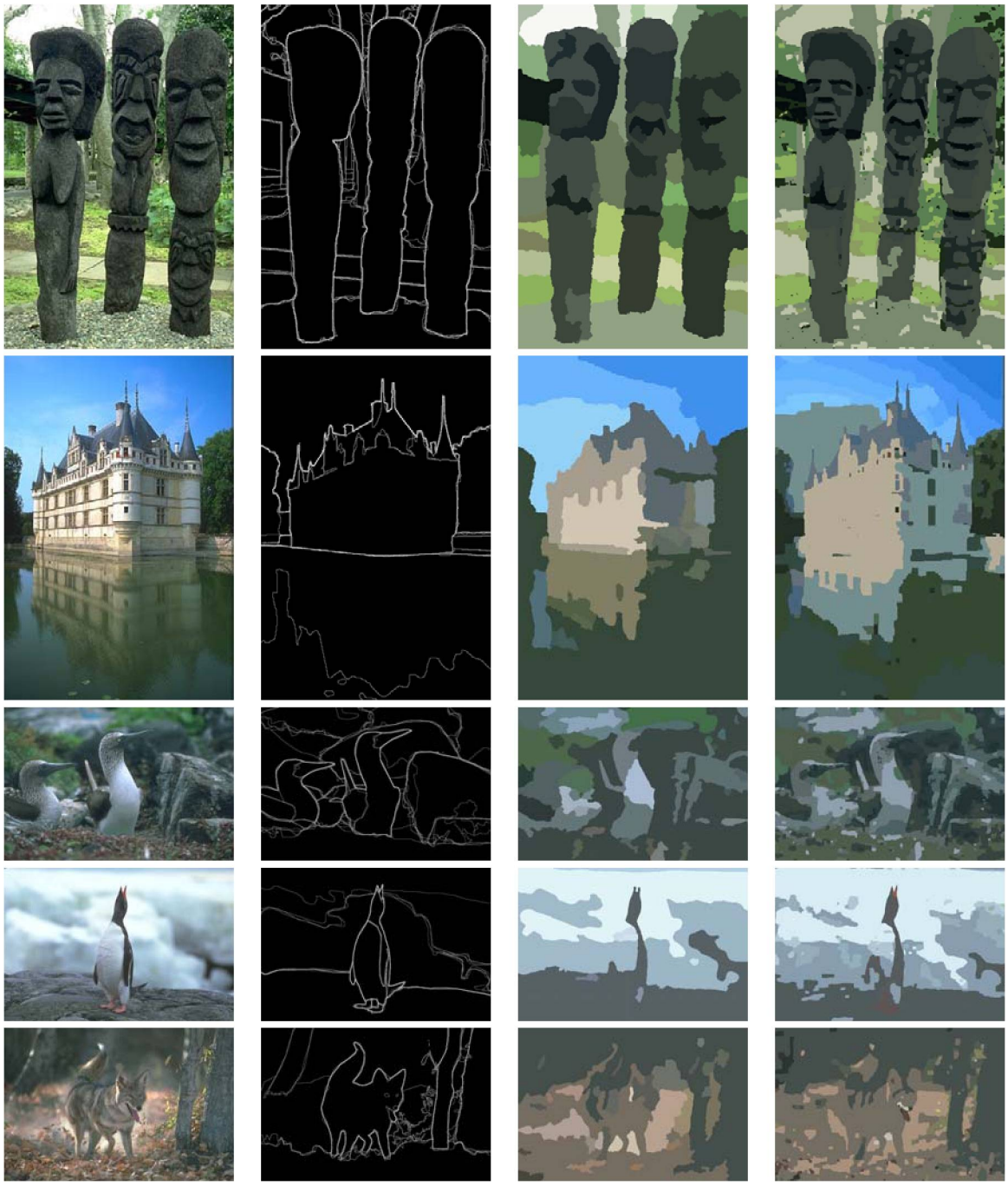
where $\mathcal{G}^c(\mathbf{f}_s^c, \psi_s)$ denotes the Gaussian energy term while $\delta(\psi_s, \psi_r) = 1$ if ψ_s and ψ_r are different and -1 otherwise. $\beta > 0$ is a parameter controlling the homogeneity of the regions. As β increases, the resulting regions become more homogeneous. The last term $(V^c(\psi_s, \eta_s^c))$ is the inter-layer clique potential. The motion layer adopts a similar energy function with some obvious substitutions.

The combined layer only uses the motion and color features indirectly, through inter-layer cliques. A label consists of a pair of color and motion labels such that $\eta = \langle \eta^c, \eta^m \rangle$, where $\eta^c \in \Lambda^c$ and $\eta^m \in \Lambda^m$. The set of labels is denoted by $\Lambda^x = \Lambda^c \times \Lambda^m$ and the number of classes $L^x = L^c L^m$. Obviously, not all of these labels are valid for a given image. Therefore the combined layer model also estimates the number of classes and chose those pairs of motion and color labels which are actually present in a given image. The energy function $U(\eta)$ is of the following form:

$$\sum_{s \in \mathcal{S}^x} (V_s(\eta_s) + V^c(\psi_s, \eta_s^c) + V^m(\phi_s, \eta_s^m))$$

$$+\alpha \sum_{\{s,r\} \in \mathcal{C}} \delta(\eta_s, \eta_r)$$

where $V_s(\eta_s)$ denotes singleton energies, $V^c(\psi_s, \eta_s^c)$ (resp. $V^m(\phi_s, \eta_s^m)$ denotes inter-layer clique potentials. The last term corresponds to second order intra-layer cliques which ensures homogeneity of the combined layer. α has the same role as β in the color layer



Original image | Human segmentation | JSEG | RJMCMC

Figure 15. Benchmark results on images from the Berkeley Segmentation Dataset

model and $\delta(\eta_s, \eta_r) = -1$ if $\eta_s = \eta_r$, 0 if $\eta_s \neq \eta_r$ and 1 if $\eta_s^c = \eta_r^c$ *and* $\eta_s^m \neq \eta_r^m$ or $\eta_s^c \neq \eta_r^c$ *and* $\eta_s^m = \eta_r^m$. The idea is that region boundaries present at both color and motion layers are preferred over edges that are found only at one of the feature layers. At any site s, we have 5 inter-layer interactions between two layers: Site s interacts with the corresponding site on the other layer as well as with the 4 neighboring sites two steps away (see Fig. 17). This potential is based on the difference of the first order potentials at the corresponding feature layers. Clearly, the difference is 0 if and only if both the feature layer and the combined layer has the same label. If the labels are different then it is proportional to the energy difference between the two labels. Finally, the singleton energy controls the number of classes at the combined layer by penalizing small classes.

EXPERIMENTS

The proposed algorithm has been tested on real video sequences. Herein we present two of these results. The computing time was around 3 minutes on a Pentium4 3GHz on 320×240 frames. We also compare the results to motion only and color only segmentation (basically a monogrid model similar to the one defined for the feature layers but without inter-layer cliques). The mean vectors and covariance matrices were computed over representative regions selected by the user. The number of motion and color classes is known a priori but classes on the combined layer are estimated during the segmentation process. Fig. 18 shows some segmentation results. Note that the head of the men on this image can only be separated from the background using motion features. Clearly, the multi-layer model provides significantly better results compared to color only and motion only segmentations. See Fig. 19 to compare the performance of the proposed method with the one from [14] on the *Mother and Daughter* standard sequence. Clearly, some of the contours are lost by [14] (the sofa, for example) while our method successfully identifies region boundaries. In particular, our method is able to separate the hand of the mother from the face of the daughter in spite of their similar color. This demonstrates again that the proposed method is quite powerful at combining motion and color features in order to detect boundaries visible only in one of the features.

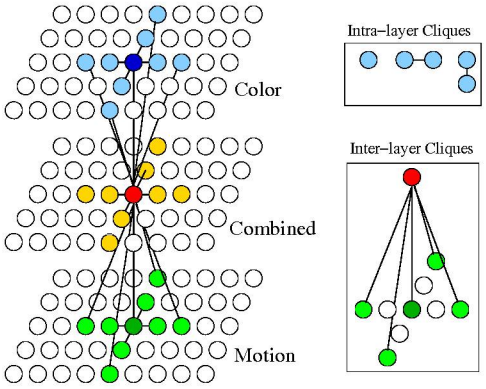


Figure 17. Multi-layer MRF model.

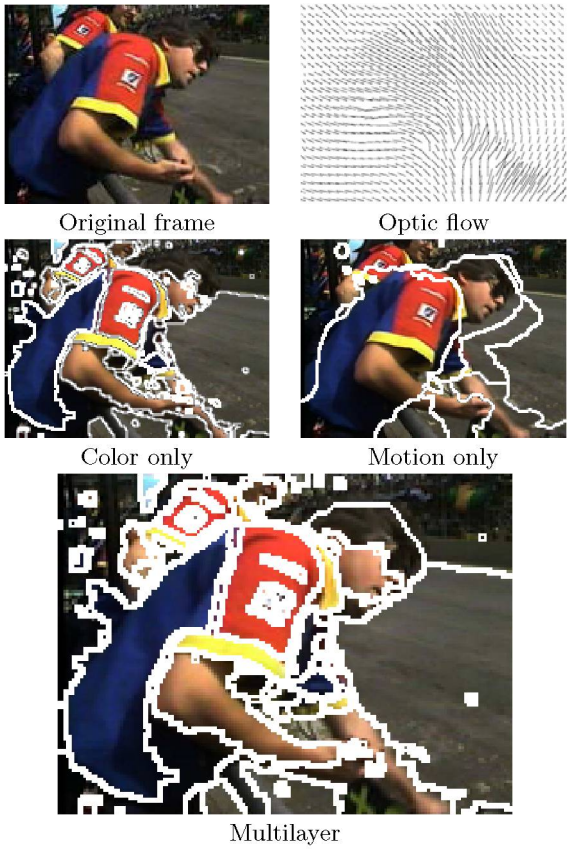


Figure 18. Segmentation results.

