High Performance Optimization:
Theory, Algorithm Design and Engineering Applications

Project Leaders: Dr. Anthony Vannelli, University of Guelph
Dr. Miguel F. Anjos, University of Waterloo

November 1, 2009

1 Title and Website

Title of Project: High Performance Optimization:
Theory, Algorithm Design and Engineering Applications

Short Title: HPO and Applications

Project Website:
`http://orion.math.uwaterloo.ca/~hwolkowi/henry/reports/mitacs.d/project_website/`

Funding Request:
$ 200,000 per year, plus $ 37,500 per year in internship funds (5 internships per year)

2 Conflict of Interest Declarations

No declarations.

3 Relationship to Other Research Support

Miguel Anjos receives funding from NSERC and (jointly with Kankar Bhattacharya) from CFI. NSERC funds his fundamental research on semidefinite programmings models for hard combinatorial problems arising in engineering applications. Although there is some overlap in that both grants support work on interior-point methods, the research supported by NSERC looks at the development of new interior-point approaches for general combinatorial problems, whereas the research supported by MITACS is concerned with the application of interior-point methods to the problems of interest to some of our non-academic partners. Furthermore, the vast majority of funding from MITACS supports students on research projects in the areas of power engineering and ambulance dispatch and deployment; these projects are co-funded by industry or other non-academic partners, as detailed in this application. The CFI New Opportunities grant supports EMSOL, the laboratory for electricity markets simulation & optimization at the Faculty of Engineering.

ankar Bhattacharya is holding a NSERC Discovery Grant (2008 - 2013) entitled, New Paradigms in Operations and Planning of Power Distribution Systems in the Deregulated Environment, which examines the electricity market impact on operations and planning aspects of power distribution systems. One PhD student has graduated (Steve Wong) in Spring 2009, who examined the planning aspects and developed optimization tools for the same. Another PhD student is currently working with the NSERC funding to examine specific problems of the impact of wind power penetration on systems operations. Detailed modeling work on the intermittent nature of wind generation, reactive power generation modelling, and merging that with system operations studies is being carried out. The present proposal to MITACS will extend the work on distribution system operations and planning to examine the effect of Smart Grids and the inter-relationship between the DG sources, demand response to real-time pricing, impact on system stability and control, and develop new strategies for improved efficiencies in the system.

Bhattacharya is a co-researcher in an OCE funded project entitled, Energy Hub Management System: Enabling and Empowering Energy Managers Through Increased Information and Control, 2008-20011. The scope of this project is to develop mathematical models and hardware systems that will allow energy users to manage effectively their energy requirements. The present proposal to MITACS is significantly different from this OCE project in research direction and content.

Bhattacharya is also a co-researcher in an OCE funded project entitled, Large-Scale Photo-voltaic Solar Power Integration in Transmission and Distribution Networks, 2009-20012. The scope of this project is to examine the techno-economic feasibility, long term system impacts, environmental impact, impact on system control and stability, due to penetration of large-scale solar PV generation in the power grid. To this effect, specific solar PV generation system modelling and control aspects are to be analyzed in detail. The present proposal to MITACS is significantly different from the above OCE project in research direction and content.

Claudio Canizares holds an NSERC Discovery grant entitled "Operation of Power Systems with Sustainable Energy Resources in Competitive Electricity Markets" (2007-2012), which has been used to complement the funds required to support some of the previously proposed MITACS work, as in the case of the energy systems work by PhD student Amirhossein Hajimiragha, who has been mostly supported from NSERC and provincial OCE funds from a recently completed project (please see "Current HQP" statistical tables for more details). For the research work in DG and Smart Grids described in the present proposal, which is also being supported with funds from ABB, NSERC funds will be likely used to expand the scope and reach of the proposed work by supporting more students than the 2 PhD students that the current ABB-MITACS contract allows for. NSERC funds will also be used to continue supporting research work in energy systems and electricity markets that it is not under the aegis of the present proposal.

Canizares is also involved in the following multimillion OCE projects with a variety of industry partners: "The Energy Hub Management System: Enabling and Empowering Energy Managers Through Increased Information and Control" (2008-2012), "Large-Scale Photovoltaic Solar Power Integration in Transmission and Distribution Networks" (2009-2012), and "Advancing Energy for the North: Towards Sustainable Energy Solutions for Remote First Nations Communities" (2010-2013). None of these projects significantly overlap with the research proposed herein, as the agreements associated with these projects require that the generated IP and the associated funds be used for the sole purpose of these projects.

Antoine Deza's current NSERC Discovery Grant overlaps with the current application to the extent that it includes research on worst-case behaviour for interior point methods. While there is some overlap with the research in this proposal, the NSERC proposal research focuses on the analogies

between worst-case behaviour for simplex methods and for interior point methods. The MITACS and NSERC are supporting different approaches towards understanding and characterizing polyhedra and hyperplane arrangements yielding worst-case complexity for linear optimization algorithms.
Samir Elhedhli's NSERC grant is for work on an analytic center cutting plane method for integer programming, a completely separate research topic from that supported by MITACS. The MITACS funding is for the project on ambulance deployment described in this project CV, in which three of his students are involved.
Steve Vavasis receives funding from NSERC and (jointly with Henry Wolkowicz and Thomas Coleman) from CFI. NSERC funds his research in preconditioning and matrix approximation. The NSERC project is aimed at different applications, such as the solution of differential equations. The CFI funds are specifically for a cluster computer for computational optimization.
Henry Wolkowicz's NSERC Discovery Grant overlaps with the current application to the extent that it included research on robust algorithms in sensor network localization. While there is some overlap with the research in this proposal, the NSERC research focuses on developing robust algorithms for this problem, while the MITACS-funded research is concerned with developing algorithms for large-scale problems. Hence the two grants are supporting different facets of research on the same problem.

4 Current Investigators

This information is provided on our project website.

5 Non-Academic Partners

Partners that are new additions since our last Project CV are indicated by an asterisk (*).

a) Industrial partners.

Organization Name: ABB Inc.
Primary Contact: Le Tang, Vice President
Head of Corporate Research
Mailing Address: 940 Main Campus Drive, Raleigh, NC 27606, USA
Phone Number: +1 919 856-3878
Fax Number: +1 919 856-2411
E-mail Address: le.tang@us.abb.com
Web Page: `http://www.abb.com/`

Organization Name: Acculogic (Internship partner) (*)
Primary Contact: Farouk Eshragi
Mailing Address: 175 Riviera Drive, Markham, Ontario, L3R 5J6
Phone Number: 1-905-475-5907
Fax Number: 1-905-475-5415
E-mail Address: f.eshragi@acculogic.com
Web Pages: `http://www.acculogic.com/`

Organization Name: AFOSR (*)
Primary Contact: Dr. Donald Hearn
Mailing Address: 875 North Randolph Street, Suite 325, Room 3112,
Arlington, VA 22203, USA
Phone Number: (703) 696-1142
Fax Number: (703) 696-8449
E-mail Address: donald.hearn@afosr.af.mil
Web Pages: `http://www.wpafb.af.mil/AFRL/afosr/`

Organization Name: Algorithmics Inc. (Internship partner)
Primary Contact: Helmut Mausser
Mailing Address: 185 Spadina Avenue, Toronto, ON, M5T2C6
Phone Number: +1-416-2171500
Fax Number: +1-416-9716100
E-mail Address: helmut.mausser@algorithmics.com
Web Pages: `http://www.algorithmics.com`

Organization Name: IBM T.J. Watson Research Center (Internship partner)
Primary Contact: Andrew J Davenport
Mailing Address: P.O. Box 218, Yorktown Heights, NY 10598, USA
Phone Number: +1 914 945-1589
Fax Number: +1 914 945-3434
E-mail Address: davenport@us.ibm.com

Web Page: `http://www.ibm.com/us/`

Organization Name: Tata Consultancy Services (*)
Primary Contact: Vijaysekhar Chellaboina
Mailing Address: Advanced Technology Center, Tata Consultancy Services, Hyderabad 500081, India
Phone Number: +91 40 6667 3588
E-mail Address: vijay@atc.tcs.com
Web Pages: `http://www.tcs.com/`

b) Federal departments and agencies.

None.

c) Provincial departments and agencies.

None.

d) Others.

