



## Activity Report 2015

# Team ACUMES

## Analysis and Control of Unsteady Models for Engineering Sciences

Inria teams are typically groups of researchers working on the definition of a common project, and objectives, with the goal to arrive at the creation of a project-team. Such project-teams may include other partners (universities or research institutions).

RESEARCH CENTER  
**Sophia Antipolis - Méditerranée**

THEME  
**Numerical schemes and simulations**



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## Team ACUMES

*Creation of the Team: 2015 January 01*

### Keywords:

#### **Computer Science and Digital Science:**

- 6. - Modeling, simulation and control
- 6.1.1. - Continuous Modeling (PDE, ODE)
- 6.1.4. - Multiscale modeling
- 6.1.5. - Multiphysics modeling
- 6.2.1. - Numerical analysis of PDE and ODE
- 6.2.6. - Optimization
- 6.3.1. - Inverse problems
- 6.3.2. - Data assimilation

#### **Other Research Topics and Application Domains:**

- 1.1.10. - Mathematical biology
- 1.1.3. - Cellular biology
- 5.2. - Design and manufacturing
- 7.1.1. - Pedestrian traffic and crowds
- 7.1.2. - Road traffic
- 8.1.1. - Energy for smart buildings
- 9.4.2. - Mathematics

## 1. Members

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## 2. Overall Objectives

### 2.1. Overall Objectives

ACUMES aims at developing a rigorous framework for numerical simulations and optimal control in engineering, with focus on multi-scale, heterogeneous, unsteady phenomena subject to uncertainty. Starting from established macroscopic Partial Differential Equation (PDE) models, we pursue a set of innovative approaches to include small-scale phenomena, which impact the whole system. Targeting real-life applications, we couple these models with robust control and optimization techniques accounting for errors and uncertainties.

Modern engineering sciences make an important use of mathematical models and numerical simulations at the conception stage. Effective models and efficient numerical tools allow for optimization before production and to avoid the construction of expensive prototypes or costly post-process adjustments. Most up-to-date modeling techniques aim at helping engineers to increase performances and safety and reduce costs and pollutant emissions of their products. For example, mathematical traffic flow models are used by civil engineers to test new management strategies in order to reduce congestion on the existing road networks and improve crowd evacuation from buildings or other confined spaces without constructing new infrastructures. Similar models are also used in mechanical engineering, in conjunction with concurrent optimization methods, to improve aerodynamic performance of aircrafts and cars, or to increase thermal and structural efficiency of buildings while, in both cases, reducing ecological cost.

Nevertheless, current models and numerical methods exhibit some limitations:

- Most simulation-based design procedures used in engineering rely on steady (time-averaged) state models. However, objectives for reduction of pollutant emissions for cars, or noise reduction for aircrafts at take-off, require finer models taking into account unsteady phenomena.
- The classical purely macroscopic approach, while offering a framework with a sound analytical basis, performing numerical techniques and good modeling features to some extent, is not able to reproduce some particular phenomena related to specific interactions occurring at lower (possibly micro) level. We refer for example to self-organizing phenomena observed in pedestrian flows, to vesicle trafficking impact on wound repair, or to the dynamics of turbulent flows for which large scale / small scale vortical structures interfere. These flow characteristics need to be taken into account to obtain a realistic model and reliable optimal solutions.
- Uncertainty related to operational conditions (e.g. inflow velocity in aerodynamics), or models (e.g. individual behavior in crowds) is still rarely considered in engineering analysis and design, yielding solutions of poor robustness.

Therefore, this project focuses on the analysis and optimal control of classical and non-classical evolutionary systems of Partial Differential Equations (PDEs) arising in a variety of applications, ranging from fluid-dynamics and structural mechanics to traffic flow and biology. The complexity of the involved dynamical systems is expressed by multi-scale, time-dependent phenomena subject to uncertainty, which can hardly be tackled using classical approaches, and require the development of unconventional techniques.

## 3. Research Program

### 3.1. Research directions

The project will develop along the following three axes:

- dynamics of novel (unconventional) PDE models, accounting for uncertainty
- optimization and control algorithms for systems governed by PDEs,

which are common to the specific problems treated in the applications. In this section, we detail the methodological tools that we plan to develop in the framework of this project.

### 3.1.1. Dynamics of novel PDE models

Dynamical models consisting of evolutionary PDEs, mainly of hyperbolic type, appear classically in the applications studied by the previous Project-Team Opale (compressible flows, traffic, cell-dynamics, medicine, etc). Yet, the classical purely macroscopic approach is not able to account for some particular phenomena related to specific interactions occurring at smaller scales. These phenomena can be of greater importance when dealing with particular applications, where the "first order" approximation given by the purely macroscopic approach reveals to be inadequate. We refer for example to self-organizing phenomena observed in pedestrian flows [104], or to the dynamics of turbulent flows for which large scale / small scale vortical structures interfere [131].

Nevertheless, macroscopic models offer well known advantages, namely a sound analytical framework, fast numerical schemes, the presence of a low number of parameters to be calibrated, and efficient optimization procedures. Therefore, we are convinced of the interest of keeping this point of view as dominant, while completing the models with information on the dynamics at the small scale / microscopic level. This can be achieved through several techniques, like hybrid models, homogenization, mean field games. In this project, we will focus on the aspects detailed below.

#### 3.1.1.1. Micro-macro couplings

Modeling of complex problems with a dominant macroscopic point of view often requires couplings with small scale descriptions. Accounting for systems heterogeneity or different degrees of accuracies. usually leads to coupled PDE-ODE systems.