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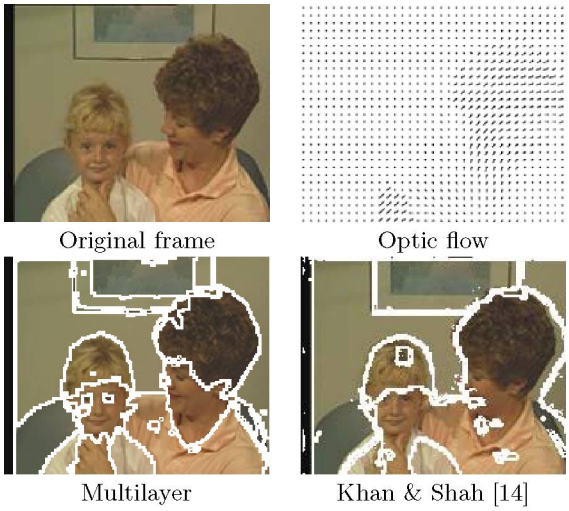

Figure 19. Comparison of the segmentation results obtained by the proposed method and those produced by the algorithm of Khan & Shah [14].

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X. COMPUTER ASSISTED SURGERY AND BIOMECHANICAL ANALYSIS

INTRODUCTION

The surgical repair of fractured bones is often a difficult task, and the fixation of these bones has to be planned very carefully. This is why trauma surgeons may use a Computer Aided Surgery (CAS) system to improve surgical accuracy.

Our goal here is to develop a suitable CAS package that is also capable of performing biomechanical tests. The program can simulate the biomechanical behavior of possible surgical solutions and calculate its deformations and material stresses. These calculations are based on Finite Element Analysis (FEA). Using these results the surgeon is able to see the week points of the fixation before the surgery. He can even try several surgical plans to pick the most promising one.

DESCRIPTION OF THE SYSTEM

The system gets its data from CT images. The first step is the segmentation [1] where the differentiation is done between various bone fragments and the background. Next, the segmented surface is approximated [3, 4] the with a triangle mesh (see Fig. 20), followed by a surface simplification [2] which reduces the number of triangles in the mesh.

This surface mesh contains all the geometrical information needed by the surgical planning module. In this module the user can move and rotate the various bone fragments with the mouse. The planning module is also the place where virtual implants (screw and fixation plate) are inserted.

To simulate the biomechanical behavior of the surgical plan the geometrical model has to be converted into a mechanical model. The FEA mesh is generated from the triangle mesh used for rendering. The addition of load and boundary conditions is handled by the user interface of the planning module. On Fig. 21. arrows indicate the area and direction of the applied load.

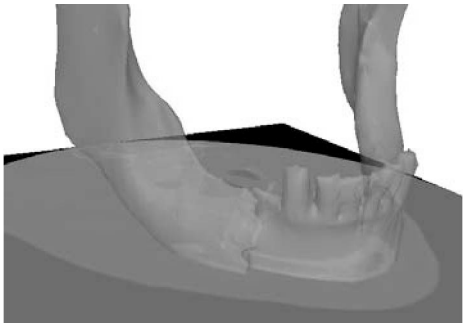

Figure 20. Combined 3D view of a CT slice and the triangle mesh.

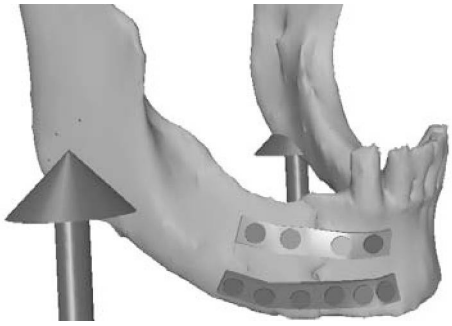

Figure 21. The surgical plan of a broken jaw. The fracture is stabilized with two fixation plates and ten screws. Arrows show the direction of the applied load.

The finite element analysis is performed by an external software. The results of the analysis, namely the deformation under the load and the material stress are presented in our system, see Fig. 22.

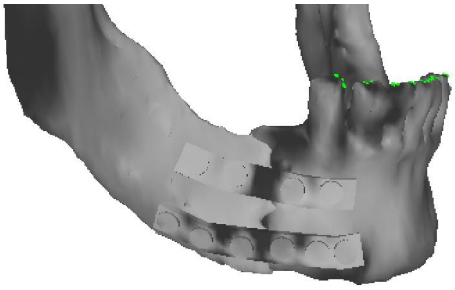

Figure 22. The result of the finite element analysis. Dark colors indicate high material stress.

CONCLUSION

A novel system was presented to help the surgeon in planning orthopedic operations. With this system a virtual biomechanical lab was created and various FEA studies of jaw, pelvis, hip, knee, and wrist were carried out. The tool can be used by the surgeon to create surgical plans for fractured bone fixation and to predict the biomechanical stability of the plan before the operation takes place.

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XI. SKELETONIZATION BY THINNING IN 3D

Skeleton is a region–based shape feature to represent the general form of an object. Skeletonization (i.e., skeleton extraction from binary objects) in 3D has become a very challenging task in various medical and engineering applications. Thinning is a frequently used technique for producing a reasoable approximation to the skeleton or extracting skeleton-like features (i.e., centerline or topological kernel).

SKELETON AS A SHAPE FEATURE

Shape is a fundamental concept in computer vision. It can be regarded as the basis for high–level image processing stages concentrating on scene analysis and interpretation. There are basically two different approaches for describing the shape of an object:

- using the boundary that surrounds it and
- using the occupied region.

Boundary–based techniques are widely used but there are some deficiencies which limit their usefulness in practical applications especially in 3D. Therefore, the importance of the region–based shape features shows upward tendency. The local object symmetries represented by the skeleton certainly cannot replace boundary–based shape descriptors, but complement and support them.

The skeleton is a region–based shape feature that has been proposed by Blum as the result of the Medial Axis Transform. A very illustrative definition of the skeleton is given using the prairie–fire analogy: the object boundary is set on fire and the skeleton is formed by the loci where the fire fronts meet and quench each others. The formal definition of the skeleton has been stated by Calabi: the skeleton of an object is the locus of the centers of all the maximal inscribed hyperspheres. The continuous skeleton of a solid 3D box is illustrated in Fig. 23.

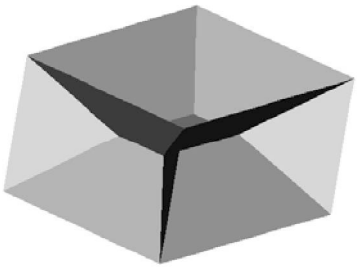

Figure 23. Example of 3D skeleton. The original object was a solid box. Note, a skeleton in 3D generally contains surface pathes (i.e., branched 2D manifolds).

SKELETONIZATION TECHNIQUES IN DISCRETE SPACES

During the last two decades skeletonization in the digital image raster has been an important research field. There are two major requirements to be complied with. The first one is geometrical. It means that the “skeleton” must be in the “middle” of the object

and invariant under geometrical transformations. The second one is topological requiring that the "skeleton" must be topologically equivalent to the original object.

There are three major discrete skeletonization methods:

- based on distance transformation,
- thinning, and
- based on Voronoi–diagram.

The first method is to find the maximal inscribed hyperspheres. It requires the following 3–step process:

1. The original binary picture is converted into another one consisting feature and nonfeature elements. The feature elements belong to the boundary of the discrete object.
2. The distance map is generated where each element has a value that approximates the distance to the nearest feature element.
3. The detection of ridges (local extremas) as the centers of maximal inscribed hyperspheres.

Unfortunately, the result of the distance transformation depends on the selected distance and the ridge extraction is a rather difficult task. The distance map based method fulfils the geometrical requirement if a good approximation to the Euclidean distance is applied, but the topological correctness is not guaranteed.

The thinning process is to simulate the fire–front propagation: a layer by layer erosion is executed until the "skeleton" is left. The iterative process is shown in Fig. 24. The topological aspect is taken care by thinning. On the other hand the geometrical requirement correctness (i.e., invariance under arbitrary rotations) is not guaranteed.

The Voronoi diagram of a discrete set of points (called generating points) is the partition of the given space into cells so that each cell contains exactly one generating point and the locus of all points which are nearer to this generating point than to other generating points. It is shown that the skeleton of an object which is described by a set of boundary points can be approximated by a subgraph of the Voronoi diagram of that generating points.

Both requirements can be fulfilled by the skeletonization based on Voronoi diagrams but it is regarded as an expensive process, especially for large and complex objects.

We prefer thinning, since it:

- preserves topology,
- makes easy implementation possible (as a sequence of local Boolean operations),
- can produce different types of skeleton-like shape features (see fig. 25),
- takes the least computational costs, and
- can be executed in parallel.

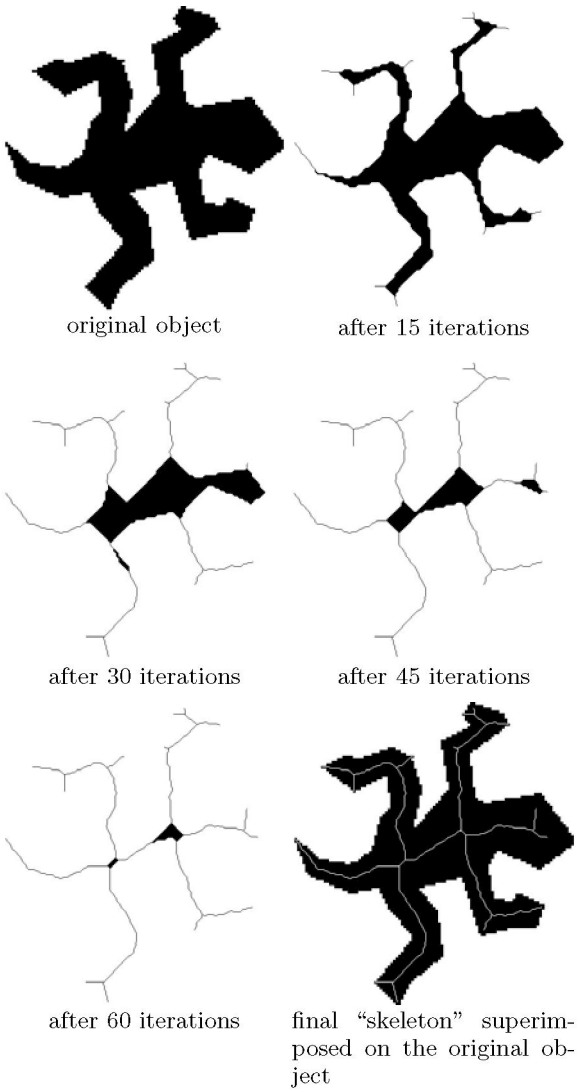

Figure 24. Example of thinning in 2D. The size of the test image is 430×460

THINNING METHODOLOGIES

A 3D binary picture is a mapping that assigns value of 0 or 1 to each point with integer coordinates in the 3D digital space denoted by $\mathbb{Z}^3$. Points having the value of 1 are called black points, while 0's are called white ones. Black points form objects of the picture. White points form the background and the cavities of the picture. Both the input and the output of a picture operation are pictures. An operation is reduction if it can delete some black points (i.e., changes them to white) but white points remain the same. There is a fairly general agreement that a reduction operation is *not* topology preserving if any object in the input picture is split (into two or more ones) or completely deleted, if any cavity in the input picture is merged with the background or another hole, or if a cavity is created where there was none in the input picture. There is an additional concept called hole in 3D pictures. A hole (that doughnuts have) is formed by 0's, but it is not a cavity. Topology preservation implies that eliminating or creating any hole is not allowed.