Organization Name: Region of Waterloo Emergency Medical Services (*)
Primary Contact: John Prno
Mailing Address: 120 Maple Grove Road, Cambridge, ON N3H 4R6
Phone Number: +1 519 650-8295 ext 8710
Fax Number: +1 519 650-3855
E-mail Address: pjohn@region.waterloo.on.ca
Web Pages: `http://www.region.waterloo.on.ca`

Organization Name: Princess Margaret Hospital (Internship partner)
Primary Contacts: Drs. Tim Craig, Douglas Moseley, Michael Sharpe, and Laura A. Dawson, MD, FRCPC
Mailing Address: 610 University Avenue, Toronto, Ontario, Canada M5G 2M9
Phone Number: +1 416 946-4501 x5025, x5594, x3340, and +1 416 946-2124
Fax Number: +1 416 946-6566
E-mail Addresses: {tim.craig, douglas.moseley, michael.sharpe}@rmp.uhn.on.ca and laura.dawson@rmp.uhn.on.ca
Web Page: `http://www.uhn.ca/pmh/index.htm`

6 Science (maximum 10 pages)

The ultimate objective of this project is to advance the theory and algorithms for high performance optimization, and their effective use to solve engineering optimization problems in the areas of matrix rank minimization, Very Large Scale Integration (VLSI) circuit design, smart power grids, finance, and emergency medical services.

a) Summary of the state of knowledge in the field

Originally proposed by Karmarkar in 1984 for solving linear optimization problems, interior-point methods (IPMs) have now been studied and developed for nonlinear optimization problems as well, including the broad and powerful class of semidefinite optimization (SDO) problems. Although the fundamental theory of SDO has been established several years ago [WSV00], important theoretical and methodological contributions continue to flourish in the field, and rapid computation of solutions can now be achieved for problems which were previously considered unapproachable.

IPMs - theory and algorithms:
After 15 years of research, there are now many algorithms and software packages for solving SDO problems. Many of these algorithms were motivated by SDO relaxations of combinatorial problems, and such relaxations continue to be used as benchmarks, see e.g. [WGMS09, WGY09]. Recently, specialized bundle methods have demonstrated extremely good performance in branch-and-bound and cutting-plane schemes for maximum-cut and equipartition problems [FGRS06, RRWar]. Nonetheless, IPMs are often advantageous for general problems because of their overall stability and convergence (in practice) in a nearly constant number of iterations regardless of the problem size. The advantages of IPMs have motivated recent research to better understand and address their limitations.

One important theoretical question is to find examples of problems that achieve the worst-case complexity for IPMs. The Klee-Minty cube is a well-known worst-case example for which the simplex method takes an exponential number of iterations as the algorithm visits all the 2^d vertices of the d-dimensional cube. While such behaviour is excluded by polynomial IPMs, it turns out that by adding an exponential number of redundant inequalities, the central path can be bent along the edges of the Klee-Minty cube. This result highlights that, although the central path is a smooth analytical curve in the interior of the set of feasible solutions, it might be severely distorted by constraints without changing the feasible set. In particular, exponentially many constraints interacting with the geometry of the problem may force the central path to take exponentially many arbitrary sharp turns. Our recent construction gives a nearly worst-case example for path-following interior-point methods and provides a counterexample for the conjectured maximal curvature [DNPT06, DNT08, DTZ09].

One important algorithmic issue for IPMs is the need for efficient warmstarts. Unlike for the simplex method, warmstarting IPMs for LP is still an active area of research. The fundamental issue is that current iterates are often not (sufficiently or at all) in the interior of the feasible set. Different notions of warmstarting exist for IPMs: one can restart from an earlier iterate (see e.g. [MB96]); adjust the current point [GG03, YW02]; or use IPMs that accept infeasible starting points [BS07]. Warmstarting is important for many applications, such as for efficiently incorporating the use of valid inequalities (cutting planes) within an IPM. It is unwise in practice to solve the relaxation of a combinatorial problem including entire classes of inequalities. It is also well known that most valid inequalities are not binding at the optimum, and hence need not be added at all to the relaxation. Hence, branch-and-cut methods replace the full relaxation by a series of smaller-sized subproblems that are solved sequentially with cutting planes added and/or removed until a solution that satisfies all the inequalities is found.

Well-aware of the importance and synergetic effects from a fruitful interplay between theory and practical applications, in addition to the further investigation of fundamental theory underlying IPMs, this project is maintaining and broadening its focus on the following applications in the areas of electrical and financial engineering, compressed sensing and sensor networks, and the health services sector.

Matrix Rank Minimization: *Matrix rank minimization* refers to the optimization problem of minimizing the rank of an unknown matrix X subject to the constraint that X lies in a certain specified convex set C. This problem is NP-hard even when the set C is an affine linear set, i.e., when X is constrained to satisfy a system of linear equalities. Many useful applications of matrix rank minimization have appeared in the literature, some of which are described below, and despite the NP-hardness of the problem, it has emerged recently that interesting instances of matrix rank minimization can be solved, sometimes to optimality, in polynomial time.
Let us first consider linear equality constrained matrix rank minimization, that is, the problem of minimizing the rank of X subject to the constraint $\mathcal{A}X = b$, where $X \in \mathcal{R}^{m\times n}$ is the unknown matrix, $\mathcal{A} : \mathcal{R}^{m\times n} \to \mathcal{R}^p$ is a linear transformation that maps X to a p-vector, and b is a p-vector. This problem is known to be NP-hard. In particular, in the special case that X is constrained to be diagonal, this problem specializes to the "sparsest vector" problem (find the vector in a given affine space with the fewest number of nonzero entries). The sparsest vector problem is NP-complete, a result known since the 1970s.
In 2007, Recht, Fazel and Parrilo [RFP07] discovered the following intriguing result. If $\mathcal{A}$ is a randomly chosen linear transformation in $\mathcal{R}^{(m\times n)\times p}$ (chosen according to a particular distribution that is quite reasonable), and if there is a sufficiently low-rank solution X^* to the constraint $\mathcal{A}X = b$, then this optimal solution X^* can be discovered by minimizing $\|X\|_*$ subject to $\mathcal{A}X = b$. Here $\|\cdot\|_*$ denotes the *nuclear norm*, that is, the sum of the singular values of X. This nuclear norm minimization optimization is convex and indeed can be reformulated as a semidefinite programming problem. Therefore, the nuclear norm relaxation can be solved to any desired accuracy in polynomial time.
This result is closely related to compressive sensing, a topic that burst into the literature in about 2005 (see, e.g., [CT05, Don06]) with the publication of several hundred papers by now. The main result of compressive sensing is that if A is a randomly chosen $m \times n$ matrix with $m \ll n$ and x is a sufficiently sparse vector (in particular, x has fewer than m nonzero entries), then x can be recovered from the knowledge of $b = Ax$ using convex optimization. Thus, this result shows that the NP-hard *sparsest vector* problem can be solved in polynomial time provided the instance is constructed in this manner. Compressive sensing is expected to have widespread applications in signal and image processing. Indeed, there are plans to build efficient digital cameras based on compressive sensing.
The Recht, Fazel and Parrilo result is quite intriguing but does not seem to be widely applicable because rank minimization problems that occur naturally do not typically have constraints of the form $\mathcal{A}X = b$ with a random transformation $\mathcal{A}$. Other recent works consider rank minimization with more natural constraints. For example, Candés and Recht and later Candés and Tao have considered the *matrix completion problem*, which is the problem of minimizing the rank of a matrix B subject to the constraint that certain entries of B are specified. They show that if the known entries follow a random pattern and the singular vectors of the unknown matrix are uncorrelated with the coordinate axes, then the nuclear norm relaxation is exact provided enough entries are specified (with respect to the rank of the solution).

Other important applications of matrix completion include distance geometry problems such as the sensor localization problem, SNL, and the molecular conformation problem. The SNL problem consists in finding the locations (in embedding dimension $r = 2$, (x, y), or $r = 3$, (x, y, z) coordinates) of n sensors that form an intercommunicating network. The given data consists of the locations of a few of the sensors (the *anchors*) as well as the Euclidean distance between certain pairs of sensors, usually those that are within radio range of each other. The problem in general is also NP-hard. It can also be framed naturally as rank minimization. In particular, let D be the *Euclidean distance matrix*, that is, the matrix whose (i, j) entry is the squared distance $\|x_i - x_j\|^2$, where for each i, x_i denotes the location of the ith sensor. Let $P = \begin{bmatrix} X \\ A \end{bmatrix}$, where the rows of X and A denote the positions of the sensors and anchors, respectively. Then there is a linear relationship between the positive semidefinite matrix $B = PP^T$ and D, denoted $\mathcal{K}(B) = D$. The EDM completion problem can now be solved by finding the positive semidefinite matrix B with the correct rank that corresponds to the given embedding dimension ($r = 2$ or $r = 3$). The linear constraints are given by $(\mathcal{K}(B))_{ij} = D_{ij}$, for all known distances D_{ij}. However, convex relaxations of SNL often do not find a sufficiently low rank positive semidefinite B that satisfies all the equality constraints. So and Ye [SY07] propose a more sophisticated relaxation that has guarantees of finding the low-rank solution under sufficient assumptions.

VLSI Circuit Design:
The problem of Very Large Scale Integration (VLSI) chip design is a prime example of a problem where traditional exact solution algorithms are becoming impractical. As modern integrated circuits increase in size, complexity and functionality, the combinatorial optimization problems of partitioning the chip into modules, placement of the modules, and routing wires to the modules are becoming increasingly complex. Due to the explosive growth in the technology for manufacturing integrated circuits, modern chips contain millions of transistors. In the past, techniques such as simulated annealing, tabu search, and interior-point-based heuristics have been used to solve the aforementioned problems, but they are often computationally expensive and tend to become trapped in local minima. The need to look at newer optimal design techniques is becoming more important because of the increasing pressures to bring chips onto the market place in a short time. Semidefinite relaxation techniques have recently been studied to solve VLSI design problems [Wol04]. Routing or wiring problems have also seen more accurate modeling and corresponding results using an integer LP formulation that was initially proposed to reduce the congestion that leads to hot spots, timing and delay problems. Our research has shown that the relaxed LP problem yields 0-1 solutions, i.e., physical wiring solutions in most large scale applications containing over 100,000 modules and wiring connections [YAV07, NYA+09]. The main option for solving realistic routing problems that contain hundreds of millions of constraints and variables is to use matrix-free IPMs as proposed by Gondzio [Gon09] that use *matrix-free* approaches and allow the main projection step in IPMs to be regularized, that is, made more numerically stable without the need to use direct factorization approaches that would not allow the matrices to be efficiently stored.

