# High Performance Computing. Image and Video processing, Global optimization and Matrix computation. TIN2005-00447

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## Abstract

This project addresses a set of problems that require intensive computation and that come from different scientific and technological fields. In these computationally expensive applications, efficient approaches are paramount for the solution of the problems in practical terms. The problems to be tackled in this project are: image processing applied to determination of the structure of biological specimens in electron microscopy; Coding and compression for progressive transmission of image and video; Nonlinear programming techniques and new global optimization (both deterministic and stochastic) methods for solving real problems; Numerical methods for the simulation of complex systems that are described by means of integral-differential equations. The research to be carried out in this project is focused from different perspectives: (1) development of novel specific methods to face the problems above mentioned; (2) Analysis, design and development of distributed computing models under heterogeneous multiprocessor systems (e.g. dynamic load balancing, hybrid computation paradigms, such as the combination multithreading-message passing, etc.) to efficiently deal with the real applications addressed in this project; (3) Implementation of the developed methods, according to the distributed computing models, to be executed on heterogeneous parallel environments.

**Keywords**: Image processing, Video compression and transmission, Global optimization, Matrix computation, Parallel Computing.

## 1 Goals

This research project is structured into four subsections which describe the main goals.

### 1.1 Image processing and tomographic reconstruction

Our global aim is to improve the methodologies for multidimensional image processing and tomographic reconstruction for their experimental application in science, particularly structural

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biology, and face their computational demands by means of high performance computing. The specific goals are the following: (1) Development and improvement of iterative methods for tomographic reconstruction. Use of global optimization techniques to tune the parameters for tomographic reconstruction. (2) Parallelization of iterative reconstruction methods and multidimensional image processing techniques, using parallel and distributed environments. Design of dynamic load balancing strategies to improve performance. (3) Development of multidimensional image processing techniques for structure-preserving noise reduction, restoration for the transfer function of the electron microscope, registration, segmentation and pattern recognition.

## 1.2 Video compression and transmission

We are interested in the design of new techniques for the coding of images and video in the context of the image and video transmission on packet-switched networks. More specifically: (1) Design of systems for the efficient transmission of images taking advantage of scalable image compressors such as the JPEG2000 standard. (2) Development of scalable video coding techniques that offer temporal, spatial and SNR scalabilities. (3) Design of systems for the efficient transmission of scalable video on, unicast, multicast and P2P networks to implement video on demand and video streaming applications.

## 1.3 Global optimization

The Global optimization research of our group is aimed at designing efficient methods to solve hard global optimization problems and parallelize them using different strategies and architectures. We work with two different kinds of global optimization methods: Interval branch and bound algorithms and Metaheuristics algorithms. In the area of Interval B&B our research focuses in the development of new devices that accelerate the exhaustive search done by branch and bound codes, mainly when they are applied to global optimization. Due to the large computational time needed to solve this kind of problems, we also study their parallel approaches. In the area of Metaheuristics our work is intended to solve NP-hard global optimization problems by designing hybrid evolutionary algorithms (memetic algorithms). Some of these heuristics have been used to solve competitive location problems. Our research interest has also been focused to the design and implementation of new heuristic methods to solve the optimal design of water distribution networks (WDN) using a multi-objective formulation. Currently we are working on parallel versions using several strategies and architectures.

## 1.4 Matrix computation

Our research in this topics is focused on the solution of Partial Differential Equations (PDEs) linked to physic phenomena that occur in science and engineering. Our general goal is to develop efficient solutions from a computational point of view. Specifically, we have studied a mathematical model for the bursting phenomenon, very common in many natural systems, from neuronal physiology to hydrodynamics. Our particular goals are: To analyse the mathematical model for different initial and/or boundary conditions, and to study several parallel strategies for determining the advantages of each strategy, in order to identify the optimal solution for every particular architecture.