Thinning must be a topology–preserving reduction. Existing 3D thinning algorithms can be classified from several points of view. One of them is the classification on the produced skeletons: surface-thinning algorithms result in medial surfaces, curve-thinning ones can produce medial lines, and shrinking algorihms extract topological kernels.

Since the fire front propagation is by nature parallel, most of the existing thinning algorithms are parallel (i.e., all border points satisfying the deletion condition of the actual phase of the process are deleted simultaneously) [1–9]. Despite of this fact, we have proposed two sequential thinning algorithms [10,11].

APPLICATIONS

Thinning is a common preprocessing operation in raster–to–vector conversion or in pattern recognition. Its goal is to reduce the volume of elongated objects.

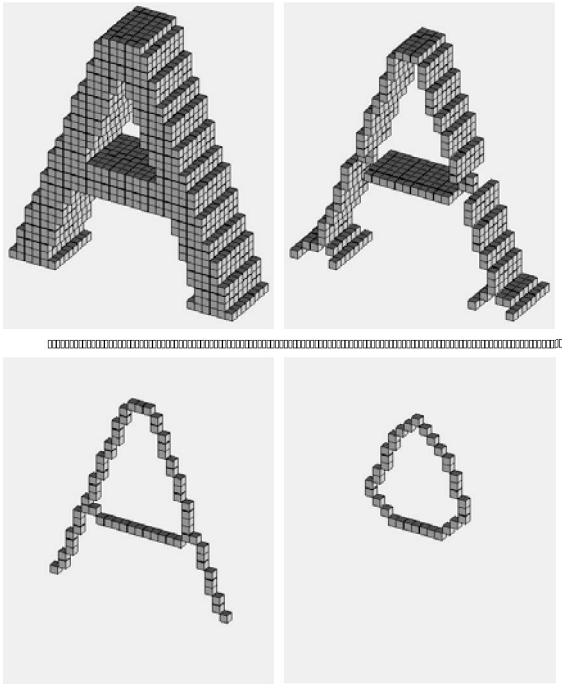

Figure 25. Different types of 3D "skeletons". The original elongated object (upper left), its medial surface produced by a surface thinning algorithm (upper right), its medial line (bottom left) extracted by a curve thinning algorithm, and its topological kernel (i.e., a minimal structure being topologically equivalent to the original object) created by a shrinking algorithm(bottom right). (Each small cube represents an object voxel.)

Some important applications have been appeared in medical image processing, too [1–7, 19–22].

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XII. QUANTITAVIVE ANALYSIS OF TUBULAR TREE STRUCTURES

The developed approach is specifically targeting skeletonization of vascular and airway tree structures in medical images but it is general and applicable to many other skeletonization tasks. It builds on the following concepts and properties: fast curve-thinning algorithm to increase computational speed, endpoint re-checking to avoid generation of spurious side branches, depth-and-length sensitive pruning, and exact tree-branch partitioning allowing branch volume and surface measurements. The method was validated in computer and physical phantoms and in in vivo CT scans of human lungs. The validation studies demonstrated sub-voxel accuracy of branch point positioning, insensitivity to changes of object orientation, high reproducibility of derived quantitative indices of the tubular structures.

INTRODUCTION

Tubular structures are frequently found in living organisms. The tubes – e.g., arteries or veins are organized into more complex structures. Trees consisting of tubular segments form the arterial and venous systems, intrathoracic airways form bronchial trees, and other examples can be found. Computed tomography (CT) or magnetic resonance (MR) imaging provides volumetric image data allowing identification of such tree structures. Frequently, the trees represented as contiguous sets of voxels must be quantitatively analyzed. The analysis may be substantially simplified if the voxel-level tree is represented in a formal tree structure consisting of a set of nodes and connecting arcs. To build such formal trees, the voxel-level tree object must be transformed into a set of interconnected single-voxel centerlines representing individual tree branches. Therefore, the aim of our work was to develop a robust method for identification of centerlines and bifurcation (trifurcation, etc.) points in segmented tubular tree structures acquired in vivo from humans and animals using volumetric CT or MR scanning, rotational angiography, or other volumetric imaging means.

There are many reasons why identifying tree skeletons is important. Skeletons can serve as one-dimensional structures allowing guidance for orderly exploration of the entire tree, they can serve as viewpoint trajectory for navigation purposes in virtual bronchoscopy or angioscopy. To facilitate quantitative analysis of the vascular or bronchial tree, e.g., luminal area or wall thickness, measurements must be obtained in cross-sections perpendicular to the long axis of the tree segments. Clearly, planes normal to the tree skeletons must be identified and skeleton correctness is of paramount importance. As such, quantitative assessment of asthma or cystic fibrosis from pulmonary CT images depends on the performance of the tree skeletonization method. Similarly, accuracy and reproducibility of arterial plaque thickness measurements from coronary CT or intravascular ultrasound depends on the ability to skeletonize tubular structures.

METHOD

The input of the proposed method is a 3D binary image representing a segmented voxel-level tree object. All main components of our method were specifically developed to deal with imaging artifacts typically present in volumetric medical image data. As such, the method consists of the following main steps:

1. correction of the segmented tree – hole and cavity filling,
2. extraction of the 3D centerline – skeletonization,
3. tree pruning,
4. generation of a formal tree structure (see Fig. 26),
5. tree partitioning (see Fig. 27), and
6. quantitative analysis.

For each partition/branch of the tree, the following measures/indices are calculated: branch length (defined as a Euclidean distance between the parent and child branch-points), branch volume (defined as a volume of all voxels belonging to the branch), branch surface area (defined as a surface area of all boundary voxels belonging to the branch), and branch radius (derived from the branch length and the branch volume).

The automated method for skeletonization, branch-point identification and quantitative analysis of tubular tree structures is robust, efficient, and highly reproducible. It facilitates calculation of a number of morphologic indices described above [1–7].

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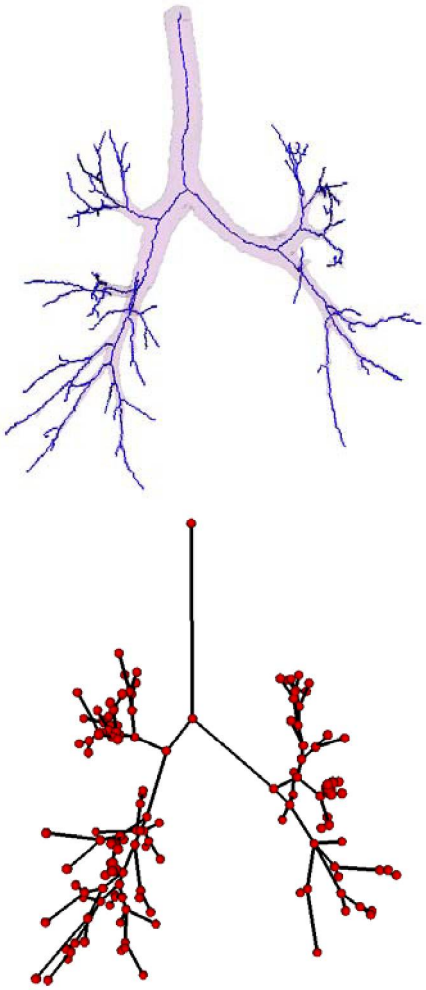

Figure 26. A human airway tree and its centerlines (up). The corresponding formal tree structure, in which a path between two branch-points is replaced by a single edge (down).

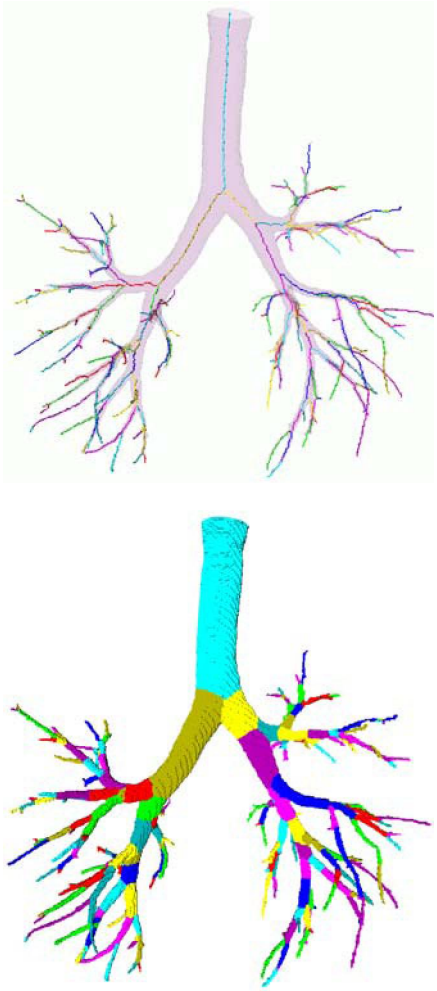

Figure 27. The aim of the partitioning procedure is to partition all voxels of the segmented tree into branches – each voxel is assigned a branch-specific label. The segmented volume and the partitioned skeletal tree (up) and the partitioned volume after label-propagation (down). (Note, that we used only 9 colors in displaying these trees, therefore, the same color was assigned to multiple branches.)