Distributed Generation in the Context of Smart Grids: Local distribution companies (LDCs) play a very critical and active role in today's power system operations as an important part of Smart Grids, which encompasses technological advancements in metering for real-time pricing, as well as advanced grid automation and control technologies. The operation of these LDCs has an impact on the electricity market and associated power system efficiency, customer electricity costs, reliability and security. Although traditional operational problems in distribution systems, such as feeder overloading, voltage profiles, high power losses, etc., continue to be important in a competitive environment, new issues have emerged in the context of Smart Grids with the penetration of distributed generation (DG) sources and inter-ties, which make for complex arrangements both from the technical and economic standpoints [AAL01]. Moreover, with the increased development of Smart Grid technologies that allow demand-side participation in electricity markets, and with increasing customer choices and options on procuring electricity, demand response programs and/or interruptible load programs, where customers receive incentives to reduce or alter their consumption patterns, power flow patterns within the distribution systems are being affected significantly, thereby affecting the economic efficiency of the market as a whole [WN04, PBCVJ05, GJ06]. This also has an effect on the operation and security of the power systems of which LDCs are an integral part [JCK02, ULR+03, ERS06]. The decision making of LDCs in this context becomes a complex exercise, which should consider the dynamics of the electricity market and its price fluctuations, as well as the effect of these decisions on the associated power system. In this context, the effects of DGs on LDCs and overall power system operation, control, and security ought to be studied and understood in detail.

Robust Financial Optimization: Although financial optimization has been an area of active research for the past forty years, dealing with uncertainty in parameter estimation remains among the key issues that are still unresolved. For several decades, stochastic programming was one of the major techniques used to address these problems, but recent advances in robust optimization have opened up new approaches for modeling uncertainty and thus offering new opportunities in the emerging area of Robust Financial Optimization (RFO) [PTW08]. This novel framework captures the uncertainty in a generic way without increasing the complexity of the original deterministic model and produces computationally tractable formulations without the inherent limit to low dimensions of classical approaches. The novel RFO framework avoids some of the difficulties of the stochastic-based models, where the size of the problem grows exponentially with the number of uncertainty sources and the span of time horizon. It also relaxes the restrictive assumption that probability distributions need to be known a priori. Many robust optimization models can be represented as a linear, second-order conic, or semi-definite programming problems, so that interior-point methods and other algorithms for conic optimization can be applied to solve instances of these models.

Ambulance Deployment:
Ambulance deployment is a challenging problem encountered in emergency medical services (EMS). Recently, the Ontario Ministry of Health and Long-Term Care has implemented the new land ambulance response time framework which states that every upper tier municipality should develop an annual response time performance plan, including response time commitments for each of 5 different patient levels. In addition, each EMS must also report on the percentage of times that sudden cardiac arrest patients received assistance from a defibrillator within six minutes from the notification of a call by an ambulances communication services; and the percentage of times that an ambulance crew has arrived on-scene to provide ambulance services to sudden cardiac arrest (or other patients at the same urgency level) within eight minutes of the time notice is received respecting such services. This new time framework requires the EMS managers to make strategic decisions on the location of the ambulances on a daily basis, and of ambulance stations over a longer period of time.
Several travel time models for predicting ambulance coverage have been developed. The models are to be used to develop coverage maps for the network, and act as input to optimal ambulance deployment strategies, the second subproject. There are two main approaches for estimating ambulance travel time: 1) find a relationship between distance and travel time or 2) estimate distance and average speeds on different types of roads through a road network and regress travel time against them. Under the first approach, Kolesar et al. [KWH75] assume that the vehicle accelerates from the origin at a

given rate until reaching a cruising speed which is maintained until the vehicle begins to decelerate (at the same rate) approaching the destination. Under the second approach, Goldberg et al. [GDC+90] regressed actual average travel time against travel distances for four different types of roads. Erkut et al. [EFK+01] regressed travel times against distances on three road types, time of day (rush vs. non-rush), and season (winter vs. summer).

Dynamic ambulance relocation models take into account the current location of the ambulances to provide a redeployment strategy that is aimed at re-establishing maximum coverage after an ambulance is dispatched to answer an emergency call. Dynamic relocation models are repeatedly solved in real time, and since it is critical to find a relocation strategy in a very short time, heuristics have been typically applied. Gendreau et al. [GLS01] presented a double coverage model for dynamic relocation and applied a tabu-search algorithm for solving the resulting model. In [GLS06], Gendreau et al. formulate and solve a dynamic problem arising in the relocation of physician vehicles. A survey of EMS location problems is presented in [BLS03].

b) Summary of the project's main achievements since the last Project CV

IPMs - theory and algorithms: We made notable advances in various areas:

- *SDO Software and Development:* Between 2004 and 2008, several notable performance improvements to SeDuMi were achieved by T. Terlaky and I. Polik of McMaster University (now both at Lehigh University). This software has gained much attention in the optimization community and is currently used by hundreds of academic and industrial researchers worldwide, and the web site `http://sedumi.mcmaster.ca` attracted over 800,000 visitors. (The website has moved to `http://sedumi.ie.lehigh.edu`.)
- *Solving Large-Scale LPs:* A new IPm is proposed that solves large-scale well-conditioned LP problems faster and more accurately than the normal equation approach [GLWW08]. It uses LSQR - an iterative solver - to find the search direction and so can exploit sparsity. Also, the approach allows for warm starts.
- *Warmstarting IPMs for LO:* The paper [EAV08] applied the strategy from [AB07] to obtain a new warmstarting technique for linear programming that is supported by a theoretical complexity analysis and achieves **iteration savings around 50% on average** for perturbations of the Netlib benchmarks and successive LP relaxations of maximum-cut and traveling-salesman problems.
- *HIPCUT Algorithm:* The aforementioned warmstarting technique is central to the success of our innovative hybrid interior-point cutting-plane method for SDP that uses feasibility indicators to dynamically add and remove cuts. Computational results indicate that this method finds optimal solutions in **less time than solving the final relaxation with all relevant cuts known in advance** [EAV09].

Matrix Rank Minimization: We have made the following important contributions:

- Nonnegative matrix factorization (NMF) is used to find features in image, text and biochemical experimental databases. We have already completed two papers recently with novel results about NMF. In one paper [Vav09], we proved that NMF is an NP-hard problem. In the other [BGV08], we proposed a new greedy heuristic for the problem that comes with some theoretical guarantees.
- Ames and Vavasis [AV09]) consider the maximum clique and biclique problems (both NP-hard) and They also show the strength of the nuclear norm relaxation when diversionary edge insertion is allowed for both problems, either by an adversary or at random. Finally, they show that their algorithm is able to find hidden structure under the assumption that it is present but is perhaps obscured by noise.

– Krislock and Wolkowicz [KW09a]) show that the SNL problem is implicitly highly degenerate, and that an algorithm called *facial reduction* can use the degeneracy to solve huge instances very efficiently. This information can be used to iteratively collapse the problem to a very small semidefinite programming problem. Problems with up to 10^5 sensors are solved in minutes on an ordinary laptop.

VLSI Circuit Design: We developed new modeling techniques which allowed the application of new algorithms for solving VLSI problems. Further advances in IPMs and SDO enabled to solve large routing and placement problems of VLSI design.

– *New Algorithms:* A new convex optimization framework was studied for unequal-areas facility layout design [JLAV07]. Two new algorithms based on nonlinear convex optimization were proposed for large-scale VLSI fixed-outline floorplanning [LAV07, LAV08].
– *Global Optimal Solutions for One-Dimensional Floorplanning:* An SDO relaxation combined with triangle inequalities was used to compute globally optimal layouts for single-row facility layout problems with up to 30 facilities, some of which had remained unsolved for nearly 20 years [AV08]. This has been deemed a real breakthrough by researchers in the area. Subsequently, an improved SDO relaxation allowed the computation of high-quality global lower bounds for instances with up to 100 departments, a problem size that was deemed unattainable only a few years ago [AY09].
– *Integer Solutions for Large-Scale VLSI Problems:* An LP relaxation has been used to obtain physical wiring solutions for practical VLSI problems containing over 100,000 modules and wiring connections [YAV07, NYA+09].