# 2 Success level achieved in the project

## 2.1 Image processing and tomographic reconstruction

In the field of 3D Reconstruction we are currently developing a new block-parallel iterative method for tomographic reconstruction based on Kaczmarz's approach, in collaboration with D. Gordon's group in Haifa. This method turns out to be very efficient, achieving solutions with good quality in just a few iterations. Also, we have implemented a global optimization approach for tuning the reconstruction parameters for the specimen subjected to structural analysis [1, 2]. In order to face their high computational burden, we have parallelized iterative reconstruction methods for structural analysis in cellular biology [3] and molecular biology [2, 4]. The parallel strategies are based on domain decomposition and show excellent levels of scalability. In addition, we are designing and exploring multithreading approaches and dynamic load balancing strategies based on Adaptive MPI to map these methods on heterogeneous environments [5, 6]. The preliminary results we are obtaining are really promising. Finally, we have made efficient implementations of our method for noise reduction that significantly reduces the memory consumption and computation time [7, 8, 9, 10], with special emphasis on clusters of SMPs using hybrid parallel programming paradigms. We have used a global optimization approach for image registration that turns out to be useful in the field of electron crystallography [11]. A method for restoration of the transfer function of the electron microscope has been developed in the field of electron tomography [12]. Also, we have worked with pattern recognition techniques based on cross-correlation to extract macromolecules in large tomographic reconstructions with the aim of computing the average repeating motif [12]. We have also adapted our method for noise reduction for its successful application in the field of materials science [13]. Our computational image processing methods have been put into practice in Biochemistry and Structural Biology [14, 15].

## 2.2 Video compression and transmission

We have developed a new data partitioning algorithm very suitable for the progressive transmission of images using the Web infrastructure and the JPEG2000 standard. Our proposal takes advantage of the Web proxies to improve the quality of the received images [16, 17]. Also, we have proposed a novel image stitching technique based in the JPEG2000 compression standard for the design of efficient virtual slide telepathology systems [18, 19, 20]. In the field of scalable video coding, we have developed a codec called FSVC (Fully Scalable Video Codec), based in Motion JPEG2000, that improves the coding efficiency of this codec. Our system can manage all the scalabilities that we mentioned before and offers an excellent coding performance compared to other non scalable video alternatives [21, 22]. We are using FSVC to implement a video streaming system based on a P2P network.

## 2.3 Global optimization

In the Branch and Bound approach, our research group has developed new algorithms to solve: i) Mixture design (Blending) problems with quadratics constraints [23, 24], ii) interval global optimization problems [25, 26, 27, 28] and iii) competitive locations problems [29]. The new blending algorithm is able to determine for each number of raw material: (1) The non existence

of a solution, (2) The region that contain a possible solution. (3) The best Pareto solution. In interval branch and bound codes, new discarding tests based on a rigorous covering of the region were developed. At this stage of the research we are working on parallel versions of our algorithms. Furthermore, rigorous interval branch and bound methods has been applied to solve the rendering of isosurfaces and real polynomials in complex space [30, 31]. Other solved problem with applications in coding theory is the packing equal circles in a square [32].

In the field of Metaheuristics algorithms we have implemented several efficient evolutionary algorithms to solve competitive location problems. We have designed algorithms to solve discrete and continuous problems when trying to locate one or several facilities simultaneously [33, 34]. Also efficient parallel versions of those algorithms have been implemented using message passing (MPI). For each sequential algorithm different parallel strategies have been implemented and analyzed [35, 36]. Also for the problem known as Leader-Follower in the location literature we have implemented the sequential version of the optimization algorithm and we are working on their parallel versions. In the field of multiobjective optimization problems we have designed new metaheutistic algorithms (sequential and parallel strategies) which successfully solve the Water Distribution Network problem [37, 38, 39, 40, 41, 42, 43, 44].

## 2.4   Matrix computation

We have developed a mathematical model for the bursting phenomenon in collaboration with the group Numerical Simulation of the University of Málaga. The model consists of four nonlinearly coupled PDEs that include fast and slow variables and exhibits bursting in the absence of diffusion. The PDEs have been discretized by means of a second–order accurate in both space and time, linearly–implicit finite difference method in equally–spaced grids. The resulting system of linear algebraic equations at each time level has been solved by means of the Preconditioned Conjugate Gradient (PCG) method. Three different parallel implementations of the proposed mathematical model have been developed; two of these implementations are based on a message passing paradigm, while the third one is based on a shared space address paradigm. These three implementations have been evaluated on a dual–processor cluster and a Shared Distributed Memory (SDM) system [45, 46, 47].