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Department of Software Engineering

I. AD-HOC MOBILE AND MULTIMEDIA NETWORKS

WIRELESS MESH NETWORKS WITH MOBILITY SUPPORT

For geographical and demographic reasons the Internet penetration in rural areas is far from that in larger cities. It seems that current business models and technologies cannot achieve a breakthrough in this area. So new business models which are closer to real life situations in rural areas and villages are needed. For example, in a small community people know each other and they try to solve any arising problems in much closer cooperation than in larger towns and cities. From the aspect of technology and business models the Wireless Mesh Network (WMN) solution seems to fit the bill. Utilizing this solution a community can achieve wireless network coverage for a small town or village. The network infrastructure is managed by volunteer citizens. As the whole system is adaptive and self-tuning, the system can be expanded in a plug-and-play manner without any special knowledge being needed. The WMN can be used to extend the range and the services of an already existing WiFi based ISP (W-ISP) or multiple WISP's. In the case of multiple WISPs the WMN can be used as a common access network. With a adaptive and volunteer run WMN the cost of the network maintenance will be significantly cheaper. As the cost of the network maintenance can be as high as 80% of the total cost using the WMN as an access network could be significantly cheaper compared to current solutions.
The limitations and the capabilities of the Wireless Mesh Network has been studied by numerous articles. Despite numerous WMN implementations and large WMN projects we have not found a solution that addresses the following issues:

- Efficient resource scheduling
- Network wide QoS guaranties
- Mobility support

As a participants in the C@R EU-Funded project, our goal is to design and develop a WiFi-based WMN solution for rural communities. One novelty of our solution is the new metric for the link selection. With this metric we will be able to minimalize the interference in the network and hence we will be able to maximalize the global throughput. Another novelty of our solution lies in the scheduling structure. The nodes with uplinks are the clusterheads in our topology. The member nodes in a cluster report the measured/tested link properties to the clusterhead. Based on this data this node will be able to optimize the frequency reuse inside and outside the cluster. As we have a strict scheduling, a fine grained QoS control will be possible. As a unique feature our mobility handling is an integrated part of our solution. For further details, read article [1].

MULTIMEDIA NETWORKS

There is an ongoing integration process in the field of communication and broadcasting. The so called "Triple Play" services are the place where the traditional telecommunication companies meet with cable TV operators and with Internet Service providers. The IP layer will be the commons basis for these services. Real-time services demand new services and strict quality features from the network layer. The multicast data communication paradigm is not a new innovation and is actually as old as the World Wide Web. Due to the technical challenges and the lack of a "killer" application, it is still not widely used. It seems that the IPTV will change this. The unicast data communication paradigm is not suitable for serving a huge number of online TV watchers. We have not found a software solution for the testing and monitoring of a multicast network. Our network testing and monitoring software solution tries to fill this gap. In the Network Testing section we will describe this tool and our result in the field of network testing and monitoring.
The Video-On-Demand is another promising area. Here cheap and scalable data storage capable of serving a high number of concurrent streams is the biggest issue that needs to be addressed. Our LanStore framework is unique among the distributed storage solutions because it uses the unused storage capacity of desktop machines. In the Distributed Storage section we will describe our results in the field of distributed consistency and storage.

NETWORK TESTING

Testing an already deployed network can provide valuable information about future situations and services. System administrators need a framework that can also supply them with traffic orchestration and measurement data. In the Campus6 EU and Hungarian state-funded research and development project, the NetSpotter framework is a general purpose network testing package that has been designed and developed. With this framework the user has the freedom to create arbitrary packets and arbitrary message sequences. The message sequences can defined by a user-friendly GUI or by an XML format of the official MSC representation. With our powerful template solution one can easily create complex test scenarios. Current test scenarios (RFC 3918) define only point to multipoint measurements. We think that to be able to correctly measure a network, we need multipoint to multipoint measurements. With this approach we can probably model the real traffic properties more precisely. Our framework provides this capability with the help of software agents. There is a central server cluster and there can be arbitrary number of agents. One can define the message sequences among the agents with the previously mentioned MSC engine.
We measured the channel-handling capabilities of the MRD6 multicast routing daemon for Linux. In the literature we have not seen results like that for MRD6 or IPv6 multicast routing solutions. In our experiments it turned out that the multicast network can be an easy target of a DoS attack. With a relatively small packet number a multicast network can be shut down.

In a real world scenario some rate limiting solution should be used. Further details about the framework and the results can be found in articles [2–4].

DISTRIBUTED STORAGE

LanStore is a highly reliable, fully decentralized storage system which can be constructed from already existing desktop machines. Our software utilizes the otherwise wasted storage capacity of these machines. Reliability is achieved with the help of a traditional erasure coding algorithm called the Reed-Solomon algorithm which generates n error correcting code items for each m data item. The distributed behavior is controlled by a voting-based quorum algorithm. This algorithm is an optimized version of the classic Paxos algorithm. Further details about the algorithm can be found in the article [5] and presentation [5]. With this solution we can tolerate up to n simultaneously failing machines. As LanStore is intended to be used in LAN environments, instead of employing an overlay multicast solution we used an IP-level multicast service. To use the bandwidth effectively, we designed a special UDP-based multicast flow control protocol. For the implementation platform we chose the Windows family and the .NET framework as they are the most popular platforms in offices and university departments. So far we have implemented a prototype version of this solution. We measured its performance and the results indicate that this solution can provide a throughput comparable to the currently used network file systems, its performance depending on the selected error correcting capability, the number of failing machines and the performance of the client machine. In special cases like video-on-demand with a high client number our solution can outperform the traditional single server solutions. Further details can be found in article [6]

CONNECTIONS OF RESEARCH TO EDUCATION

Students can take part in the R&D projects as part time participants or they can do their graduate work on a selected part of an R&D project. E.g: The LanStore software was developed by more than fifteen graduating students. As we are involved in the Cisco academy network, the students can use the latest network devices for their studies.

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II. OPEN SOURCE DEVELOPMENT FOR EMBEDDED SYSTEMS

INTRODUCTION

Nowadays, and according to the trends, in the future embedded systems and devices get more and more widespread - their market is about 100 times the size of the desktop market, and will also grow exponentially in the next decade.

Embedded systems are omnipresent nowadays and make possible the creation of systems with a functionality that cannot be provided by human beings. Example application areas are consumer electronic products (e.g. CD players, microwave ovens), telecommunication (e.g. mobile phones), medical systems (e.g. pacemakers), traffic control (e.g. intelligent traffic lights), driving and car control (e.g. ABS), airborne equipment (e.g. fly-by-wire), and plant control (e.g. packaging machines, wafer steppers).

Due to their importance, the researchers of the department are working on several embedded system-related research areas. These research topics were suggested by industrial partners, and most of the results are immediately utilized in real products.

OPTIMIZING FOR ENERGY

One of the big design challenges for mobile devices is the optimal usage of the typically very limited energy resources. Within the framework of the Bilateral German-Hungarian Collaboration Project on Ambient Intelligence Systems (BelAmI), we have been conducting research on the possibilities of reducing the energy consumption of software with the help of compilers since late 2005. The evaluation of software optimisation techniques requires the ability to accurately measure the power consumption of a system. The most trivial solution is to perform measurements on a real hardware. However, in some scenarios, e.g., where automatic collection and evaluation of large amount of results is required, hardware measurements can be overly expensive or impractical. In these situations an accurate simulation tool can be used. Thus, we have created a cycle-accurate energy simulator tool for the ARM v5TE architecture-based XScale processor cores. The power dissipation graphs showing the accuracy of the created simulator compared to real measurement are shown in Figure 28.

Currently, the simulator is used to assess the effect of various optimisation methods on energy consumption. Our focus is on static and dynamic voltage and frequency scaling techniques.

OPTIMIZING FOR SIZE

In the resource constrained domain of embedded systems the program size is an important aspect as

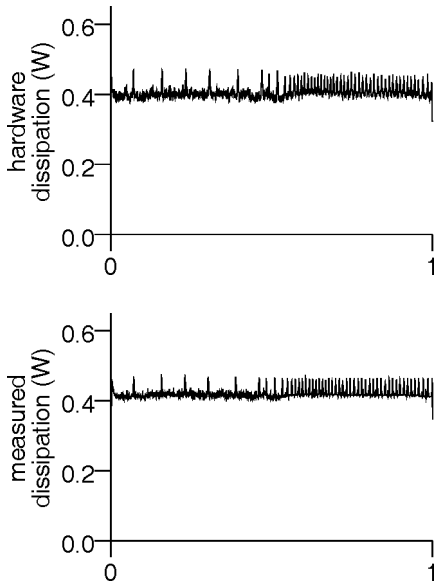

Figure 28. Measured and simulated power dissipation.

well. However, since the majority of compiler developers are interested in the performance of the generated code, this objective is often neglected. Several benchmarks exist that measure the performance of the generated code on a daily basis, however benchmark for code size have not existed previously. We have developed a benchmark called CSiBE (Code Size Benchmark) [1], which regularly measures the size of the code generated by GCC. We continuously maintain the benchmark and look for irregular changes in the result and act if required. Thanks to the existence of the benchmark, the compiler has been improved several times to generate a smaller code. Now it is considered as the standard GCC benchmark for size, which is used on a daily basis by several developers. The website gets more than 100 hits daily on average, and the offline version was downloaded by more than 500 times. We presented our work related to the measurement of the code size generated by GCC in two talks at the GCC Developers Summit, which gathered the key participants of this open source project [4, 5].

Besides the measuring, we worked on algorithms for code size reduction as well. We implemented code factoring algorithms in GCC and developed an enhanced procedural abstraction technique, which provides superior results compared to the existing solutions [7].

FLASH FILE SYSTEM IMPROVEMENTS

Embedded systems mostly use flash memory as storage device. The embedded systems which are complex enough to run a real operating system (in open source environment it is Linux), need a special flash file system to store their base (root) file system. Using an ordinary file system would wear out the flash prematurely.