Distributed Generation in the Context of Smart Grids: For the past 2 years, we have made significant progress on the following topics:

– *Reactive Power Management:* This has been one of our main research thrusts, co-funded by ABB and OCE. In this area we have concentrated on the development, implementation and testing of reactive power markets and associated mixed integer nonlinear program (MINLP) optimization models and solution techniques. As a result of this work 4 high-quality journal papers [CBES+09, TCVZ09, LCH09, ESBC+08] and one technical report [HCBES08] have been published, and our PhD student Ismael El-Samahy received the 2008 MITACS **Best Novel Use of Mathematics in Technology Transfer Award**.
– *Energy Systems:* In this area, we have concentrated on the modeling, analysis and optimization of energy systems with multiple energy carriers, especially hydrogen and electricity. In particular, the use of hydrogen as a means to store electricity from wind power and the production of hydrogen from the power grid for transportation purposes have been studied in detail. The latter has led to some preliminary studies of the optimal use of the power grid for charging PHEVs. This work has been published in 4 high-quality journal papers [HCFE09, HFC09, TFCV09, TCFV08a] and 2 papers presented at top international conferences [TCFV08b, HFC08], and led as well to our PhD student Amirhossein Hajimiragha receiving the 2009 MITACS **Best Novel Use of Mathematics in Technology Transfer Award**.
– *Stability-constrained Optimal Power Flows:* This work has concentrated on the development, analysis and testing of optimal power flow models that more accurately represent power system security for market clearing and dispatch applications. This work has led to 2 paper submissions [BCC+09, GMCFE+09] and 2 published papers [ACMC09, KC07] in top journals in power systems, as well as 1 invited conference paper [ACA08] at the premier conference in the area.
– *Distribution System Planning:* This work has led to the development of new mathematical optimization models for electric power distribution systems planning considering the penetration of

DG resources in a deregulated electricity market environment [WBFnt].

- *Other results:* novel optimal power flow solution technique, resulting in 1 journal submission [STC09]; interval arithmetic techniques to study data uncertainty in power flows, resulting in 1 journal paper [VCV09b] and 1 conference paper [VCV09a]; and electricity market studies, leading to 2 journal papers [ZBC09, ZCB07].

Robust Financial Optimization: This new area of research has begun with the recent paper [PTW08] that represents the transaction costs for portfolio optimization by using an objective function that is piecewise linear and separable. The non-smoothness of the objective function is handled using spline approximations. The problem is then solved using a primal-dual IPM with a crossover (near optimality) to an active set method. Computational results show that this method can solve large-scale problems efficiently and accurately.

Ambulance Deployment: The first outcomes of this new and most important line of research are:

- We developed a new regression model that relates actual travel times with the distances travelled; speeds are accounted for by taking into account the percentage of each distance travelled on highways, regional roads or municipal roads. It was found that using this segmentation of the the data, the travel times have lognormal distributions with means that depend on the mean travel distance.
- The regression model is used in conjunction with a novel optimization model that extends the MECRP of Gendreau, Laporte and Semet [GLS06] and refines the model MEXCLP+PR of Ingolfsson et al. [BIE08]. We have successfully incorporated fire trucks as additional emergence response units for sudden cardiac arrest patients, and we take into account the different response time requirements according to each patient's triage level. This complete package provides the support needed by the EMS manager to develop the annual response time performance plan.
- We modeled the dynamic ambulance relocation problem as a stochastic optimization model. Solving the dynamic model to optimality is computationally expensive and cannot be implemented as a real-time system. We developed a search heuristic that provides good quality solutions in a very short amount of time.

c) Statement of project objectives

The overall project objective is to advance theory, methodology, and implementation of High Performance Optimization algorithms to enhance the solution of large-scale problems arising in engineering applications. To accomplish this goal, we focus on IPMs, SDO, MISDO, and MINLO as well as problems of critical importance in electrical, financial, and biomedical engineering. Through fundamental theoretical investigation, algorithm development, and modeling of engineering problems we are determined to pursue our research towards highly efficient modeling, algorithms and software tools not only for our own benefit, but also for the benefit of the entire optimization and engineering community. Some specific goals follow.

IPMs - theory and algorithms:

- Develop new feasible and infeasible IPMs.
- Generalize the IPM warmstarting in [EAV09] to second-order conic optimization and SDO.
- Develop, text, and benchmark high performance IPM software.

Matrix Rank Minimization:

- Investigate the use of nuclear norm and other convex relaxations for further data mining problems.
- Develop new approaches for sensor localization based on our facial reduction combined with Candès-Tao.

– Another interesting question is whether facial reduction works for noisy distance data.
– Solution approaches based on solving a polynomial number of convex programming problems, as opposed to a single convex problem.

VLSI Circuit Design:
– Study VLSI circuit design problems that arise in multi-layer chip design.
– Develop the more detailed models for routing in VLSI circuits.
– Apply a matrix-free IPM to obtain 0-1 optimal solutions for truly practical VLSI problems.
– Implement and test global VLSI circuit design software.

Distributed Generation in the Context of Smart Grids: The main objectives of the proposed research work will be to:
– Develop short-term operational analysis tools for Smart Distribution Grids operating in a retail competition environment, accounting for various technical constraints and economic objectives.
– Develop mathematical models of short-term operation of LDCs, considering electricity market dynamics and issues pertaining to Smart Grids for decision-making by LDC operators in day-ahead and real-time.
– Study the effects of LDC operation and market decisions in power system operation and security in the context of Smart Grids.

Robust Financial Optimization:
– Extend the results in [PTW08] to the special structures that arise in RFO.
– Develop specialized algorithms and software tools that enable the solution of large-scale RFO models within the required time frame in practice.
– Establish the connection between risk measures and robust uncertainty sets and develop better models for portfolio optimization, Sharpe ratio maximization, and asset liability management in multi-stage and uncertain environments in the presence of realistic constraints and assumptions.
– Develop novel methods and techniques based on novel parametric programming methods to produce the efficient (Pareto) frontier when multiple conflicting objectives are present.
– Implement these algorithms efficiently for applicability to industrial large-scale problems.

Ambulance Deployment:
– Develop and evaluate alternate models for predicting ambulance coverage in an urban network where the nodes are geographical regions of 1 square km.
– Develop a new contingency table for ROWEMS that provides the optimal location for a given number of ambulances, when there are multiple levels of response time goals.
– Study the operational problem of how to dynamically redeploy ambulances when the number of available ambulances changes.

d) Methodology

The study of high performance optimization and its applications cries out for researchers with strong backgrounds in a variety of mathematical, computer science and engineering disciplines. One need to take particular care in developing clear and sound proofs of the new theory and algorithms, to study their complexity, and to further develop highly efficient software. New algorithms must be implemented and tested on real engineering problems. These engineering problems must be modeled carefully to insure accurate conclusions.

IPMs - theory and algorithms: Future focus will examine how to reduce the effort required in calculating the Newton steps in IPMs, how to deal with round-off errors appropriately, and how

preprocessing and warmstarting can aid in IPMs.
Matrix Rank Minimization: Our methodology addresses NP-hard problems with convex relaxations. This is an old technique; for example, the traveling salesman problem was addressed with linear programming heuristics even in the 1960s. The recent methodological and theoretical breakthroughs are the proofs in many papers that this relaxation is exact (i.e., it returns the exact solution to the NP-hard problem) for input instances constructed in a certain way. In the case of clique, for example, our relaxation is exact for graphs that consist of a clique united with many edges inserted at random that hide the clique.
VLSI Circuit Design: A new focus on the theoretical development and new solutions techniques for MINLO models, as well as new SDO relaxation techniques will be used to advance knowledge in VLSI design.
Distributed Generation in the Context of Smart Grids: In order to accomplish the aforementioned objectives, proper simulation and optimization models of the power distribution network with DG penetration, considering Smart Grid technologies such as real-time measuring and interactive control capabilities at the customer and utility levels, will be developed while also including upstream transmission system effects and impact of external electricity market dynamics. The models will be used to evaluate the optimal and secure operation of DG units as an integral part of Smart Grids, and to study their effects on distribution systems and the overall grid. The development of new optimization models and solution methods associated with the aforementioned research objectives, as well as their practical implementation are at the core of this work. Hence, a good understanding of power systems' modeling and analysis, DG and smart grid technologies, and electricity markets, as well as LP, NLP and MINLP models and solution techniques and tools are necessary to accomplish these objectives.
Robust Financial Optimization: The research focuses on theoretical development in the areas of risk theory and robustness and on implementing efficient algorithms for solving large-scale real financial optimization problems.
Ambulance Deployment: Incorporate the results already achieved into a complete solution that meets the needs of ROWEMS, and of the Ministry's new framework. The models will be tested and validated using ROWEMS data, but the general modelling principles and techniques will be published and extended for applicability in other areas with similar locational and deployment fleet problems.

e) Description of subprojects

IPMs - theory and algorithms: The study of IPMs focuses on further enhancing the theory behind IPMs and designing new algorithms based on the basic principles of IPMs.
Matrix Rank Minimization:
VLSI Circuit Design: Work of VLSI design focuses on developing novel algorithms to solve the partitioning, placement, and routing subproblems of chip design.
Distributed Generation in the Context of Smart Grids: This subproject will examine critical aspects of operation, control, stability and planning of power distribution networks with DG resources in the context of Smart Grids.
Robust Financial Optimization: New theoretical investigation of relationships between risk measures and robustness. New models and algorithms for large-scale financial problems.
Ambulance Deployment: New modeling approaches to fleet deployment, with a focus on ambulances and other emergency vehicles. Development of optimization techniques to solve these models and obtain solutions satisfying the prescribed requirements.

f) Significance of results obtained: Industrial, economic, and social relevance

With the development of new optimization tools and algorithms, problems once considered out of reach are now approachable by modern optimization methodology and thus ignite renewed interest in modeling and solving real-life problems via High Performance Optimization. Besides the well-documented scientific contributions and major breakthroughs of our team to the state-of-the-art of the theory and practice of IPMs and SDO, our overall achievements reach far beyond to also create impact in various areas of industrial, economic and social human activity.