In the case of heterogeneous problems the coupling is "intrinsic", i.e. the two models evolves together and mutually affect each-other. For example, accounting for the impact of a large and slow vehicle (like a bus or a truck) on traffic flow leads to a strongly coupled system consisting of a (system of) conservation law(s) coupled with an ODE describing the bus trajectory, which acts as a moving bottleneck. The coupling is realized through a local unilateral constraint on the flow at the bus location, see [78] for an existence result and [63], [77] for numerical schemes.

If the coupling is intended to offer higher degree of accuracy at some locations, a macroscopic and a microscopic model are connected through an artificial boundary, and exchange information across it through suitable boundary conditions. See [69], [97] for some applications in traffic flow modelling.

We plan to pursue our activity in this framework, also extending the above mentioned approaches to problems in two or higher space dimension, to cover applications to crowd dynamics or fluid-structure interaction.

#### 3.1.1.2. Non-local flows

Non-local interactions can be described through macroscopic models based on integro-differential equations. Systems of the type

$$\partial_t u + \operatorname{div}_{\mathbf{x}} F(t, \mathbf{x}, u, W) = 0, \quad t > 0, \mathbf{x} \in \mathbb{R}^d, d \geq 1, \quad (1)$$

where  $u = u(t, \mathbf{x}) \in \mathbb{R}^N$ ,  $N \geq 1$  is the vector of conserved quantities and the variable  $W = W(t, x, u)$  depends on an integral evaluation of  $u$ , arise in a variety of physical applications. Space-integral terms are considered for example in models for granular flows [50], sedimentation [56], supply chains [99], conveyor belts [100], biological applications like structured populations dynamics [121], or more general problems like gradient constrained equations [51]. Also, non-local in time terms arise in conservation laws with memory, starting from [75]. In particular, equations with non-local flux have been recently introduced in traffic flow modeling to account for the reaction of drivers or pedestrians to the surrounding density of other individuals, see [33], [37] [62], [66], [134]. While pedestrians are likely to react to the presence of people all around them, drivers will mainly adapt their velocity to the downstream traffic, assigning a greater importance to closer vehicles. In particular, and in contrast to classical (without integral terms) macroscopic equations, these

models are able to display finite acceleration of vehicles through Lipschitz bounds on the mean velocity [33], [37] and lane formation in crossing pedestrian flows.

General analytical results on non-local conservation laws, proving existence and eventually uniqueness of solutions of the Cauchy problem for (1), can be found in [52] for scalar equations in one space dimension ( $N = d = 1$ ), in [67] for scalar equations in several space dimensions ( $N = 1, d \geq 1$ ) and in [30], [68], [72] for multi-dimensional systems of conservation laws. Besides, specific finite volume numerical methods have been developed recently in [30], [37] and [109].

Relying on these encouraging results, we aim to push a step further the analytical and numerical study of non-local models of type (1), in particular concerning well-posedness of initial - boundary value problems, numerical schemes and micro-macro limits.

### 3.1.1.3. Measure-valued solutions

The notion of measure-valued solutions for conservation laws was first introduced by DiPerna [80], and extensively used since then to prove convergence of approximate solutions and deduce existence results, see for example [88] and references therein. Measure-valued functions have been recently advocated as the appropriate notion of solution to tackle problems for which analytical results (such as existence and uniqueness of weak solutions in distributional sense) and numerical convergence are missing [54], [91]. We refer, for example, to the notion of solution for non-hyperbolic systems [36], for which no general theoretical result is available at present, and to the convergence of finite volume schemes for systems of hyperbolic conservation laws in several space dimensions, see [91].

In this framework, we plan to investigate and make use of measure-based PDE models for (vehicular and pedestrian) traffic flows. Indeed, a modeling approach based on (multi-scale) time-evolving measures (expressing the agents probability distribution in space) has been recently introduced (see the monograph [74]), and proved to be successful for studying emerging self-organised flow patterns [73]. As mentioned in Section 3.1.1.2, the theoretical measure framework proves to be also relevant in addressing micro-macro limiting procedures [45]. We recall that a key ingredient in this approach is the use of the *Wasserstein distances* [137], [138]. Indeed, as observed in [122], the usual  $L^1$  spaces are not natural in this context, since they don't guarantee uniqueness of solutions.

### 3.1.1.4. Mean-field games

Mean Field Games (MFG) is a branch of Dynamic Games which aims at deriving macroscopic decision processes involving a very large population of indistinguishable, interacting rational agents, who have limited information on the game, and choose their optimal strategy depending on the available macroscopic information on the action of the other players (see the seminal paper [112]).

Even if we haven't actively contributed to this sector up to now, we believe that this approach is promising for some of the applications targeted by the team, such as traffic flow and cell dynamics. Our aim is to consider situations where  $N$  agents interact in other ways than through non-linear dynamical stochastic processes. In cell dynamics, interaction processes would be contact-inhibition, linear elastic transmission in cell-cell interaction, normal stress transmission in cell-matrix, etc; in traffic modelling, through the velocity field. The classical mean field game approach provides an approximation of the Nash, or rational expectation, equilibrium behaviour through solutions of a suitable Hamilton-Jacobi-Bellman PDE of the form

$$\partial_t \phi(t, x) + H(t, x, \nabla \phi(x, t), \rho) = 0 \quad t > 0, x \in \mathbb{R}^d,$$

with, possibly, a diffusion term. To the HJB equation above, one must add the limit equation (e.g. Fokker-Planck) which describes the evolution of the density of the agents  $\rho$ . The resulting system is fully coupled because the Hamiltonian  $H$  depends on the macroscopic state variable  $\rho$  and, in turn, the viscosity solution  $\phi$  affects the second equation, for example through the selection of the velocity field. For our applications, the agents are postulated to obey to more or less complex PDEs, like the second order elliptic equations (describing elastic behavior of cells controlled by the distribution of their F-actin network) or conservation laws (accounting for mass conservation for pedestrians), and one must compare these popular models to those



derived as limit of Nash equilibria of non-cooperative non-atomic anonymous games with a continuum of players (a.k.a. MFG), notably through numerical simulations [47].