The most effective and most popular open-source flash file system is JFFS2. To make it more powerful we improved its compression performance [6], and speed (speeded up its mount/boot time 5-10 times). Our improvements [2] were partially sponsored by Nokia Finland, and the results were approved by the open-source community. Now it is the official part of

Figure 29. Blackdog, a small Linux server utilizing JFFS2

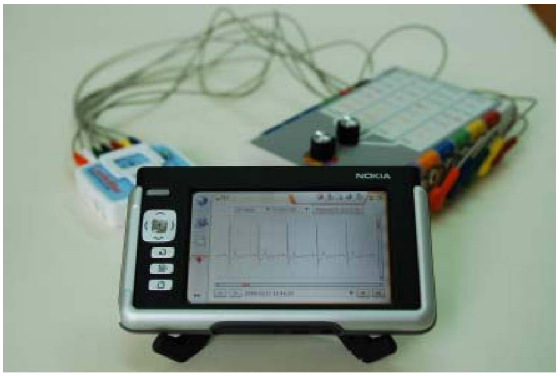

Figure 30. The Nokia770-based mobile ECG application.

the JFFS2 filesystem and the Linux kernel, and part of many industrial products such as Nokia 770 and N800 and small Linux server of Realm called Blackdog (see Figure 29).

Unfortunately JFFS2 has reached its limit: it was designed more then 5 years ago, and it cannot be tuned for larger flash than 512M. The problems are in the design level of the filesystem, so the development of a new generation of this filesystem (JFFS3) was necessary. This development is partially sponsored by Nokia, and is still in the designing phase.

ECG APPLICATION DEVELOPMENT

The above developments are close to the system level. To validate their effectiveness, we started an application development project on Nokia 770 in 2006, which was based on open source techniques.

We cooperated with Meditech Ltd., an ECG manufacturer company, and improved the functionality of their mobile ECG device (called CardioBlue) with some useful features using a Nokia 770 device: it displays ECG diagrams, extends the capacity of CardioBlue, configures CardioBlue, etc. The created application [3] is capable of transfering real-time ECG data to a remote PC as well, thus it makes remote medical consultation possible.

The application was introduced at the Medica international workshop in November, 2006. Figure 30 shows an example setup of the application.

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III. STATIC AND DYNAMIC PROGRAM ANALYSIS

INTRODUCTION

Program slicing is a powerful program analysis technique. It can be used for debugging, maintenance, reverse engineering and testing of programs. A slice consists of all statements and predicates that might affect a set of variables at a certain program point. A slice may be an executable program or a subset of the program code. Static slicing methods compute those statements which influence the value of a variable occurrence for all possible program inputs, while dynamic slicing methods take only one specific input into account.

The Department of Software Engineering of the Institute of Informatics performs significant research activity in the field of program analysis and specifically program slicing, both in theoretical and practical aspects. In the period 2003–2006 the following results have been achieved.

SLICING BINARY PROGRAMS

The original slicing algorithms were developed for high-level structured programs and comparatively little attention has been paid to the slicing of binary executable programs. However, the application domain for slicing binaries is similar to that for slicing high-level languages. Furthermore, there are special applications of the slicing of programs without source code like assembly programs, legacy software, and viruses. E.g., the slicing of binary executables can be a useful method for source code recovery or for helping extract security critical code fragments.

To address the above needs we gave a method for the interprocedural static slicing of binary executables [7]. We presented a conservative dependence graph based approach and also improvements. We evaluated both approaches on programs compiled for ARM architecture.

We also experimented with several methods on how to reduce the size of static slices. In [6], we described how superfluous edges can be removed from the statically computed call graph with the help of dynamically gathered information. The evaluation of this method demonstrated that the slice size could be dramatically reduced if the application being analysed made extensive use of indirect function calls.

THEORY OF SLICING

Previously, a large number of different slicing techniques have been introduced. Each preserves some aspect of a programs behaviour and simplifies the program to focus exclusively upon this behaviour. Their definitions, when given, have been operational, and their descriptions have been algorithmic. However, in order to understand the similarities and differences between slicing techniques, a formal mechanism is required.

We used a projection theory of slicing to provide a declarative formulation of the definition of the different forms of slicing [5]. With the help of the theory we uncovered the precise relationship between various forms of dynamic slicing and static slicing and produced formal and executable definitions of forward slicing. Our analysis of dynamic slicing introduced by Korel and Laski revealed that the subsumes relationship between static and dynamic slicing is more intricate that previous authors have claimed.

In all applications of slicing, the size of slices is crucial: the smaller the better. Based on the projection theory we established a formal mechanism for comparing sets of minimal slices, which form the ideal for any slicing algorithm, to reveal the ordering relationship between various static and dynamic slicing techniques [2]. This allows us to determine whether one definition of slicing leads to inherently smaller slices than another. This puts statements such as "dynamic slices are smaller than static slices" on a firm theoretical footing.

The extended versions of the theoretical results have been published in journals [3,4].

EFFICIENT DYNAMIC SLICING

Dynamic Dependence Graph-based methods for dynamic program slicing are well understood but inappropriate for practical use due to their inefficiency in terms of space requirements. Namely, many traditional methods for computing dynamic program slices are based on this graph representation, which captures the dynamically occurring dependences among program elements. The problem is that, being dependent on the size of the execution history, this approach produces data structures of unbounded size.

We proposed a common framework and different algorithms within it, which compute dynamic slices based on the same dynamic dependences that the DDG is built on, but without requiring the DDG itself to be used. Rather, specialized data structures are applied depending on the slicing scenario. Although some researchers mention similar algorithms, we are not aware of any other such comprehensive overview of the basic dependence-based dynamic slicing algorithms. These algorithms have been presented in a conference paper with the discussion about their complexities and application scenarios [1]. The scenarios are categorized along three dimensions: forward/backward slicing, demand driven/global, and

forward/backward trace processing. Of the eight possibilities, two are unfeasible while the others vary in their complexity.

This work has been selected for publication in a special issue of the *Journal of Software Maintenance and Evolution: Research and Practice* published by John Wiley & Sons, Ltd. expectedly in 2008.

ONGOING RESEARCH

There are two topics in the field of program analysis in which we produced the first results only recently.

The concept of *union slices* – the union of dynamic slices corresponding to different executions – proved to be useful as a replacement to static slices, which are in many cases overly conservative and hence imprecise. We continued the verification of our previous results in this field on Java programs, which was presented by a 5th year student at the Student Research Competition in 2006.

The second topic deals with approximate algorithms for program analysis. Although there are well elaborated methods (to which we also contributed significantly) that compute program dependences at the lowest instruction level, the computational cost of these algorithms is inappropriate in many applications. Therefore, more efficient though less precise methods are welcome. An approximate method for the computation of dynamic dependences among functions (without requiring instruction level analysis) has been elaborated with applications to impact analysis, debugging and program testing. The first publication of this algorithm was made by a 5th year student at the Student Research Competition winning the first prize in 2006.

Also, both of these results are accepted for presentation at the 2007 European Conference on Software Maintenance and Reengineering.

CONFERENCE ORGANIZATION

The 21st event of the most significant software maintenance conference, the *International Conference on Software Maintenance* (ICSM 2005) was organized by the Department of Software Engineering in 2005. The local organization issues of the *Fifth Workshop on Source Code Analysis and Manipulation* (SCAM 2005) held in Budapest were coordinated by Ákos Kiss.

R&D PROJECTS

Static and dynamic program analysis techniques can be utilized in many practical problems related to the maintenance of large software systems. The application of different techniques, including program slicing, to industrial software systems was verified in the scope of R&D projects partly financed by national grants and performed with partners from industry. The purpose of the JARTA (Java regression testing and analysis) project (duration: 2005–6, our share of the grant: 4 MFt) was to produce a prototype tool that integrates various program analysis techniques for program understanding and regression testing, most notably instruction level program slicing. Similarly, in the CREG++ (C++ regression testing and analysis) project (duration: 2005–6, our share of the grant: 31.5 MFt) efficient methods were implemented for the analysis of large C++ software systems. In both projects, the role of the Institute of Informatics was the development of the program analysis front end, and the implementation of block-level program instrumentation method, which is used by the regression testing method.

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Research Group on Artificial Intelligence

I. MACHINE LEARNING ALGORITHMS IN NATURAL LANGUAGE PROCESSING

The application of ML (Machine Learning) to practical problems is an emerging field of research and development. In many cases only machine learning can provide feasible approaches to algorithms, testing, and validation. Researchers at the Institute of Informatics are studying a number of areas related to NLP (Natural Language Processing) and extensively use machine learning algorithms for solving various problems [16].

THE NATURAL LANGUAGE PROCESSING

Investigating characteristic features of Hungarian language by means of information technology is a tradition at the Institute of Informatics. The history of it goes back to László Kalmár's work in the seventies. The intensity of research into this area substantially increased in 1998 when the institute, as a participant of the ESPRIT LTR20237 "ILP2" project, began to deal with the application of machine learning algorithms to NLP (Natural Language Processing).

The Institute of Informatics initiated a Hungarian NLP consortium in 1999 consisting of Research Institute for Linguistics at the Hungarian Academy of Sciences and MorphoLogic Ltd. Budapest, and the Institute of Informatics at the University of Szeged. The institute is a founding member of the international TEI (Text Encoding Initiative) Consortium (`http://www.tei-c.org`) as well.

The Hungarian NLP consortium successfully applied for R&D grants from the Hungarian Ministry of Education and Ministry of Economy. These grants provided financial support which enabled them doing the research described below.

THE SZEGED CORPUS AND ITS SUCCESSOR – THE SZEGED TREEBANK

Development work of the manually annotated Hungarian corpus began in 2000. At that time there was no sufficiently large morpho-syntactically annotated and disambiguated corpus for Hungarian. The Hungarian NLP consortium won the support of the Ministry of Education (grant OM IKTA 27/2000) with a project aiming the creation of a 1 million-words-long disambiguated corpus. The project ended in 2002.

Later, during the NKFP 2/017/2001 project 20% more text was added as well as every hierarchic NP (noun phrase) annotation. This database was a preliminary 1.0 version of the Szeged Treebank. The word *treebank* means a syntactically analyzed and annotated corpus. The recent, Szeged Treebank 2.0 has been finalized by 2005 in the framework of the OM IKTA 37/2002 project when all ADVPs (adverbial phrases), ADJPs (adjectival phrases), PPs (postnoun phrases), CLs (clausal phrases), and VPs (verb phrases) were annotated. Using this corpus as a training and validation database the consortium are developing syntax rules and an effective syntactic parser for Hungarian [7], [8], [9], [5], [11].