Among our recent examples of the success of convex relaxation for data mining problems have been the clique and biclique problems. The clique and biclique problems were chosen for this study because they both arise in data mining. In particular, the clique problem has been used in the study of brain activity leading up to seizures in epileptic patients [IPSS01], and the biclique problem has been used to find features in image databases [GG08]. For any kind of data mining problem, a reasonable question to ask is whether an algorithm is able to find the hidden structure under the assumption that it is present but is perhaps obscured by noise. Our answer is affirmative for the nuclear norm algorithm for both clique and biclique under suitable assumptions.

The SNL problem has broad applications in environmental monitoring, physical security of facilities, and even magnetic resonance imaging of large molecules such as proteins. For example, in the environmental setting, a collection of sensors may be deposited in a remote area by helicopter, and it is crucial that the sensors calibrate their positions in order to perform their monitoring task. Another important example is the tracking of humans, animals, equipment, or weather. The sensors are often referred to as smart dust. And to quote Horst Stormer (Nobel Prize, Physics) in '21 Ideas for the 21st Century", Business Week. 8/23-30, 1999:

> Untethered micro sensors will go anywhere and measure anything - traffic flow, water level, number of people walking by, temperature. This is developing into something like a nervous system for the earth, a skin for the earth. The world will evolve this way.

The advances in modeling techniques and robust SDO algorithms have prompted great consequences for the **industrial sector**, which is now able to actively employ new and more powerful models for MRI design, molecular conformation and protein folding for better gene prediction and drug design, network stability of power systems, and the improved efficiency of electricity networks and market auctions. For VLSI, our methods achieved notable reductions of current wire lengths yielding significant cost savings for the chip producing industry [LAV08].

The research on Smart Grids and the role of DGs in power distribution systems is envisaged to bring in important findings in efficient system operations and control. The research will also consider the critical role of the demand-side, i.e. electricity customers and the effect of real-time pricing on their response and consequently on the grid. The research will also examine the role of demand elasticity and conservation, penetration of renewable energy sources and the long-term impact on environmental emissions.

Finally, of **social relevance** are the novel way to control the operation of sensor networks [KW09b] due to their high relevance for natural habitat monitoring, earthquake detection, and disaster relief, as apparent from the 2004 Indian Ocean earthquake or the 2005 Hurricane Katrina, and our recent contributions to ambulance deployment and planning.

7 List of Publications

This information is provided on our project website.

8 Development of Highly Qualified Personnel

The project's dedication to the development of highly qualified personnel can primarily be seen in our remarkably successful and steadily growing graduate programs, our strong and distinguished conference and seminar series, and our members' various contributions to summer schools and short courses both as organizers and as invited lecturers. Over the last two years, we have seen a spectacular growth in the number of graduate students trained as part of our regular curricula and through their active involvement in the research projects outlined in this proposal. To maintain and further strengthen the expertise of our current and coming personnel and train our students and visiting fellows to become future leaders in academia, industry, and/or government, we are heavily committed to use most of the requested funds for the continued support of our successful graduate students and postdoctoral fellows.

a) HQP Involvement with Partner Organizations

Based on the determined goal to prepare our students for successful careers and lasting impacts in academia, industry and government, we strongly support and create many networking opportunities for students to also interact with our non-academic partners (also consult the Section "Networking" of this project proposal). While the invitation of external guest speakers to our Seminar Series regularly opens the basis for first informal contacts, stimulating conversation on topics of relevance, and vivid exchange of ideas for further research, recently we were also successful to arrange for several internships of our HQP with one of our collaborating partners.

Student Feng Xie of McMaster University worked at IBM Watson through an internship aimed at tackling some of the engineering challenges in implementing a constraint programming-based scheduling engine to scale well on massively parallel computer hardware. In particular, we have been targeting our solvers to work in high performance computer environments such as the IBM Blue-Gene/P supercomputer. On such hardware parallelism is enabled at the software level using message passing, based on the MPI standard. Feng investigated a parallelization scheme based on a dynamic decomposition and reallocation of the search space during search. The initial results show good scaling behavior on challenging resource-constrained project scheduling problems up to 1024 processors on the IBM BlueGene/P supercomputer.

During the past two years, McMaster Ph.D. student Olesya Peshkoo and postdoctoral fellow Yuriy Zinchenko were involved in a total of 16 months **internships with Princess Margaret Hospital** (PMH) in Toronto, which is well-known and recognized as one of the leading cancer-research hospitals in the world. In collaboration with the Ontario Cancer Institute hosted at PMH, Olesya's PhD thesis is co-supervised by Douglas Moseley from PMH and Tamás Terlaky at McMaster University, opening a fruitful dialogue and ensuring continued collaboration between the two partners in the following years. Doron Pearl and Voicu Chis, two other McMaster students, are also working on collaborative projects with the PMH, and the Windsor Regional Cancer Center offered an 8-month internship for one of Chitra Ragan's students in Windsor in January 2008.

On a separate front, Waterloo Ph.D. student Joe Naoum-Sawaya and Masters students Kian Alladini and Jie Hu have been involved in a collaboration with the Emergency Medical Services of the Region of Waterloo (ROWEMS). Although this work is still in its early stages, a recent presentation was given at ROWEMS headquarters by most of the researchers and students involved, and ROWEMS personnel are very pleased with the results to far. It is expected that the results of this research will be operationalized by ROWEMS within the next 12 months in order to meet the deadline imposed by the Ontario Ministry of Health and Long-Term Care for implementing the new land ambulance response time framework.

For the Smart Grid research, the researchers will interact with the supporting organization, namely ABB, with the students working in close collaboration with the partner company to develop new techniques and tools for analysis of power systems in the presence of DG sources in a Smart Grid environment using a variety of tests with realistic data and on the requirements and needs of the company. The proposed project is mainly geared towards training highly qualified personnel to work in industry and/or academia, as most of the requested funds will be used to fully or partially support Ph.D. students Postdoctoral fellows and Research Associates. At least 2 PhD students will be directly and fully funded from the requested funds to carry out the proposed research work. This trained manpower will be readily available to work in the power industry and/or academia in Canada.

We are eager to intensify these and other emerging relationships which do not only create significant new training opportunities for our own students, but which will also produce higher qualified personnel in these critical and steadily expanding application areas.

b) Initiated Training Activities

Our commitment to personnel training of students and visiting scholars as well as our substantial engagement in lasting contributions to Canadian's educational infrastructure in the Engineering Sciences is clearly laid out in a number of recent developments, highlighted by but not limited to the recently opened "McMaster School for Computational Engineering and Science" and the further growing "Electricity Market Simulation and Optimization Laboratory" at the University of Waterloo (see the previous paragraph).

The **McMaster School for Computational Engineering and Science** (**MSCES**) was established on July 1, 2005. The School is an equal partnership between the Faculties of Engineering and Science, with outreach to the School of Business and the Faculty of Health Science, and leverages McMasters existing expertise and excellent infrastructure in computational sciences and computationally intensive engineering. Its **new curriculum** emphasizes industry relevant academic research and development to prepare masters students for a career in industry or the public sector where independent critical thinking and advanced state-of-the-art knowledge of modern computational methodology are indispensable.

Two other developments indicate the active engagement of our team into University Administration and Educational Training. **Anthony Vannelli**, formerly Professor and Chair in the Department of Electrical and Computer Engineering and Associate Dean of Research and External Partnerships in the Faculty of Engineering at the University of Waterloo, has recently accepted a position as **Dean of the College of Physical and Engineering Sciences (CPES)** at the University of Guelph. During his earlier tenure as chair in Waterloo, his department had introduced interdisciplinary programs in software engineering, nanotechnology engineering, and a new online graduate degree program in the power area, and following his tremendous achievements and contributions at Waterloo he looks forward to also integrate newer disciplines and strategic directions into the existing research and teaching curricula at Guelph.

At Waterloo, **Miguel Anjos** was **Associate Chair for Graduate Studies and Research** in the Department of Management Sciences for 2007-2009. He played a leading role in coordinating curriculum development and other teaching activities in his department. In particular, he was actively involved in the significant expansion of the graduate program that nearly doubled the number of Master and PhD students to over 200 in the Fall term 2009. In the period 2007 to 2009, he hosted and trained five postdoctoral fellows (one current), four PhD students (one current), eight Master students (five current), and four undergraduate research assistants funded through the project.