In the context of crowd dynamics, including the case of several populations with different targets, the mean field game approach has been adopted in [58], [59], [81], [111], under the assumption that the individual behavior evolves according to a stochastic process, which gives rise to parabolic equations greatly simplifying the analysis of the system. Besides, a deterministic context is studied in [126], which considers a non-local velocity field.

For cell dynamics, in order to take into account the fast processes that occur in the migration-related machinery, a framework such the one developed in [76] to handle games "where agents evolve their strategies according to the best-reply scheme on a much faster time scale than their social configuration variables" may turn out to be suitable.

Even though the proposed MFG models appear promising and encourage the application of mean field games theory to crowd motion, traffic flows, and cell dynamics, this research topic is still at an early stage and many things remain to be done. From the analytical point of view, while existence for the mean field game equations is quite established, uniqueness is still an issue. Moreover, a qualitative study of solutions with analytical tools is completely missing, and interesting phenomena (segregation between populations, lanes formation, coordinated actin networks) are observed in numerical or biological experiments only. Another challenge is represented by handling bounded domains. Finally, up to our knowledge, MFG have not been implemented to study vehicular traffic nor cell dynamics. An attempt in this direction could be to consider a mean field system on a graph [61].

#### 3.1.1.5. Uncertainty in parameters and initial-boundary data

Different sources of uncertainty can be identified in PDE models, related to the fact that the problem of interest is not perfectly known. At first, initial and boundary condition values can be subject to uncertainty. For instance, in traffic flows, the time-dependent value of inlet and outlet fluxes, as well as the initial distribution of vehicles density, are not perfectly determined [60]. In aerodynamics, inflow conditions like velocity, temperature and pressure are subject to fluctuations depending on atmospheric conditions [102], [120]. For some engineering problems, the geometry of the boundary can also be uncertain, due to structural deformation, mechanical wear or disregard of some detail [82]. Another source of uncertainty is related to the value of some parameters in the PDE models. This is typically the case of parameters in turbulence models in fluid mechanics, which have been calibrated according to some reference flows but are not universal [132], [136], or in traffic flow models, which may depend on the type of road, weather conditions, or even the country of interest (due to differences in driving rules and conductors behaviour). This leads to equations with flux functions depending on random parameters [133], [135], for which the mean and the variance of the solutions can be computed using different techniques. Indeed, uncertainty quantification for systems governed by PDE systems has become a very active research topic in the last years. Most approaches are embedded in a probabilistic framework and aim at quantifying statistical moments of the PDE solutions, under the assumption that the characteristics of uncertain parameters are known. Note that classical Monte-Carlo approaches exhibit low convergence rate and consequently accurate simulations require huge computational times. In this respect, some enhanced algorithms have been proposed, for example in the balance law framework [117]. Different approaches propose to modify the PDE solvers to account for this probabilistic context, for instance by defining the non-deterministic part of the solution on an orthogonal basis (Polynomial Chaos decomposition) and using a Galerkin projection [102], [108], [114], [140] or an entropy closure method [79], or by discretizing the probability space and extending numerical schemes [46]. Alternatively, some other approaches maintain a fully deterministic PDE resolution, but approximate the solution in the vicinity of the reference parameter values by Taylor series expansions based on first- or second-order sensitivities [127], [136], [139].

Our objective regarding this topic is twofold. In a pure modeling perspective, we aim at including uncertainty quantification in models calibration and validation for predictive use. In this case, the choice of the techniques will depend on the specific problem considered [55]. Besides, we intend to keep on our developments based on sensitivity analysis by extending previous works [82] to more complex and more demanding problems. Concerning aerodynamic applications, unsteady flows will be considered. Moreover, we plan to improve the

capture of shock moves due to uncertainties. This difficult topic requires a modification of the sensitivity equation method to account for Dirac distributions arising from the discontinuity in the solution. A second targeted topic is the study of the uncertainty related to turbulence closure parameters, in the context of detached flows for which a change of flow topology may arise. Our ambition is to contribute to the emergence of a new generation of simulation tools, which will provide solution densities rather than values, to tackle real-life uncertain problems.

### 3.1.2. Optimization and control algorithms for systems governed by PDEs

The focus here is on the methodological development and analysis of optimization algorithms and paradigms for PDE systems in general, keeping in mind our privileged domains of application in the way the problems are mathematically formulated.

#### 3.1.2.1. Robust design and control

Most physical phenomena are subject to uncertainties, arising from random variations of physical parameters, and affecting the design performance. Therefore, a major challenge in design optimization is the capability to account for various forms of uncertainty and a large number of uncertain parameters. Most approaches found in the literature rely on a statistical framework, by solving optimization problems based on statistical quantities (expectation, variance, value-at-risk, etc) as criteria [106], [113], [118], [127]. These approaches clearly outclass multi-point approaches, used in the industry for a long time, which simply aggregate objectives computed for different parameter values [119], [144].

We intend to develop and test a new methodology for robust design that will include uncertainty effects. More precisely, we propose to employ the Multiple-Gradient Descent Algorithm (MGDA) (see Section 3.1.2) to achieve an effective improvement of all criteria simultaneously, which can be of statistical nature or discrete functional values evaluated in confidence intervals of parameters. Some recent results obtained at ONERA [124] by a stochastic variant of our methodology confirm the viability of the approach. A PhD thesis has also been launched at ONERA/DADS.

#### 3.1.2.2. Hierarchical methods

Solving optimization problems including real-life applications requires more sophisticated strategies than the simple use of an optimizer coupled with a PDE solver. The analysis of industrial problems are more and more based on a set of simulation tools, of variable fidelity and computational cost, possibly coupled and used in conjunction with experimental data. Conducting a rigorous optimization task in this context is still a challenge.