# 3   Results indicators

## 3.1   Goal achievement

Globally, we have achieved most of the goals set in the project proposal. In the next months, in the field of Image processing and tomographic reconstruction we plan to progress further with the improvement of methods for image processing and reconstruction, and with the application of high performance computing to face their computational demands. In addition to supercomputers and computer clusters, we also plan to design new strategies to exploit the computational power of modern stand-alone computers (e.g simultaneous multithreading, multi-core, multimedia extensions, etc). In the field of Video compression and transmission we are planning to port our algorithms to mobile communication systems like PDA's and telephone devices. In the field of Global optimization we have developed new algorithms to solve the blending and facility location problems. Moreover we have improved the general purpose

interval global optimization algorithm. Distributed and shared memory parallel algorithms for blending and interval global optimization problems have also been developed. The following step is to use heterogeneous multicomputer to run a mixture version of previous algorithms and to parallelize the leader-follower problem using different hybrid parallel strategies in different architectures.

## 3.2 Relevance and originality of results

We have published our works in journals with medium-high impact index. We have also presented our works in well-known and prestigious congresses. Despite the recent publication, some of the articles are already getting cites (as seen with Scopus or ISI Web of Science).

## 3.3 Scientific publications

- Intern. Journals [1, 3, 4, 5, 7, 11, 12, 13, 14, 15, 20, 25, 23, 24, 26, 34, 33, 39, 42, 40, 44, 48]

- Lecture Notes in Computer Science [8, 22, 27, 46, 47]; PhD theses [2, 45, 49, 28, 29]

- International books [32]; Chapters in international books [9, 35, 37, 38, 43]

- International congresses [6, 10, 41, 30, 31, 21, 17, 19, 18, 16, 50, 36]

## 3.4 Utility of results and their role in economic and social development

Our methods for multidimensional image processing and tomography are currently put into practice in laboratories of structural and molecular biology worldwide. In particular, our packages for tomographic reconstruction, noise reduction and restoration for the transfer function are now used in more than a dozen of labs in USA and EU in the field of electron tomography. This fact is also reflected in the cites to our scientific publications. We also have an ongoing technology-transfer project with Holcim, one of the world's leading suppliers of cement and aggregates, to develop image processing methods to automatically assess the quality of the cement clinker. Our technology in the field of image and video coding and transmission is being applied to the design of commercial software by the company IRC Crawler to perform video streaming on the Internet and telephone mobile networks. Two technology-transfer contracts between our group and this company have been established.

## 3.5 Human Resource Development

In 2006, JR Bilbao-Castro got his PhD degree on "High performance computing in high resolution three dimensional electron microscopy" [2] and Siham Tabik her PhD degree on "Parallel Computing of Partial Differential Equations-based Applications". In 2007, Raul Baños Navarro with the work entitled "Meta-heurísticas Híbridas para optimización Mono-objetivo y Multi-objetivo. Paralelización y Aplicaciones", J.A. Martínez García with the work "Métodos de acotación en algoritmos de optimización global intervalar" and Boglárka Tóth with the work "Interval Methods for Competitive Location Problems" got their PhD degree. Currently, three more people are developing their PhD funded by the MEC and Junta de Andalucia.

## 3.6  Collaborations with other European or international groups

In the field of Image processing and tomographic reconstruction we maintain fruitful collaborations with the Spanish National Center for Biotechnology (CSIC, Madrid, Spain; groups of JM Carazo, JL Carrascosa, C Risco and JM Valpuesta). Thanks to these collaborations, our research group is now an *Associated Unit* of the Spanish National Research Council (CSIC). Furthermore, we also have an intense cooperation with the Laboratory of Molecular Biology (Medical Research Council, Cambridge, UK; groups of RA Crowther and S Li), one of the world's leading lab in molecular biology, with several Nobel laureates. In the field of Video compression and transmission we are cooperating (in the field of the Telepathology) with the department of Pathological Anatomy of the University of La Laguna (group of O. Ferrer-Roca).

In the field of Global Optimization we are cooperating with the department of Statistics and Operations Research of the University of Murcia (group of Dr. B. Pelegrín), with the operation research group of Wageningen University (NL) and with the Applied Informatics research group of Szeged (Hungary). We also have research links with the members of the Centre for Emergent Computing of Napier University, Edinburgh.

In the field of matrix computation we are cooperating with the group Numerical Simulation of the University of Málaga.

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