In the same department at Waterloo, department chair **Elizabeth Jewkes** and **Associate Chair for Undergraduate Studies** Samir Elhedhli have led the development, approval and launch of a new undergraduate program in **Management Engineering**. The first class was admitted in September 2009 into this program, the first of its kind in Canada. In the period 2007 to 2009, Jewkes and Elhedhli together are hosting and training three PhD students and two Masters students involved in and funded (fully or partially) through our project.

Also at Waterloo, **Claudio Cañizares** has been recently awarded the Hydro One Endowed Chair, which is a 5-year research chair position, renewable in perpetuity, supported by a $1.5 million endowment from Hydro One to support the research program undertaken by the Chair in support of Hydro One activities, particularly in the area of Smart Networks and Emerging Industry Infrastructure. The funds made available through this endowment will be mainly used to support graduate students working to support the research initiatives of the Chair. Given the overlap of research activities of the present proposal in the area of Smart Grids with the endowed chair position, it is important to highlight the fact that these endowment funds will be used to further support the proposed research program and especially the students working in the Smart Gird research topics.

Together with **Kankar Bhattacharya**, Cañizares introduced an online course-based Master of Engineering / Graduate Diploma Program in Electric Power Engineering. The program received full approval from the Ontario Council on Graduate Studies in November 2005. It was established with the strong support of Hydro One Inc., the leading power transmission and distribution company based in Ontario. The main objective of the program is to provide advanced state-of-the-art training, skill development and education to power engineering personnel employed at various power companies so as to help develop specialized manpower base for employment in the power and energy business. The courses offered are relevant to the power industry to help re-train their personnel with up-to-date knowledge of the advancements in the field. The courses are also available to electrical engineering graduates and professionals working in other areas and wishing to make a career in the power and energy sector. **This is a unique on-line MEng program in Canada and possibly globally** offering such a facility for HQP training. Currently the Program offers 18 on-line courses covering a wide range of topics in electric power engineering, such as electric power systems, high voltage engineering and power electronics and drives. All the courses are conducted on-line in a multi-media e-learning environment that encourages a learn-while-you-work philosophy through the use of internet and other associated modern-day communication technologies. The Program has already graduated more than 25 students with the MEng / GDip degrees and there are more than 70 participants enrolled in the program currently. The program participants are mainly from the power industry in Canada, although in recent years there have been participants from other countries, including the U.S.A., U.K., and Qatar.

At McMaster, **Antoine Deza** was recently appointed **Associate Chair (Graduate)** in the Department of Computing and Software and is responsible for over 100 research students, playing a leading role in the graduate teaching of the department. He has been training 14 students in the last two years, of which 5 are PhD students supported through this project.

Our training of highly qualified individuals is further enhanced by the ongoing organization of our well-attended **Optimization Seminar Series**. Both McMaster and Waterloo host weekly seminars that broaden the understanding of optimization and its applications. The Advanced Optimization Laboratory at McMaster also hosts a weekly student seminar, which provides new students with a valuable platform to train their public speaking skills. The **Continuous Optimization Seminar Series** was re-launched at Waterloo by Anjos and Wolkowicz in Fall 2007. It brings together optimization researchers from the Faculties of Engineering and Mathematics at Waterloo, and nurtures their interactions both within Waterloo and with outside researchers.

Some of our students are also involved in MITACS student activities. In particular, Elspeth Adams, supervised by Anjos at Waterloo, is a member of the MITACS Student Advisory Committee, and Olesya Peshko has served as a McMaster University representative on the MITACS student council.

Finally, our group continues its involvement in numerous workshops and conferences, in Canada and around the world, supporting a high level of student involvement in terms of both organizational and presentation contributions. All the details of these activities within the last two years are on our project's webpage.

c) Successes of Past and In-Course Trainees

Our remarkable success in training graduate students to produce and present research results of high scientific quality and relevance is well-reflected in the numerous **Modeling and Paper Prizes and Presentation Awards** they have received over the years. The list below collects only prizes awarded during the last 2 years.

- Ismael El-Samahy from the University of Waterloo was awarded a 2008 **MITACS Best Novel Use of Mathematics in Technology Transfer Award** for his work on a novel reactive power market structure and an MINLP model for the optimal procurement of reactive power in competitive electricity markets. His work was supervised and co-authored by K. Bhattacharya, C. Cañizares and M.F. Anjos.
- Amirhossein Hajimiragha from the University of Waterloo was awarded a 2009 **MITACS Best Novel Use of Mathematics in Technology Transfer Award** for his work on an MILP model to analyze in detail the optimal utilization of Ontario's power grid during off-peak hours for hydrogen production for transportation applications.
- Tams Terlaky from McMaster University was awarded a 2008 **MITACS Award for Excellence in Mentorship**.
- Yuriy Zinchenko from McMaster University was awarded a 2008 **MITACS Best Novel Use of Mathematics in Technology Transfer Award**.
- Oleksandr Romanko from McMaster University was awarded 2nd Place at the MITACS 2009 Annual Meeting Poster Competition for his poster *Credit Risk Portfolio Optimization*.

9 Networking

9.1 List of Networking Events

The list of networking events is provided on our project website.

9.2 Future Networking Events

We intend to continue a number of networking activities that have been carried out regularly in recent years. These include the weekly "Advanced Optimization Seminar Series" at McMaster, the weekly "Continuous Optimization Seminar Series" at Waterloo, and the "Industrial Optimization Seminar Series" at the Fields Institute. In the past, these seminar series have successfully brought high-profile individuals from both the academic and industrial sectors to speak and network with the project members.

The project has already resulted in a very high level of collaboration and networking activities between the researchers working in the area of electricity markets and energy systems with those working in mathematical optimization, as well as colleagues in other filed and foreign research labs. The Smart Grid project will continue to develop and build upon the existing collaborative research between the power engineering researchers (Canizares and Bhattacharya) with researchers working on optimization techniques (Anjos, Vannelli and Fuller). New optimization tools and methods will be applied to solve complex problems arising in power grid operations and planning in the context of Smart Grids. There will be co-supervised PhD students between the two research groups to further strengthen the existing network.

10 Knowledge Exchange and Technology Transfer

Based on the project's main emphasis to advance theory and implementation of high performance optimization algorithms for application in the engineering sciences, a large number of research reports and refereed journal articles has appeared whose *copyrights* are typically transferred to the respective publisher.

Profs. Canizares and Bhattacharya's work on reactive power procurement and dispatch, under the auspices of ABB, NSERC, OCE, OPA and the IESO, is the main reason for the support this proposal is receiving from ABB. As a matter of fact, the proposed research work has been already approved and funded by ABB and MITACS through a 2-year research contract signed back in April 2008, and the 2 PhD students that will be carrying out the main research activities have started in the project back in September 2008. ABB is an international corporation with significant corporate presence throughout Canada, and ABB US Corporate Research is in charge of funding research initiatives of ABB's direct interest throughout the US and Canada, particularly in the areas related to Smart Grids, as this is now a strategic priority for the company:
(`http://www.abb.com/cawp/db0003db002698/145abc3534b16460c12575b300520d8b.aspx`).
ABB's participation will follow the model that has been successful applied to previous collaborations, which includes bi-annual live meetings with the member of ABB's technical staff assigned to manage the project. The project manager will closely monitor progress and fulfillment of the aforementioned research objectives, as well as provide advice to the research team from a practical standpoint. Continuous channels of communication will be maintained between the project manager and the research team through electronic means. Finally, besides written reports, the industrial partner will be given copies of all models, techniques and tool prototypes developed for the project.

11 Additional Information

Our tremendous qualifications and past experiences in the proposed project area of High Performance Optimization put us into an excellent position to achieve many significant research results of importance to scientific researchers and practitioners in academia or industry and the economic or government sectors. In addition, we are committed to the steady development and training of new and highly qualified individuals that will manifest the workforce of tomorrow and become future leaders in many different areas of human activity. Therefore, we are convinced that our funding request is reasonable and necessary to fully accomplish the proposed project objectives and to achieve the maximal outcome from our team effort for the benefit of our students and, thus, the society at large.

The expected success of our project is based on our the large number of previous research papers at flagship conferences and leading journals in the field of theoretical and computational optimization (see the Section “List of Publications” and our project website). In addition, our regular presence at conferences, workshops, or seminars gives a clear indication of the high reputation we have gained for our contributions in each of our respective areas of expertise (see Subsection b) in the Section “Development of Highly Qualified Personnel”). Our well-trained students are among the best in the field and key to the many current accomplishments summarized in this proposal, which is prominently recognized by the number of awards granted by experienced professionals and researchers at leading conferences or other modeling and paper competitions (see Subsection c) in the same section as above). Based on their strong self-motivation and discipline, some of our students are also already engaged in independent consulting activities significantly adding to their personal learning process.

Among the many important goals of this project is also to increase and create new collaborations between the individual institutes involved in this project themselves. For example, through the networks created as part of this project, many joint research projects have been initiated across departments and between the participating universities. These new connections have also resulted in the ability to jointly host post-doctoral fellows and other visitors and motivated team members to spent their sabbatical years at one of the other partnering institutions.