Therefore, we intend to continue our developments of hierarchical strategies, based either on a hierarchy of models or a hierarchy of design variables. The coordination within an optimization loop, of a high-fidelity (phenomenological) model with a low-fidelity (statistical) model [110], associated with a hierarchical parameter basis [115] (e.g. through CAD representation of the geometry) has revealed very effective during the former Opale activity [85].

More precisely, we propose to develop a methodology based on Gaussian Process (meta-)models to account for multi-fidelity evaluations, error (spatial discretization, temporal integration, etc.) and uncertainty of numerical solvers [93], [123] and possibly including experimental data. Besides, the study of the recently proposed isogeometric analysis paradigm [71], based on the integration of geometry and analysis using a unique hierarchical representation, will be pursued in collaboration with AROMATH Team [141].

#### 3.1.2.3. Multi-objective descent algorithms for multi-disciplinary, multi-point, unsteady optimization or robust-design

In differentiable optimization, multi-disciplinary, multi-point, unsteady optimization or robust-design can all be formulated as multi-objective optimization problems. In this area, we have proposed the *Multiple-Gradient Descent Algorithm (MGDA)* to handle all criteria concurrently [83] [84]. Originally, we have stated a principle according which, given a family of local gradients, a descent direction common to all considered objective-functions simultaneously is identified, assuming the Pareto-stationarity condition is not satisfied. When the family is linearly-independent, we dispose of a direct algorithm. Inversely, when the family is linearly-dependent, a quadratic-programming problem should be solved. Hence, the technical difficulty is mostly

conditioned by the number  $m$  of objective functions relative to the search space dimension  $n$ . In this respect, the basic algorithm has recently been revised [86] to handle the case where  $m > n$ , and even  $m \gg n$ , and is currently being tested on a test-case of robust design subject to a periodic time-dependent Navier-Stokes flow.

The multi-point situation is very similar and, being of great importance for engineering applications, will be treated at large.

Lastly, we note that in situations where gradients are difficult to evaluate, the method can be assisted by a meta-model [143].

#### 3.1.2.4. Constraint elimination in Quasi-Newton methods

In single-objective differentiable optimization, Newton's method requires the specification of both gradient and Hessian. As a result, the convergence is quadratic, and Newton's method is often considered as the target reference. However, in applications to distributed systems, the functions to be minimized are usually 'functionals', and even through a parameterization by means of a finite set of parameters, as it may be the case in shape-optimization, these functionals depend on the optimization variables by the solution of an often complex set of PDE's, through a chain of computational procedures. Various approaches exist to calculate the gradients : (i) by the simultaneous simulation of an adjoint system, that is linear, but equal or superior in complexity to the original system, and ill-conditioned; (ii) by automatic differentiation (e.g. by TAPENADE); (iii) sometimes by carefully-calibrated finite-differences. Calculating second derivatives is even more difficult. For example in automatic differentiation, the gradient is often calculated in the inverse mode, and then, for each "directional second-derivative" the direct mode is applied to it. For  $n$  variables, there are a total of  $n(n + 1)/2$  second derivatives. Hence, the exact calculation of the full Hessian is a complex and costly computational endeavor, often making Newton's method a chimera.

This has fostered the development of "quasi-Newton's methods" that mimic Newton's method but use only the gradient, the Hessian being iteratively constructed by successive approximations inside the algorithm itself. Among such methods, the Broyden-Fletcher-Goldfarb-Shanno algorithm (BFGS) is well-known and commonly employed. In this method, the Hessian is corrected at each new iteration by rank-one matrices defined from several evaluations of the gradient only. The BFGS method has "super-linear convergence". When the minimized function is quadratic in  $n$  variables, full convergence is achieved in  $n + 1$  iterations, so long as one-dimensional minimizations are carried out to full convergence, that is, exactly. For a general smooth functions, after a first phase of Hessian build-up, abrupt convergence is observed.

However, another difficulty arises in the application of the BFGS algorithm. In its standard formulation, it is devised for unconstrained optimization, while practical problems originating from engineering or sciences involve constraints, sometimes in large number. Certain authors have developed so-called "Riemannian BFGS", e.g. [129]. that have the desirable convergence property in constrained problems. However, in this approach, the constraints are assumed to be known formally, by explicit expressions. Again, such a restriction is not practical in case of functionals.

Our research is done in collaboration with ONERA-Meudon. We are exploring the possibility of representing constraints, in successive iterations, through local approximations of the constraint surfaces, splitting the design space locally into tangent and normal sub-spaces, and eliminating the normal coordinates through a linearization, or more generally a finite expansion, and applying the BFGS method through dependencies on the coordinates in the tangent subspace only. Preliminary experiments on the difficult Rosenbrock test-case, although in low dimensions, demonstrate the feasibility of this approach. On-going research is on theorizing this method, and testing cases of higher dimensions.

#### 3.1.2.5. Decentralized strategies towards efficient thermoelastography

Thermoelastography is an innovative non-invasive control technology, which has numerous advantages over other techniques, notably in medical imaging [116]. Indeed, it shows more robustness than thermography alone, a technology that is promoted in e.g. detection and monitoring of breast cancer though it does not prove to be reliably effective and many national health organizations <sup>1</sup> do not advise it as a substitute to

<sup>1</sup><http://cancerscreening.gov.au/internet/screening/publishing.nsf/Content/br-policy-thermography>

e.g. mammography. It is well known that most pathological changes are associated with changes in tissue stiffness, while remaining isoechoic, and hence difficult to detect by ultrasound techniques. As palpation is an effective method for lesion detection, popular among clinicians, thermoelastography turns out to be of a high efficiency potential. Based on elastic waves and heat flux reconstruction, thermoelastography shows no destructive or aggressive medical sequel, unlike X-ray and comparables techniques, making it a prominent choice by patients.