The corpus is available in XML and was encoded using the TEIXLITE[3] P2 or the P4 DTD scheme. Texts were collected from six different areas of recent Hungarian written sources (fiction, newspapers, legal texts, computer-oriented texts, teenage compositions, short business news). The HLT group maintain a software environment that supports the annotation works [4]. The different versions of the Szeged Corpus and the Treebank can be freely obtained for research and education purposes after registration [3], see `http://www.inf.u-szeged.hu/hlt`.

THE HUNGARIAN EUROWORNET DATABASE

Semantic analysis of natural language texts requires a comprehensive database containing possible meanings of concepts, so-called *senses*. Such databases have already been available for foreign languages and they are called *wordnets*. The EuroWordnet [4] family of wordnets provides not only a mean to establish interconnections between senses in different European languages (by making use of the ILI, the International Language Index) but also for representing different kinds of feature hierarchies. In 2005 the Hungarian NLP consortium began to build a Hungarian EuroWordnet database starting from the English wordnet by translating about 30 000 general terms and adding 10 000 new ones [1]. This project was financed by the Ministry of Economy in the framework of GVOP AKF 2004/0191 grant.

PROCESSING NATURAL LANGUAGE TEXTS

Researchers at the institute are studying the application of formal techniques at different stages of NLP. Besides the preprocessing of texts, three particular tasks are mentioned below where the application of formal approaches seems to be promising, as reported in the publications.

PART-OF-SPEECH TAGGING

The task of a POS tagger is, for a given text, to provide for each text word its contextually disambiguated part-of-speech *tag*. In the first experiments in 1999, the annotated Hungarian TELRI corpus from the MULTEXT-East[5] project was used. In [2], authors presented a preliminary study designed to illustrate the capabilities and limitations of current ILP and non-ILP algorithms on the Hungarian POS-tagging task. The popular C4.5 and Progol systems as propositional and ILP representatives were selected, adding experiments with methods AGLEARN, a C4.5 preprocessor based on *attribute grammars*, and two ILP approaches PHM and RIBL. Each algorithm produced disambiguation rules and, by applying these rules in a working tagger, a 96-97% per-word accuracy

[3] http://www.tei-c.org
[4] http://www.illc.uva.nl/EuroWordNet/
[5] http://nl.ijs.si/ME/

could be attained. The work was done in cooperation with researchers from the Fraunhofer Institute in Bonn.

When the Szeged Corpus was ready for use researchers studied several different learning algorithms for making a real-world POS-tagger program for Hungarian. After several attempts at using first-order (ILP) learning methods, a cascade of a TnT (`http://www.coli.uni-sb.de/ thorsten/tnt`) and a Brill tagger (`http://www.cs.jhu.edu/ brill`) currently gives the best results trained on a larger part of the 1.2 million-word corpus [18], [19].

LEARNING SYNTAX RULES FOR HUNGARIAN

Similar to many other languages, Hungarian also relies heavily on the use and interrelation of elementary word structures (syntagmas). NPs (Noun Phrases) are the most distinctive units of Hungarian sentences, hence shallow parsing primarily focuses on NP recognition.

Named entities, like person names, geographic names, organizations' names etc. play special role among noun phrases. Correct recognition of them, especially of those that have multiple words before syntactic parsing may have strong influence on the accuracy of further parsing. Researchers developed a method for Hungarian that made use of only lexical features of text words [12]. Later it has been successfully applied in an international environment [22].

Sometimes, there are cases when the task is not to collect the recognized named entities, but to remove them from the text. In some medical research electronic health records are processed by computers but before that the texts have to be anonymized in order to protect privacy of the patients. In the named entity removal task the above mentioned method attained an exceptionally good result for English [21].

For producing a recognizer for general NP structures researchers used parse trees collected from the Szeged Treebank as input. They produced NP syntax rule sets from frequent tree patterns occurred. Since the number of such tree patterns were high, they made experiments on generalization of rules and in such a way unite the similar ones [15].

When in 2005 the complete syntax annotation for the Szeged Treebank was ready, they applied the previously developed methods to produce rules for the full syntax [13]. Later, attempts were made to investigate on how to compress the initially large rule sets, and on how this compression can be aided by statistical or machine learning algorithms [5], [14].

INFORMATION EXTRACTION

The aim of the IE (Information Extraction) is to provide a structured, queriable dataset from the content of natural language texts. This does not require a program to fully understand the text. The approach to IE investigated at the institute is to set up templates (frames) with slots to be filled with information – so-called *semantic frames* –, then try to match sentences to these templates. This approach is similar to the one that has been introduced by C. J. Fillmore in the FrameNet project [6].

Machine learning algorithms have been successfully used in learning semantic frames from training data. Researchers at the institute created a learning dataset with 2000 short business news items as a basis for further investigation. Studying the applicability of ML in learning semantic frames is investigated in [16].

In the framework of the GVOP AKF 2004/0119 grant of the Ministry of Economy the consortium partners developed a prototype of an IE system, that processes abstracts of biomedical publications can be retrieved from the PubMed[7] database. It collects information on gene interactions from the sentences, i.e. after reading an abstract it predicts whether the referred publication deals with interactions of two or more genes, it tries to determine the type of the interactions between the genes as well [6]. An experiment with different realizations of an IE system for English language medical discharge records can be found in [20].

The Institute of Informatics together with its consortium partners is developing a tool-chain of NLP modules necessary for building experimental IE systems. An example prototype system is able to extract information from short business news related to certain types of events in business life, such as acquisitions, balance reports, mid-term reports, contracts, or fusion.

Formal specification of semantic-frames can be formulated at a higher level of abstraction after the Hungarian EuroWordnet database will be finished in 2007. Semantic frame definitions then can refer not only to lexical words, but to concepts with synonyms, and restrictions on senses can also be applied. The development works are supported by the grant GVOP AKF 2004/0191.

OTHER APPLICATIONS OF LANGUAGE TECHNOLOGY

The researchers at the institute began to assemble a Hungarian named entity corpus. Its name is NER (Named Entity Recognition) corpus and contains named entities collected by members of the NLP consortium and other stakeholders during the past years. A smaller sense annotated corpus is currently being built in connection with the EuroWordnet project, the so-called wsd corpus. This can later be used as a test database for word sense disambiguation algorithms.

RESEARCH CONNECTIONS IN EDUCATION

This research activities relate to the following fields in Computer Science: Artificial Intelligence, Machine Learning, Knowledge Discovery, Computational Linguistics, Information Extraction, Formal Languages, Theory of Compiling and Parsing.

Unsolved problems are being studied by several PhD students and investigated in students' scientific projects, in masters and bachelor theses. The homepage of Human Language Technology group is: `http://www.inf.u-szeged.hu/hlt`. The web site contains up-to-date information about R & D projects, consortium partners, researchers, publications, and downloadables provided by the group.

THE MSZNY CONFERENCE SERIES

In 2003 the Institute of Informatics organized the First Hungarian Conference on Computational Linguistics, MSZNY 2003 in Szeged. About hundred participants from all over Hungary came and presented

[6] http://framenet.icsi.berkeley.edu/

[7] http://www.pubmed.gov

an overview of their work. A special issue of the international journal Acta Cybernetica has been published in 2004 containing the best papers of the conference.

Since then this tradition was going on and in each year from 2003 the Institute of Informatics organized the MSZNY 2004, MSZNY 2005 and MSZNY 2006 conferences. An issue of Acta Cybernetica containing the best papers of MSZNY 2004 has been published in the Spring of 2006. See the conference homepage at the `http://www.inf.u-szeged.hu/mszny2006`.

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II. PEER-TO-PEER ALGORITHMS AND SYSTEMS

INTRODUCTION

During the past decade the Internet has undergone an impressive growth and has reached very high levels of penetration into homes and businesses. This has lead to a radical shift in the possibilities it offers and new applications such as (illegal) file sharing and collective computation have appeared. Many of these applications, mostly due to legal pressure, have obtained a truely *peer-to-peer* (P2P) character, in that they are fully decentralized, extremely fault tolerant and scalable.

These systems and their success have contributed to revitalizing the interest of the scientific community in fully decentralized, scalable, robust distributed systems, since they have many legitimate applications as well, such as content distribution networks, sensor networks, network monitoring, distributed data mining, and so on.

In the past years, we have worked in this area developing several P2P algorithms for data aggregation [9,10,12,14,16], overlay network topology management [6,7,13,15,17], peer sampling [8,19] and load balancing [11].

We have also worked on an integrated framework where these components can be combined together in a natural way [3, 4, 11]. Finally, we have attempted to distill some of the main design ideas we applied in the form of design patterns [1, 2], that capture basic approaches to achieve certain functionalities based on fully decentralized and local communication models.

In the following we briefly discuss some examples to illustrate our approach to P2P protocol design.

EXAMPLE ALGORITHMS

Our algorithms are based on the gossip-based paradigm. Gossip-style protocols are attractive since they are extremely robust to both computation and communication failures. They are also extremely responsive and can adapt rapidly to changes in the underlying communication structure without any additional measures.

The skeleton of a generic gossip-based protocol is shown in Figure 31. Each node possesses a local state and executes two different threads. The *active* one periodically initiates an *information exchange* with a peer node selected randomly, by sending a message containing the local state and waits for a response from the selected node. The *passive* thread waits for messages sent by an initiator and replies with its local state.

Method UPDATE builds a new local state based on the previous local state and the state received during the information exchange. The output of UPDATE depends on the specific function implemented by the protocol. The local states at the two peers after an information exchange are not necessarily the same, since UPDATE may be non-deterministic or may produce different outputs depending on which node is the initiator.

In the following we describe example instantiations we have developed, indicated by the gray components in Figure 32, that illustrates the dependence relations between these and various other existing or planned components.

NEWSCAST

In NEWSCAST [8], the state of a node is given by a *partial view*, which is a set of peer descriptors with a fixed size c. A *peer descriptor* contains the address of the peer, along with a *timestamp* corresponding to the time when the descriptor was created.

Method GETPEER returns an address selected randomly among those in the current partial view. Method UPDATE merges the partial views of the two nodes involved in an exchange and keeps the c freshest descriptors, thereby creating a new partial view. New information enters the system when a node sends its partial view to a peer. In this step, the node always inserts its own, newly created descriptor into the partial view. Old information is gradually and automatically removed from the system and gets replaced by newer information. This feature allows the protocol to "repair" the overlay topology by forgetting dead links, which by definition do not get updated because their owner is no longer active.