The Smart Grid project has resulted in some critical and important partnerships between the participating researchers and the industry. In particular, the previous phase of the Smart Grid subproject has led to strong collaborations between the associated researchers (Canizares and Bhattacharya) with ABB Inc., Hydro One, IESO and other utilities. In fact, funds from ABB Inc. have already been secured for the proposed research work in Smart Grids. The research results have provided some new findings of importance to the power industry and has proposed some new paradigms in operations of power systems.

We are excited about pursuing and extending our collaborative achievements, and we are certain that the coming years will yield continued successes and growing societal impact.

References

[AAL01] T. Ackermann, G. Andersson, and L.Soder. Distributed generation: a definition. *Electric Power Systems Research*, 57:195–204, 2001.

[AB07] M.F. Anjos and S. Burer. On handling free variables in interior-point methods for conic linear optimization. *SIAM J. Optim.*, 18(4):1310–1325, 2007.

[ACA08] R. J. Avalos, C. A. Canizares, and M.F. Anjos. A practical voltage-stability-constrained optimal power flow. In *Proc. IEEE-PES General Meeting*, 2008.

[ACMC09] R. J. Avalos, C. A. Canizares, F. Milano, and A. Conejo. Equivalency of continuation and optimization methods to determine saddle-node and limit-induced bifurcations in power systems. *IEEE Transactions on Circuits and Systems I*, 56(1):210–223, 2009.

[AV08] M.F. Anjos and A. Vannelli. Computing globally optimal solutions for single-row layout problems using semidefinite programming and cutting planes. *INFORMS J. Comp.*, 20(4):611–617, 2008.

[AV09] B. Ames and S. Vavasis. Nuclear norm minimization for the planted clique and biclique problems. URL:`http://arxiv.org/abs/0901.3348`, 2009.

[AY09] M.F. Anjos and G. Yen. Provably near-optimal solutions for very large single-row facility layout problems. *Optim. Methods Softw.*, 24(4):805–817, 2009.

[BCC+09] C. Battistelli, C. A. Canizares, M. Chehreghani, V. J. Gutierrez-Martinez, and C. R. Fuerte-Esquivel. Practical security-boundary-constrained dispatch models for electricity markets. *IEEE Transactions on Power Systems*, submitted May 2009.

[BGV08] Michael Biggs, Ali Ghodsi, and Stephen A. Vavasis. Nonnegative matrix factorization via rank-one downdating. In *Proceedings of the 2008 International Conference on Machine Learning*, 2008. Proceedings published online at `http://icml2008.cs.helsinki.fi/abstracts.shtml`, Preliminary version of the full paper in arxiv.org, 0808.0120.

[BIE08] S. Budge, A. Ingolfsson, and E. Erkut. Optimal ambulance location with random delays and travel times. *Health Care Management Science*, 11:262–274, 2008.

[BLS03] L. Brotcorne, G. Laporte, and F. Semet. Ambulance location and relocation models. *European J. Oper. Res.*, (3):451–463, 2003.

[BS07] H.Y. Benson and D.F. Shanno. An exact primal-dual penalty method approach to warmstarting interior-point methods for linear programming. *Comput. Optim. Appl.*, 38(3):371–399, 2007.

[CBES+09] C. A. Canizares, K. Bhattacharya, I. El-Samahy, H. Haghighat, J. Pan, and C. Tan. Re-defining the reactive power dispatch problem in the context of competitive electricity markets. *IET Generation, Transmission and Distribution*, to appear, accepted August 2009.

[CT05] E. Candes and T. Tao. Decoding by linear programming. *IEEE Trans. Information Theory*, 51(12):4203–4215, 2005.

[DNPT06] A. Deza, E. Nematollahi, R. Peyghami, and T. Terlaky. The central path visits all the vertices of the Klee-Minty cube. *Optim. Methods Softw.*, 21(5):851–865, 2006.

[DNT08] A. Deza, E. Nematollahi, and T. Terlaky. How good are interior point methods? Klee-Minty cubes tighten iteration-complexity bounds. *Math. Program.*, 113(1, Ser. A):1–14, 2008.

[Don06] D. L. Donoho. Compressed sensing. *IEEE Trans. Information Theory*, 52(4):1289–1306, 2006.

[DTZ09] A. Deza, T. Terlaky, and Y. Zinchenko. Central path curvature and iteration-complexity for redundant klee-minty cubes. *Advances in Mechanics and Mathematics*, 17:223–256, 2009.

[EAV08] A. Engau, M.F. Anjos, and A. Vannelli. On interior-point warmstarts for linear and combinatorial optimization. Technical report, University of Waterloo, 2008.

[EAV09] A. Engau, M.F. Anjos, and A. Vannelli. A hybrid interior-point cutting-plane method for semidefinite programming relaxations in discrete optimization. Technical report, University of Waterloo, 2009.

[EFK+01] E. Erkut, R. Fenske, S. Kabanuk, Q. Gardiner, and J. Davis. Improving the emergency service delivery in St. Albert. *INFOR*, 39:416–433, 2001.

[ERS06] I. Erlich, K. Rensch, and F. Shewarega. Impact of large wind power generation on frequency stability. In *Proc. IEEE-PES General Meeting*, 2006.

[ESBC+08] I. El-Samahy, K. Bhattacharya, C. A. Canizares, M.F. Anjos, and J. Pan. A procurement market model for reactive power services considering system security. *IEEE Transactions on Power Systems*, 23(1):137–149, 2008. Invited for presentation at the Panel "Reactive Power Management and Payment Mechanisms in Competitive Electricity Markets," IEEE-PES General Meeting 2008, Pittsburgh, PA, June 2008.

[FGRS06] I. Fischer, G. Gruber, F. Rendl, and R. Sotirov. Computational experience with a bundle approach for semidefinite cutting plane relaxations of Max-Cut and equipartition. *Math. Program.*, 105(2-3, Ser. B):451–469, 2006.

[GDC+90] J. Goldberg, R. Dietrich, J. M. Chen, M. G. Mitwasi, T. Valenzuela, and E. Criss. Validating and applying a model for locating emergency medical vehicles in tucson, az. *European J. Oper. Res.*, 49:308–324, 1990.

[GG03] J. Gondzio and A. Grothey. Reoptimization with the primal-dual interior point method. *SIAM J. Optim.*, 13(3):842–864 (electronic) (2003), 2003.

[GG08] N. Gillis and F. Glineur. Nonnegative factorization and the maximum edge biclique problem. Available from `http://arxiv.org/abs/0810.4225`, 2008.

[GJ06] H. A. Gil and G. Joos. On the quantification of the network capacity deferral value of distributed generation. *IEEE Transactions on Power Systems*, 21:1592–1599, 2006.

[GLS01] M. Gendreau, G. Laporte, and F. Semet. A dynamic model and parallel tabu search heuristic for real-time ambulance relocation. *Parallel Computing*, 27:1641–1653, 2001.

[GLS06] M. Gendreau, G. Laporte, and F. Semet. The maximal expected coverage relocation problem for emergency vehicles. *Journal of the Operational Research Society*, 57:22–28, 2006.

[GLWW08] M. GONZALEZ-LIMA, H. WEI, and H. WOLKOWICZ. A stable iterative method for linear programming. *Comp. Optim. Appl.*, to appear(Springer online):DOI 10.1007/s10589–007–9157–2, 2008.

[GMCFE+09] V. J. Gutierrez-Martinez, C. A. Canizares, C. R. Fuerte-Esquivel, A. Pizano-Martinez, and X. Gu. Neural-network security-boundary constrained optimal power flow. *IEEE Transactions on Power Systems*, submitted March 2009.

[Gon09] J. Gondzio. Matrix-free interior point method. Technical Report ERGO-2009-012, University of Edinburgh, 2009.

[HCBES08] H. Haghigh, C. A. Canizares, K. Bhattacharya, and I. El-Samahy. Implementation of a reactive power market for ontario electricity market. Technical report, Final Report, ABB-OCE-MITACS Grants, August 2008.

[HCFE09] A. Hajimiragha, C. A. Canizares, M. Fowler, and A. Elkamel. Optimal transition to plug-in hybrid vehicles in ontario-canada considering the electricity grid limitations. *IEEE Transactions on Industrial Electronics*, to appear, accepted June 2009.

[HFC08] A. Hajimiragha, M. Fowler, and C. A. Canizares. Hydrogen economy impact on optimal planning and operation of integrated energy systems. In *Proc. MICRO-COGEN*, April 2008.

[HFC09] A. Hajimiragha, M. Fowler, and C. A. Canizares. Hydrogen economy transition in ontario-canada considering the electricity grid constraints. *International Journal of Hydrogen Energy*, to appear, accepted April 2009.

[IPSS01] L.D. Iasemidis, P. Pardalos, J. C. Sackellares, and D.-S. Shiau. Quadratic binary programming and dynamical system approach to determine the predictability of epileptic seizures. *Journal of Combinatorial Optimization*, 5(1):9–26, 2001.