Physical principles of thermoelastography originally rely on dynamical structural responses of tissues, but in a simplified first approach, we only consider static responses of linear elastic structures.

The mathematical formulation of the thermoelasticity reconstruction is based on data completion and material identification, making it a harsh ill posed inverse problem. We have demonstrated in previous works [22], [23] that Nash game approaches are efficient to tackle ill-posedness.

With our collaborators M. Kallel and R. Chamekh (Ph.D.) ((Université de Tunis), we intend to extend the results obtained for Laplace equations in [22] to the following problems (of increasing difficulty) :

- Simultaneous data and parameter recovery in linear elasticity, using the so-called Kohn and Vogelius functional (ongoing work, some promising results obtained).
- Data recovery in coupled heat-thermoelasticity systems.
- Data recovery in linear thermoelasticity under stochastic heat flux, where the imposed flux is stochastic.
- Data recovery in coupled heat-thermoelasticity systems under stochastic heat flux, formulated as an incomplete information Nash game.
- Application to robust identification of cracks.

## 4. Application Domains

### 4.1. Active flow control for transportation systems

The reduction of CO<sub>2</sub> emissions represents a great challenge for the automotive and aeronautic industries, which committed respectively a decrease of 20% for 2020 and 75% for 2050. This goal will not be reachable, unless a significant improvement of the aerodynamic performance of cars and aircrafts is achieved (e.g. aerodynamic resistance represents 70% of energy losses for cars above 90 km/h). Since vehicle design cannot be significantly modified, due to marketing or structural reasons, active flow control technologies are one of the most promising approaches to improve aerodynamic performance. This consists in introducing micro-devices, like pulsating jets or vibrating membranes, that can modify vortices generated by vehicles. Thanks to flow non-linearities, a small energy expense for actuation can significantly reduce energy losses. The efficiency of this approach has been demonstrated, experimentally as well as numerically, for simple configurations [142]. However, the lack of efficient and flexible numerical models, that allow to simulate and optimize a large number of such devices on realistic configurations, is still a bottleneck for the emergence of this technology in an industrial context. In particular, the prediction of actuated flows requires the use of advanced turbulence closures, like Detached Eddy Simulation or Large Eddy Simulation [98]. They are intrinsically three-dimensional and unsteady, yielding a huge computational effort for each analysis, which makes their use tedious for optimization purpose. In this context, we intend to contribute to the following research axes:

- *Sensitivity analysis for actuated flows.* Adjoint-based (reverse) approaches, classically employed in design optimization procedure to compute functional gradients, are not well suited to this context. Therefore, we propose to explore the alternative (direct) formulation, which is not so much used, in the perspective of a better characterization of actuated flows and optimization of control devices.
- *Hierarchical optimization of control devices.* The optimization of dozen of actuators, in terms of locations, frequencies, amplitudes, will be practically tractable only if a hierarchical approach is adopted, which mixes fine (DES) and coarse (URANS) simulations, and possibly experiments. We intend to develop such an optimization strategy on the basis of Gaussian Process models (*multi-fidelity kriging*).

## 4.2. Performance optimization in water sports

Phenomena encountered in water sports provide challenging modeling and optimization problems. Complex flows are usually considered in this context, including turbulence with strong unsteadiness effects and free surface. These problems can be multi-physic, for instance the simulation of a sail behavior requires to solve a fluid-structure interaction problem. Moreover, from an optimization point of view, a delicate compromise between performance and robustness with respect to the uncertain environment is usually sought. Nevertheless, a significant improvement of the performance can be achieved in this area, for which the use of simulation and optimization methods is just beginning. In this context, we are working with specialists of different disciplines (racing kayak and yachting) to develop specific optimization strategies. In particular, the use of meta-modeling techniques, able to aggregate simulations of different accuracies, is studied, as well as robust optimization formulations to account for uncertainties.

## 4.3. Concurrent design for building systems

The lifetime of a building goes through three stages: construction, use and destruction. To each of these phases correspond quality criteria related in particular to:

- Safety: structural, fire, evacuation, chemical spread, etc.
- Well-being of its occupants: thermal and acoustic comfort.
- Functionality of its intended use.
- Environmental impact.

These stages and criteria form a complex system, the so-called building system, whose overall quality (in an intuitive sense) is directly impacted by many factors, very heterogeneous, such as the geographical location or the shape or material composition of some of its components (windows, frames, thermal convectors positions, etc.) It is obvious that the optimization process of these settings must be performed at the "zero" stage of the project design. Moreover, the optimization process has to follow a global approach, taking into account all the concurrent criteria that intervene in the design of building systems.

The application of up-to-date concurrent optimization machinery (games, Pareto Fronts) for multiphysics systems involved in the building is an original approach. With our industrial partner, who wishes routine use of new high performance components in the construction of buildings, we expect that our approach will yield breakthrough building performances (with respect to the above criteria) compared to the current standards.

The research project relies on the ADT BuildingSmart (see software development section) for the implementation of industrial standard software demonstrators.

## 4.4. Vehicular and pedestrian traffic flows

Intelligent Transportation Systems (ITS) is nowadays a booming sector, where the contribution of mathematical modeling and optimization is widely recognized. In this perspective, traffic flow models are a commonly cited example of "complex systems", in which individual behavior and self-organization phenomena must be taken into account to obtain a realistic description of the observed macroscopic dynamics [103]. Further improvements require more advanced models, keeping into better account interactions at the microscopic scale, and adapted control techniques, see [57] and references therein. In particular, we will focus on the following aspects:

- *Junction models.* We are interested in designing a general junction model both satisfying basic analytical properties guaranteeing well-posedness and being realistic for traffic applications. In particular, the model should be able to overcome severe drawbacks of existing models, such as restrictions on the number of involved roads and prescribed split ratios [70], [96], which limit their applicability to real world situations. Hamilton-Jacobi equations could be also an interesting direction of research, following the recent results obtained in [107].