In NEWSCAST, the overlay topology is defined by the content of partial views. We have shown in [8] that the resulting topology has small diameter and is very close to a random graph with out-degree c. According to our experimental results, choosing $c = 20$ is already sufficient for very stable and robust connectivity. We have also shown that, within a single cycle, the number of exchanges per node can be modeled through a random variable with the distribution $1 + \text{Poisson}(1)$. The implication of this property is that no node is more important (or overloaded) than others.

T-MAN

Another instantiation of the gossip skeleton we de-

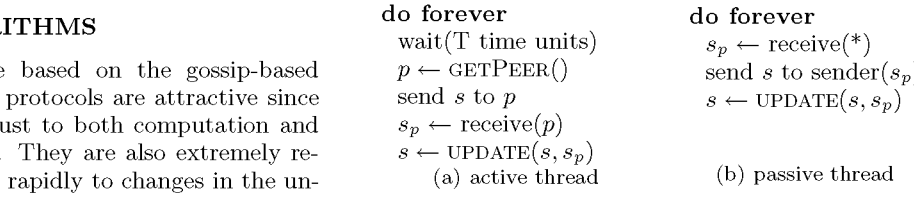


Figure 31. The skeleton of a gossip-based protocol. Notation: s is the local state, s_p is the state of the peer p.

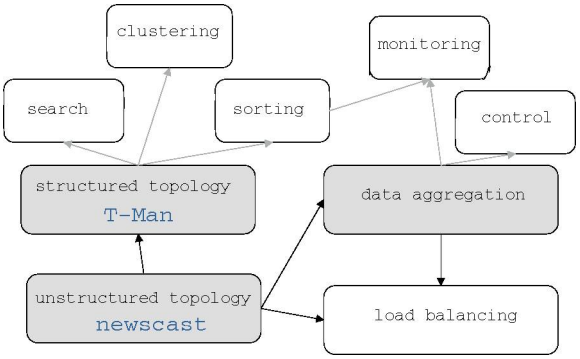


Figure 32. Dependence relations between components.

veloped is T-MAN [7], a protocol for creating a large class of topologies. The idea behind the protocol is very similar to that of NEWSCAST. The difference is that instead of using the creation date (freshness) of descriptors, T-MAN applies a ranking function that ranks any set of nodes according to increasing distance from a base node. Method GETPEER returns neighbors with a bias towards closer ones, and, similarly, UPDATE keeps peers that are closer, according to the ranking.

Figure 33 illustrates the protocol, as it constructs a torus topology. In [7] it was experimentally shown that the protocol converges in logarithmic time even for networks of 10^6 nodes and for other topologies including rings and binary trees. With the appropriate ranking function, T-MAN can also be used to sort a set of numbers.

T-MAN relies on another component for generating an initial random topology which is later evolved into the desired one. In our case this service is provided by NEWSCAST.

GOSSIP-BASED AGGREGATION

In the case of gossip-based aggregation [10,12,16], the state of a node is a numeric value. In a practical setting, this value can be any attribute of the environment, such as the load or the storage capacity. The task of the protocol is to calculate an aggregate value over the set of all numbers stored at nodes. Although several aggregate functions may be computed by our protocol, in this paper we provide only the details for the average function.

In order to work, this protocol needs an overlay protocol that provides an implementation of method GETPEER. Here, we assume that this service is provided by NEWSCAST, but any other overlay could be used.

To compute the average, method UPDATE(a, b) must return $(a + b)/2$. After one state exchange, the sum of the values maintained by the two nodes does not change, since they have just balanced their values. So the operation does not change the global average either; it only decreases the variance over all the estimates in the system.

In [10] it was shown that if the communication topology is not only connected but also sufficiently random, at each cycle the empirical variance computed over the set of values maintained by nodes is reduced by a factor whose expected value is $2\sqrt{e}$. Most importantly, this result is independent of the network size, confirming the extreme scalability of the protocol.

In addition to being fast, our aggregation protocol is also very robust. Node failures may perturb the final result, as the values stored in crashed nodes are lost; but both analytical and empirical studies have shown that this effect is generally marginal [16]. As long as the overlay network remains connected, link failures do not modify the final value, they only slow down the aggregation process.

NOTES ON COMBINING THE BUILDING BLOCKS

The combination of the building blocks is done in the traditional way: a building block has a local interface (within one node) towards the other components, and it has a protocol and an implementation associated with it. The implementation can differ over different nodes, just like the local interface. For this reason, we have focused on protocols in the above discussion. Nodes using the same protocol (for example, aggregation) form a "layer" in the system. This, however, is not a layer in the usual sense: we allow for arbitrary dependency relations between the building blocks. In general, the directed graph that describes the dependencies (such as the example shown in Figure 32) will not contain cycles, however, this is not strictly required. Two "layers" can mutually depend on each other's services; for instance, in a bootstrapping phase when they can catalyze each other's performance.

Having said that, we need to mention one exception. There is a "lowest layer" in our framework, which in a sense represents the group abstraction: the set of nodes that form the domain of the other components. This layer is the random network component, which provides the *peer sampling service* (see Section II. and [8]). The main requirement for this service is that it must return all nodes with equal probability, in particular, no nodes are to be excluded forever. The peer sampling service is used to support and bootstrap other services like aggregation or structured topologies.

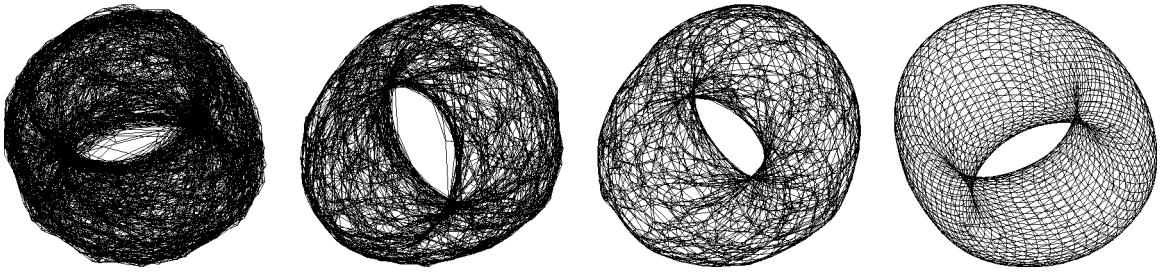
Finally, the aspect of *time-scale* should also be noted. While all of the protocols are based on the scheme given in Figure 31, the waiting time T can be different for different building blocks. This degree of freedom allows for certain architectures that otherwise would not be possible. For example, if an up-to-date aggregate value is needed "instantly" according to the timescale of a relatively slow layer, like load balancing, then we can simply apply aggregation at a relatively faster timescale.

OPEN SOURCE SOFTWARE

We did project administrating and developing (with Alberto Montresor) for the PeerSim open source project that develops a simulator for large scale peer-to-peer algorithms and networks [18]. The number of times the simulator has been downloaded now approaches 5000.

CONFERENCE ORGANIZATION AND EDITING

We involved in organizing the invitation-only workshop "International Workshop on Self-∗ Properties in Complex Information Systems", in Bertinoro, Italy, in 2004, with Ozalp Babaoglu, Alberto Montresor, Christof Fetzer, Aad van Moorsel, Stefano Leonardi and Maarten van Steen. After the workshop we edited a post-proceedings [5].



after 2 cycles after 3 cycles after 4 cycles after 7 cycles

Figure 33. Illustrative example of constructing a torus over $50 \times 50 = 2500$ nodes, starting from a uniform random graph: 20 random entries in each view, with $m = 20, \psi = 10$ and $K = 4$.

We also took part in organizing the "The Fourth International Workshop on Engineering Self-Organizing Applications (ESOA'06)" togeather with Sven Brueckner, Salima Hassas and Dan Yamins. The workshop was a satellite workshop of the "2006 International Conference on Autonomous Agents and Multiagent Systems" in Hakodate, Japan.

With Ozalp Babaoglu and Robert Laddaga, we edited a special issue of "IEEE Intelligent Systems", published as volume 21, number 2, in 2006. The theme of the issue was "Self-Management through Self-Organization in Information Systems".

PROGRAM COMMITTEE MEMBER

1. IEEE Conference on Peer-to-Peer Computing (P2P) 2006 and 2007
2. IEEE Congress on Evolutionary Computation (CEC) 2007 special session on EC for decentralized systems
3. International Conference on Parallel Processing (ICPP) 2007, P2P track
4. International Conference on Computer Communications and Networks (ICCCN) 2006 and 2007, P2P track
5. Workshop on Data Processing in Ubiquitous Information System (DPUbiq) 2007
6. Workshop on Modeling, Simulation and Optimization of Peer-to-peer environments (MSOP2P) 2007
7. Workshop on Multi-Agents for modeling Complex Systems (MA4CS) 2006
8. International Conference on Bio inspired Models of Network, Information and Computing Systems (BIONETICS) 2006
9. European Conference on Parallel Computing (Euro-Par) 2005 and 2006, vice chair of topic: Peer-to-Peer and Web Computing
10. IEEE International Workshop on Self-Managed Networks, Systems and Services(SelfMan) 2006
11. International Conference on Distributed Computing Systems (ICDCS) 2006, P2P track
12. International Workshop on Security and Trust in Decentralized/Distributed Data Structures (STD3S) 2006
13. IEEE Workshop on Stochasticity in Distributed Systems (StoDiS) 2005
14. Engineering Self-Organising Applications (ESOA) 2005
15. Socially Inspired Computing Symposium at the AISB convention on Social Intelligence and Interaction in Animals, Robots And Agents (AISB SIC) 2005

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III. SPEECH TECHNOLOGY

During the period 2003-2006 our speech technology team achieved many new results both in inventing novel speech recognition related algorithms and in constructing working speech recognition systems for Hungarian. Two of our colleagues obtained their Ph.D. degree from the results of this research [10,48]. The most recent and probably most important development was a 3-year IKTA-6 project for the design and implementation of a medical dictation system.

SPEECH IMPEDIMENT THERAPY

In 2004 the IKTA-4 project for the development of the "SpeechMaster" speech impediment therapy system ended, and the software was made available to many elementary schools and speech therapy institutes for testing. Since then we have received a lot of feedback, and teachers seem to be very satisfied with the results achieved thanks to the application of the software in both reading teaching and speech impediment therapy. We published numerous papers on the pedagogical, linguistic and technological aspects of "SpeechMaster" [6,8,14,16,17,20,21,23,24,26–28, 30,31,40,41,43,46].