[JCK02] A. Jain, J. Choi, and B. Kim. Impact of integrating the photovoltaic and wind energy sources on generation system reliability and operation economics. In *Proc. PowerCon 2002*, volume 4, pages 2437–2442, 2002.

[JLAV07] I. Jankovits, C. Luo, M. F. Anjos, and A. Vannelli. A convex optimisation framework for the unequal-areas facility layout problem. *Submitted to the European Journal of Operational Research*, 2007.

[KC07] S. K. M. Kodsi and C. A. Canizares. Application of a stability-constrained optimal power flow to tuning of oscillation controls in competitive electricity markets. *IEEE Transactions on Power Systems*, 22(4):1944–1954, 2007.

[KW09a] N. Krislock and H. Wolkowicz. Explicit sensor netowrk localization using semidefinite representations and clique reductions. Available from `http://orion.uwaterloo.ca/~hwolkowi/henry/reports/cliques.pdf`, 2009.

[KW09b] N. Krislock and H. Wolkowicz. Explicit sensor network localization using semidefinite representations and clique reductions. Technical Report CORR 2009-04, University of Waterloo, Waterloo, Ontario, Canada, 2009.

[KWH75] P. Kolesar, W. Walker, and J. Hausner. Determining the relation between fire engine travel times and travel distances in new york city. *Oper. Res.*, 23:614–627, 1975.

[LAV07] C. Luo, M. F. Anjos, and A. Vannelli. A nonlinear optimization methodology for VLSI fixed-outline floorplanning. *Submitted to the Journal of Combinatorial Optimization*, 2007.

[LAV08] C. Luo, M. F. Anjos, and A. Vannelli. Large-scale fixed-outline floorplanning design using convex optimization techniques. *Proceedings of ASP-DAC*, 2008.

[LCH09] M. B. Liu, C. A. Canizares, and W. Huang. Reactive power and voltage control in distribution systems with limited switching operations. *IEEE Transactions on Power Systems*, 24(2):889–899, 2009.

[MB96] J.E. Mitchell and B. Borchers. Solving real-world linear ordering problems using a primal-dual interior point cutting plane method. *Ann. Oper. Res.*, 62:253–276, 1996.

[NYA+09] A. Nour, Z. Yang, M. Anis, S. Areibi, A. Vannelli, and I. Elmasry. A power-efficient multi-pin ilp based routing methodology. *IEEE Transactions on Circuits and Systems*, to appear, accepted January 2009.

[PBCVJ05] R. Palma-Behnke, A. J. L. Cerda, L. S. Vargas, and A. Jofré. A distribution company energy acquisition market model with integration of distributed generation and load curtailment options. *IEEE Transactions on Power Systems*, 20:1718–1727, 2005.

[PTW08] M. POTAPTCHIK, L. TUNÇEL, and H. WOLKOWICZ. Large scale portfolio optimization with piecewise linear transaction costs. *Optim. Meth. Softw.*, 23(6):929–952, 2008.

[RFP07] B. Recht, M. Fazel, and P. Parrilo. Guaranteed minimum-rank solutions of linear matrix equations via nuclear norm minimization. See `http://arxiv.org/abs/0706.4138`, 2007.

[RRWar] F. Rendl, G. Rinaldi, and A. Wiegele. Solving max-cut to optimality by intersecting semidefinite and polyhedral relaxations. *Math. Program.*, to appear.

[STC09] A. A. Sousa, G. L. Torres, and C. A. Canizares. Robust optimal power flow solution using trust region and interior-point methods. *IEEE Transactions on Power Systems*, submitted January 2009.

[SY07] A. So and Y. Ye. Theory of semidefinite programming for sensor network localization. *Mathematical Programming*, 109:367–384, 2007.

[TCFV08a] G. Taljan, C. A. Canizares, M. Fowler, and G. Verbic. The feasibility of hydrogen storage for mixed wind-nuclear power plant. *IEEE Transactions on Power Systems*, 23(3):1507–1518, 2008. Highlighted on a news report at PhysOrg.com, August 6, 2008 `http://www.physorg.com/news137238782.html`.

[TCFV08b] G. Taljan, C. A. Canizares, M. Fowler, and G. Verbic. Study of mixed wind-nuclear-hydrogen power plants. In *Proc. North American Power Symposium (NAPS)*, 2008.

[TCVZ09] B. Tamimi, C. A. Canizares, and S. Vaez-Zadeh. Effect of reactive power limit modeling on maximum system loading and active and reactive power markets. *IEEE Transactions on Power Systems*, to appear, accepted June 2009.

[TFCV09] G. Taljan, M. Fowler, C. A. Canizares, and G. Verbic. Hydrogen storage for mixed wind-nuclear power plants in the context of a hydrogen economy. *International Journal of Hydrogen Energy*, 33(17):4463–4475, 2009.

[ULR+03] J. Usaola, P. Ledesma, J. M. Rodriguez, J. L. Fernandez, D. Beato, R. Iturbe, and J. R. Wilhelmi. Transient stability studies in grids with great wind power penetration: Modelling issues and operation requirements. In *Proc. IEEE-PES General Meeting*, 2003.

[Vav09] Stephen A. Vavasis. On the complexity of nonnegative matrix factorization. *SIAM J. Optim.*, 20(3):1364–1377, 2009.

[VCV09a] A. Vaccaro, C. A. Canizares, and D. Villacci. Simple and reliable algorithm for computing boundaries of power flow solutions due to system uncertainties. In *Proc. IEEE PowerTech*, 2009.

[VCV09b] A. Vaccaro, C. A. Canizares, and D. Villacci. An affine arithmetic based methodology for reliable power flow analysis in the presence of data uncertainty. *IEEE Transactions on Power Systems*, to appear, accepted August 2009.

[WBFnt] S.M. Wong, K. Bhattacharya, and J.D. Fuller. Electric power distribution system design and planning in a deregulated environment. In *IET Proceedings on Generation, Transmission and Distribution*, in print.

[WGMS09] Z. Wen, D. Goldfarb, S. Ma, and K. Scheinberg. Row by row methods for semidefinite programming. Technical report, IEOR, Columbia University, 2009.

[WGY09] Z. Wen, D. Goldfarb, and W. Yin. Alternating direction augmented lagrangian methods for semidefinite programming. Technical report, IEOR, Columbia University, 2009.

[WN04] C. Wang and M. H. Nehrir. Analytical approaches for optimal placement of distributed generation sources in power systems. *IEEE Transactions on Power Systems*, 19:2068–2076, 2004.

[Wol04] H. Wolkowicz. Solving semidefinite programs using preconditioned conjugate gradients. *Optimization Methods & Software*, 19(6):653–672, 2004.

[WSV00] H. Wolkowicz, R. Saigal, and L. Vandenberghe, editors. *Handbook of semidefinite programming*. International Series in Operations Research & Management Science, 27. Kluwer Academic Publishers, Boston, MA, 2000.

[YAV07] Z. Yang, S. Areibi, and A. Vannelli. An ilp based hierarchical global routing approach for vlsi asic design. *Optimization Letters*, 1(3):281–297, 2007.

[YW02] E.A. Yildirim and S.J. Wright. Warm-start strategies in interior-point methods for linear programming. *SIAM J. Optim.*, 12(3):782–810 (electronic), 2002.

[ZBC09] H. Zareipour, K. Bhattacharya, and C. A. Canizares. Economic benefits of improving electricity market price forecasting accuracy: A demand-side analysis. *IEEE Transactions on Power Systems*, to appear, accepted May 2009.

[ZCB07] H. Zareipour, C. A. Caizares, and K. Bhattacharya. The ontario competitive electricity market: Overview, experiences, and lessons. *IEEE Transactions on Power Systems*, 22(4):1782–1793, 2007.

Short Project Description

(suitable for public release)

Whether computers become faster, power supply more reliable, or cancer treatment more effective, the common driving force underlying modern technological, economic, and social prosperity is high performance optimization. The multidisciplinary "High Performance Optimization" team combines leading experts and researchers in the areas of mathematical and engineering sciences who are developing novel sophisticated models and state-of-the-art optimization algorithms to solve these models with the ultimate goal to achieve innovative solutions to problems of critical importance in electrical engineering, financial engineering, and the health services sector.

The main objective of the research being carried out by the *High Performance Optimization* team of researchers is to develop highly efficient optimization algorithms for solving important engineering optimization problems in the areas of matrix rank minimization, Very Large Scale Integration (VLSI) circuit design, smart power grids, finance, and emergency medical services

For some of the most complex circuit design and wireless communication problems, the team has provided powerful approximation algorithms that have excellent theoretical bounds and find close to optimal solutions of guaranteed quality in very short time, outperforming even the best previously known heuristic methods. The team has also been developing novel game theoretical models to enable secure, reliable and affordable power supply in competitive electricity markets and explored innovative approaches for maximizing system security in optimization-based dispatch and pricing tools. In the context of the Smart Grids, we have already proposed some novel operating paradigms with regard to reactive power markets settlement, pricing and dispatching and new solution algorithms have been developed that can handle large-sized practical power systems. It is envisaged that the project will continue to work on critical issues pertaining to Smart Grids and evolve solutions to problems with DG penetration and the complexities arising in stability, control and operations.