- *Data assimilation.* In traffic flow modeling, the capability of correctly estimating and predicting the state of the system depends on the availability of rich and accurate data on the network. Up to now, the most classical sensors are fixed ones. They are composed of inductive loops (electrical wires) that are installed at different spatial positions of the network and that can measure the traffic flow, the occupancy rate (i.e. the proportion of time during which a vehicle is detected to be over the loop) and the speed (in case of a system of two distant loops). These data are useful / essential to calibrate the phenomenological relationship between flow and density which is known in the traffic literature as the Fundamental Diagram. Nowadays, thanks to the wide development of mobile internet and geolocalization techniques and its increasing adoption by the road users, smartphones have turned into perfect mobile sensors in many domains, including in traffic flow management. They can provide the research community with a large database of individual trajectory sets that are known as Floating Car Data (FCD), see [105] for a real field experiment. Classical macroscopic models, say (hyperbolic systems of) conservation laws, are not designed to take into account this new kind of microscopic data. Other formulations, like Hamilton-Jacobi partial differential equations, are most suited and have been intensively studied in the past five years (see [64], [65]), with a stress on the (fixed) Eulerian framework. Up to our knowledge, they have not been studied in the time-Lagrangian as well as space-Lagrangian frameworks, where data coming from mobile sensors could be easily assimilated, due to the fact that the Lagrangian coordinate (say the label of a vehicle) is fixed.
- *Control of autonomous vehicles.* Traffic flow is usually controlled via traffic lights or variable speed limits, which have fixed space locations. The deployment of autonomous vehicles opens new perspectives in traffic management, as the use of a small fraction of cars to optimize the overall traffic. In this perspective, the possibility to track vehicles trajectories either by coupled micro-macro models [78], [97] or via the Hamilton-Jacobi approach [64], [65] could allow to optimize the flow by controlling some specific vehicles corresponding to internal conditions.

## 4.5. Modeling cell dynamics

Migration and proliferation of epithelial cell sheets are the two keystone aspects of the collective cell dynamics in most biological processes such as morphogenesis, embryogenesis, cancer and wound healing. It is then of utmost importance to understand their underlying mechanisms.

The cells in epithelial sheets (monolayers) maintain strong cell-cell contact during their collective migration. Although it is well known that under some experimental conditions apical and basal sites play distinctive important roles during the migration, as well as the substrate itself [130], we consider here biological experiments where the apico-basal polarization does not take place. Thus, the cell monolayer can be considered as a 2 dimensional continuous structure. These epithelial monolayers, as the Madin-Darby Canine Kidney (MDCK) cells [53], [90], are universally used as multicellular models to study the migratory mechanisms.

Semilinear reaction-diffusion equations are widely used to give a phenomenological description of the temporal and spatial changes occurring within cell populations that undergo scattering (moving), spreading (expanding cell surface) and proliferation. We have followed the same methodology and contributed to assess the validity of such approaches in different settings (cell sheets [101], dorsal closure [49], actin organization [48]). However, epithelial cell-sheet movement is complex enough to undermine most of the mathematical approaches based on *locality*, that is mainly traveling wavefront-like partial differential equations. In [89] it is shown that MDCK cells extend cryptic lamellipodia to drive the migration, several rows behind the wound edge. In [125] MDCK monolayers are shown to exhibit similar non-local behavior (long range velocity fields, very active border-localized leader cells).

Our aim is to start from a mesoscopic description of interaction of the cells (at the cell-cell level, including the F-actin, but not e.g. the migration-related protein scale). Considering cells as independent anonymous agents, we plan to investigate the use of mathematical techniques adapted from the mean-field game theory. Otherwise, looking at them as interacting particles, we will use a multi-agent approach (at least for the actin

dynamics). We intend also to consider approaches stemming from compartment-based simulation in the spirit of those developed in [87], [92], [94].

## 4.6. Nanotechnologies

Our team takes part in a larger collaboration with CEA/LETI (Grenoble), initiated by the Inria Project-Team Nachos, and related to the Maxwell equations. Our component in this activity relates to the optimization of nanophotonic devices, in particular with respect to the control of thermal loads.

We have first identified a gradation of representative test-cases of increasing complexity :

- infrared micro-source
- micro-photoacoustic cell
- nanophotonic device.

These cases involve from a few geometric parameters to be optimized to a functional minimization subject to a finite-element solution involving a large number of dof's. CEA disposes of such codes, but considering the computational cost of the objective functions in the complex cases, the first part of our study is focused on the construction and validation of meta-models, typically of RBF-type. Multi-objective optimization will be carried out subsequently by MGDA, and possibly Nash games.

This research activity is aimed to make our methodologies and application fields more diverse, and we expect to be confronted to novel optimization problematics raised by the specific context.

## 5. New Software and Platforms

### 5.1. BuildingSmart

BuildingSmart interactive visualization

KEYWORDS: Physical simulation - 3D rendering - 3D interaction

- Contact: Abderrahmane Habbal

The aim of the BuildingSmart project is to develop a software environment for the simulation and interactive visualization for the design of buildings (structural safety, thermal confort). The software is to be integrated in an immersive space (<https://www.youtube.com/watch?v=wAm7faixBak>) The project is hosted by the ACUMES team (<https://team.inria.fr/acumes>) in collaboration with the SED service (Service d'Expérimentation et de Développement) and Experts from ArcelorMittal Construction. The project is financed by an Inria ADT which recruited an experienced engineer (starting in december 2015), whose main task is to study and develop solutions dedicated to interactive visualization of building performances (heat, structural) in relation to the Building Information Modeling BIM framework.