SPEECH RECOGNITION RESEARCH

We have continued the development of our modular speech recognition system "OASIS". Most importantly, it was extended with a statistical language model, so we are now able to conduct experiments on realistic continuous speech recognition tasks. Besides its original segment-based acoustic model, the system was adapted to be able to work following the conventional frame-based scheme as well. Huge efforts were made to investigate and understand the similarities and differences between the segment-based and the frame-based acoustic modelling technique [29]. Quite recently we experimented with the hybrid HMM/ANN technology in acoustic modelling, and compared its behavior with our conventional ANN-based segmental modelling scheme [32, 34, 49]. We investigated several search space pruning techniques in order to obtain a faster and more efficient decoding performance [2, 5, 19, 22, 25, 36, 47]. Our colleagues experimented with novel types of machine learning algorithms [12, 35] and knowledge source combination techniques [1,3,9,15,26] to achieve the highest possible phone recognition performance. On the acoustic

side the so-called modulation or 2D-cepstum features were introduced to our system, and were shown to yield a noticeable improvement [42].

DATABASE CONSTRUCTION

In 2004 the Department of Informatics at the University of Szeged and the Laboratory of Speech Acoustics of the Budapest University of Technology and Economics began a project with the aim of collecting and/or creating the basic resources needed for the construction of a continuous dictation system for Hungarian. The project lasted for three years (2004-2006), and was financially supported by the national fund IKTA-056/2003. To support the training of dictation systems, the project included the creation of a large speech corpus of phonetically rich sentences that allows the training of general-purpose dictation systems. Hence in the first phase of the project we designed, assembled and annotated a speech database called the MRBA ("Hungarian Reference Speech Database") corpus [18]. The contents of the database were designed by the Laboratory of Speech Acoustics, based on the phone and diphone statistics of a phonetically transcribed large text corpus. From this corpus 1992 sentences and 1992 words were selected, and then they were recorded from 332 speakers, each reading 12 sentences and 12 words. Both teams participated in the collection of the recordings, which was carried out in four big cities. The sound files were cleaned up and annotated at the Laboratory of Speech Acoustics, while the Research Group on Artificial Intelligence manually segmented and labelled one third of the files at the phone level. This part of the corpus is intended to support the initialization of phone models.

CONSTRUCTION OF A MEDICAL DICTATION SYSTEM

Besides the collection of a speech corpus, the IKTA project also contained the creation of a prototype dictation system. To make the task more manageable, especially the language modelling part, we restricted the target domain of the dictation to a specific type of medical report. Although this task is clearly easier than general dictation, we chose this application area with the intent of assessing the capabilities of our technologies. Depending on the findings, we later hope to extend the system to more general dictation domains. As our team focused on the task of the dictation of thyroid scintigraphy medical reports, we summarize these results in the following [37–39,42].

At the level of acoustic modelling we have been experimenting with two quite different technologies. One of these is a quite conventional Hidden Markov Model (HMM) decoder that works with the usual mel-frequency cepstral coefficient (MFCC) features.The phone models applied have the usual 3-state left-to-right topology and are monophone models, that is no context-dependent models were tested in the system. The decoder built on these HMM phone models performs a combination of Viterbi and multi-stack decoding. For speed efficiency it contains several built-in pruning criteria. With the proper choice of parameters the decoder on a typical PC runs faster than real-time on the medical dictation task.

Our alternative, experimental acoustic model employs the HMM/ANN hybrid technology. The basic difference between this and the standard HMM scheme is that here the probabilities are modelled by Artificial Neural Networks (ANNs) instead of the conventional Gaussian mixtures (GMM). As ANNs seem to be more capable of modelling the observation context than GMMs, hybrid models are usually trained over longer time windows. Knowing that the modulation components play an important role in human speech perception, a frequency analysis over the feature trajectories seems to be a reasonable representation technique. We apply this analysis to the cepstral coefficients, that produces the so-called 2D-cepstrum.

In order to construct the domain-specific language models we got 9231 medical reports from the Department of Nuclear Medicine of the University of Szeged. These thyroid scintigraphy reports were written using various software packages during 1998 to 2004, so first of all we had to convert them to a common format, followed by several steps of routine error correction. After this the corpus contained approximately 2500 different word forms, so we were confronted with a medium-sized vocabulary dictation task. Thanks to this limited vocabulary we could avoid the use of a morphological model. Although 2500 words could be easily managed even by a simple list ('linear lexicon'), we organized the words into a lexical tree where the common prefixes of the lexical entries are shared. Apart from storage reduction advantages, the prefix tree representation also speeds up decoding, as it eliminates redundant acoustic evaluations.

The limited size of the vocabulary and the highly restricted (i.e. low-perplexity) nature of the sentences used in the reports allowed us to create very efficient n-grams. The system applies 3-grams by default, but it is able to 'back off' to smaller n-grams (in the worst case to a small ϵ constant) when necessary. During the evaluation of the n-grams the system applies a language model lookahead technique.For this reason the lexical trees are stored in a factored form, which allows a more efficient pruning of the search space.

Besides word n-grams we also tried constructing class n-grams. For this purpose the words were grouped into classes according to their parts-of-speech category. The words were categorized based on their MSD code, and we constructed the class n-grams over these codes. In previous experiments we found that the application of the language model lookahead technique and class n-grams brought about a 30% decrease in the word error rate when it was applied in combination with our HMM-based fast decoder [39].

For testing purposes we recorded 20-20 medical reports from 2 male and 2 female speakers. The language model applied in the tests was constructed based on just 500 reports instead of all the 8546 we had collected. This subset contained almost all possible sentence types, so this restriction just reduced the dictionary by removing rarely occurring words (e.g. dates and disease names). Besides the HMM decoder we tested the HMM/ANN hybrid system with the conventional features and the 2D-cepstrum features as well. The results are listed in Table 3 below. As can be seen, each configuration performed well above 90%, but for some reason the HMM system did not like the set of female voices. In the next part we plan to extend the language model to cover all the available data and to test the system over other dictation domains as well. We also intend to implement speaker adaptation and context-dependent models within the HMM system and to continue our research on observation context modelling in the HMM/ANN system.

Model Type	Feature Set	Male 1	Male 2	Female 1	Female 2
HMM	MFCC + Δ + $\Delta\Delta$	97.75%	98.22%	93.40%	93.39%
HMM/ANN	MFCC + Δ + $\Delta\Delta$	97.65%	97.37%	96.78%	96.91%
HMM/ANN	2D-cepstrum	97.88%	97.83%	96.86%	96.42%

Table 3. Word recognition accuracies of the various models and feature sets.

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IV. MACHINE LEARNING AND COMPUTATIONAL LEARNING THEORY

INTRODUCTION

Machine learning and computational learning theory deal with the automatic acquisition of knowledge from data, for example, in the form of classification or regression rules. The field developed rapidly in the past decade, in terms of the construction of new, efficient learning algorithms, the theoretical understanding of the possibilities and limitations of efficient learning methods, and also in terms of the scope of application areas.

Results achieved at the Research Group on Artificial Intelligence (RGAI) in the area of learning during 2003-2007 involved work in all these directions: the development of SpeechMaster, a successful software product which uses machine learning technology, research on the development of machine learning algorithms such as kernel and support vector methods, and theoretical results in various formal models of computational learning theory, such as theory revision in query and mistake-bounded models.

SPEECHMASTER, APLLICATIONS OF MACHINE LEARNING IN SPEECH RECOGNITION

The software package SpeechMaster was developed for speech impediment therapy and the teaching of reading. It is freely available at

`www.inf.u-szeged.hu/beszedmester`

The system uses machine learning methods as part of speech recognition technology. The objective in the two tasks is to provide visual phonetic feedback and to reinforce the correct association between the phoneme/grapheme pairs. A brief overview of the various functionalities of the system is given in [6].

Research completed in the course of the development of the system includes a comprehensive evaluation of several recent machine learning algorithms, such as kernelized versions of principal component analysis (KPCA), independent component analysis (KICA), linear discriminant analysis (KLDA) and springy discriminant analysis (KSDA) in the context of speech recognition tasks [7], several of which has been developed earlier at the research group. A comparison of several learning methods for the particular task of phoneme classification is given in [8]. Besides kernel methods, another important recent development in machine learning is the construction of efficient techniques for combining classifiers, such as boosting. The paper [1] gives a detailed computational study of the different combination methods for speech recognition tasks, and [4] compares the combination methods for natural language processing tasks. [17] discusses a sampling scheme handling the important practical problem of imbalances in training data. The paper [18] gives a general algorithmic framework to provide experimental evidence and explanation for the success of Hidden Markov Model techniques in

speech recognition, in spite of the simplistic independence assumptions inherent in the model.

MACHINE LEARNING ALGORITHMS

Convex Networks (CN), a new learning method combining certain attractive features of neural networks and support vector machines (SVM), is introduced in [10] and developed further in [11]. Classification techniques leading to simpler optimization problems than SVM techniques have been developed in [9]. These techniques are computationally more efficient than SVM, but produce classifiers competitive with SVM and other methods, when compared on standard benchmark data sets. Margin Maximizing Discriminant Analysis (MMDA), a new feature extraction method, is developed in [5]. It has linear and non-linear (kernelized) versions, has attractive computational features and it is competitive with other related methods. The method is applied for the development of feature extraction algorithms for regression problems in [16]. The MMD approach is integrated with the CVM (Core Vector Machine) method in [19]. CVM is a recent approach to classification and regression, which is significantly faster than SVM (Support Vector Machines) and competitive with it in learning quality.

COMPUTATIONAL LEARNING THEORY

Theory revision provides efficient concept learning algorithms given an initial theory which is an approximation of the target. Several theory revision algorithms are presented in query models [2,14] and mistake bounded models [13,15]. [12] considers the effect on the size of a DNF formula, of incorporating exceptions into the formula. This problem is motivated by applications in computational learning theory. The paper [3] studies learnability consequences of restrictions on the tree width and clique width of first-order logic structures, by studying combinatorial parameters such as the Vapnik-Chervonenkis dimension and the strong consistency dimension.

CONFERENCES ORGANIZED

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