### 5.2. Interoperability between Num3sis and Axel Platforms

Num3sis (<http://num3sis.inria.fr>) is a modular platform devoted to scientific computing and numerical simulation developed at Inria Sophia Antipolis Mediterranee Center. It is not restricted to a particular application field, but is designed to host complex multidisciplinary simulations. Main application fields are currently Computational Fluid Dynamics and pedestrian traffic simulation (by Acumes team), Computational Electro-Magnetics (by Nachos project-team). Some components of the platform are also used by Tosca project-team for CO2 market simulation and wind simulation (in collaboration with Ciric Inria-Chile), and by Inria Project-Lab C2S@EXA for high-performance computing applications. Finally, Lemon team will initiate developments for coastal environment simulation in a near future.

To facilitate the coupling between simulation and CAD (Computer-Aided Design), a refactoring of the grid management has been achieved (supported by ADT Simon). This allows interoperability between num3sis and Axel platform, which is developed by Galaad team and is devoted to algebraic geometry. From a practical point of view, grids generated by Axel can now be used by Num3sis for simulation, while PDE solvers in Num3sis libraries can be used interactively by Axel to simulate physical problems.

## 6. New Results

### 6.1. Mathematical analysis and control of macroscopic traffic flow models

#### 6.1.1. Vehicular traffic

**Participants:** Guillaume Costeseque, Paola Goatin, Christophe Chalons [UVST], Simone Göttlich [U Mannheim, Germany], Jérôme Härrı [EURECOM], Oliver Kolb [U Mannheim, Germany], Sosina Mengistu-Gashaw [EURECOM], Francesco Rossi [U Aix-Marseille], Stefano Villa [U Milano-Bicocca].

In collaboration with the University of Mannheim and in the framework of the PHC Procope project "Transport Networks Modeling and Analysis", we studied how to manage variable speed limits combined with coordinated ramp metering within the framework of the LWR network model. Following a "first discretize then optimize" approach, we derived the first order optimality system and explained the switch of speeds at certain fixed points in time and the boundary control for the ramp metering as well. Sequential quadratic programming methods are used to solve the control problem numerically. For application purposes, we present experimental setups where variable speed limits are used as a traffic guidance system to avoid traffic jams on highway interchanges and on-ramps, see [35].

The thesis of S. Mengistu-Gashaw, funded by the Labex UCN@Sophia (<http://ucnlab.eu/>) and co-supervised by P. Goatin and J. Härrı, is devoted to understanding and modeling mobility characteristics of scooters and motorcycles for user-centric ITS application. We are currently developing a macroscopic model for heterogeneous traffic including car and motorcycles.

A new traffic flow model has been designed in [44] for taking into account the multiclass and multilane features of real traffic. This model is based on a system of coupled Hamilton-Jacobi PDEs for an appropriate choice of framework that mixes spatial and Lagrangian coordinates. The coupling conditions emerge from the moving bottleneck theory that has been developed in the traffic flow literature several years ago but for which a real mathematical sound basis lacked. Very recently, there were some new results dealing with the existence of a solution under suitable assumptions. However, these results were set for the hyperbolic conservation law in Eulerian coordinates and they are not straightforward to extend to Hamilton-Jacobi equations in different coordinates. Despite that the well-posedness of the problem is still an open problem, a numerical method is developed and it takes advantage of the classical representation formula available for HJ PDEs. This numerical scheme has been proved to provide good qualitative results.

In collaboration with F. Rossi, we proved existence and uniqueness of solutions to a transport equation modelling vehicular traffic in which the velocity field depends non-locally on the downstream traffic density via a discontinuous anisotropic kernel. The result is obtained recasting the problem in the space of probability measures equipped with the  $\infty$ -Wasserstein distance. We also show convergence of solutions of a finite dimensional system, which provide a particle method to approximate the solutions to the original problem. See, [45].

Finally, the internship of S. Villa, co-supervised by M. Garavello (U Milano-Bicocca), was devoted to the analytical and numerical study of the Aw-Rascle-Zhang model with moving bottleneck. Two Riemann Solver have been proposed, and two numerical strategies have been developed. A journal article is in preparation in collaboration with C. Chalons.

#### 6.1.2. Crowd motion

**Participants:** Paola Goatin, Matthias Mimault.



M. Mimault defended his PhD on December 14th, 2015. The last part of his thesis was devoted to the numerical study of scalar conservation laws with non-local flow in two space dimensions. These equations are meant to model crowd motion, where the movement direction of each pedestrian depends on a weighted mean of the crowd density around him. In particular, he implemented a finite volume numerical scheme which has been used for flow optimization purposes: he applied the adjoint method to compute the gradient for the evacuation time minimization depending on the initial crowd distribution.

## 6.2. Characterization of model uncertainty for turbulent flows

**Participants:** Régis Duvigneau, Jérémie Labroquère, Emmanuel Guilmineau [CNRS ECN, Nantes], Marianna Brazza [CNRS IMFT, Toulouse], Mathieu Szubert [CNRS IMFT, Toulouse].

The uncertainty related to turbulence modeling is still a bottleneck in realistic flows simulation. Therefore, some studies have been conducted to quantify this uncertainty for two problems in which turbulence plays a critical role. Firstly, the impact of the model choice has been estimated in the case of a massively detached flow over a 2D backward facing step including an oscillatory active control device, whose parameters are optimized [41], [34]. Secondly, the influence of the transition point location has been investigated, in the case of the 3D flow around a bluff-body, using models ranging from RANS to DES models [40].

## 6.3. Sensitivity analysis for unsteady flows

**Participants:** Régis Duvigneau, Dominique Pelletier [Ecole Polytechnique Montreal], Alexander Hay [Ecole Polytechnique Montreal].

Although sensitivity analysis is now commonly used for steady systems, usually on the basis of the adjoint equation method, the application to unsteady problems is still tedious, due to the backward time integration required. Therefore, an alternative approach, namely the sensitivity equation method, has been studied in the framework of the compressible Navier-Stokes equations. A continuous version has preferred to the discrete one for its flexibility and easier implementation. The proposed approach has been verified on several problems of increasing difficulty and the computational efficiency quantified [42].

## 6.4. Optimization accounting for experimental and numerical uncertainties

**Participants:** Régis Duvigneau, Olivier Le Maitre [CNRS LIMSI, Orsay], Matthieu Sacher [Ecole Navale, Brest], Alban Leroyer [ECN, Nantes], Patrick Queutey [CNRS ECN, Nantes].

Optimization of real-life applications requires to account for the uncertainties arising during the performance evaluation procedure, that could be either experimental or numerical. A Gaussian-Process based optimization algorithm has been proposed to efficiently determine the global optimum in presence of noise, whose amplitude can be user-defined or inferred from observations. The method has been applied to two very different problems related to performance optimization in sport.

The first case corresponds to the optimization of the shape of a racing kayak. The performance is estimated by coupling Newton's law with Navier-Stokes equations to compute the kayak velocity from the effort of the athlete, considered as input. The proposed method has been used here to filter the noise arising from the numerical simulation.

The second case corresponds to the optimization of a sail trimming, whose performance can be estimated either experimentally in a wind tunnel, or numerically by solving a fluid-structure interaction problem. In the former case, uncertainty has been estimated according to measurements accuracy, while in the latter case the numerical noise has been inferred from a set of observations collected during the optimization.

## 6.5. High-order numerical schemes for convection-dominated problems

**Participants:** Régis Duvigneau, Asma Gdhami [ENIT, Tunisia].

The use of high-order numerical schemes is necessary to reduce numerical diffusion in simulations, maintain a reasonable computational time for 3D problems, estimate accurately uncertainties or sensitivities, etc. Consequently, we work to develop high-order numerical schemes for the applications targeted by the team, in particular for convection-dominated problems. More precisely, we intend to include in a unified framework, based on Discontinuous Galerkin approximations, numerical methods accounting for complex geometries (isogeometric methods), uncertainty propagation (high-dimensional cubature) and sensitivity analysis.

## 6.6. Validation of time dependent diffusion approaches for activated and inhibited cell sheet closure

**Participants:** Abderrahmane Habbal, H el ene Barelli [Univ. Nice Sophia Antipolis, CNRS, IPMC], Gr egoire Malandain [Inria, EPI Morpheme], Boutheina Yahyaoui [PhD, LAMSIN, Univ. Tunis Al Manar], Mekki Ayadi [LAMSIN, Univ. Tunis Al Manar].

We have studied in [21] five MDCK cell monolayer assays in a reference, activated and inhibited migration conditions. Modulo the inherent variability of biological assays, we have shown that in the assay where migration was not exogeneously activated or inhibited, the wound velocity was constant and the Fisher-KPP equation was able to accurately predict, until the final closure of the wound, the evolution of the wound area, the mean velocity of the cell front, and the time at which the closure occurred. When activated or inhibited, the F-KPP equation with constant parameters was unable to reproduce the observed biological cell sheet behavior. We modify the original equation, making the diffusion and proliferation parameters time dependent, following a sigmoid profile. We then set up an optimization loop to identify the sigmoids parameters, by computing a classical error indicator (difference between a computed density and the observed one, obtained through image processing) as done in the cited reference. We then obtain results which convincingly show that our approach is efficient : in both cases, inhibited and activated, the time varying identified parameters allow us to accurately predict until the final closure the evolution of the wound area.

## 6.7. Game strategies for joint data completion and parameter identification

**Participants:** Abderrahmane Habbal, Rabeb Chamekh [PhD, LAMSIN, Univ. Tunis Al Manar], Moez Kallel [LAMSIN, Univ. Tunis Al Manar], Nejib Zemzemi [Inria Bordeaux, EPI CARMEN].

We have demonstrated in previous works [22], [23] that Nash game approaches are efficient to tackle ill-posedness for linear second order elliptic Cauchy problems. We next developed a mathematical formulation for the linear elasticity model. The reconstruction is based on data completion and material identification, making it a harsh ill posed inverse problem. Up to now, we have obtained successful results for the Lam e parameter recovery in linear elasticity, using the so-called Kohn and Vogelius functional. Simultaneous data completion and parameter identification is under investigation.

## 6.8. Revised definition of the Multiple Gradient Descent Algorithm (MGDA)

**Participant:** Jean-Antoine D esid eri.

The Multiple Gradient Descent Algorithm (MGDA) had been defined originally to identify a descent direction common to a set of gradient vectors. According to a completely general principle, the direction is opposite to the vector of minimum Euclidean norm in the convex hull of the gradients. The Euclidean norm is defined via a general scalar product in  $\mathbf{R}^n$ . From a theoretical viewpoint, the notion of Pareto-stationarity had been introduced and it was established that if a point is Pareto-optimal and if the objective functions are locally differentiable and convex, then the point is Pareto-stationary. From a computational viewpoint, the descent direction can be determined as the solution of a Quadratic-Programming (QP) formulation. However, when the gradients are linearly independent a direct construction via a Gram-Schmidt orthogonalization process was preferred. We have now generalized the orthogonalization process by the introduction of a hierarchical strategy in the ordering of the subfamily of gradients utilized to construct the orthogonal basis. This strategy aims at making the (multi-dimensional) cone associated with the convex hull of the subfamily as large as possible. As

a result, in the case of linearly-dependent gradients, the orthogonalization process not only provides a basis of the spanned subspace, but the subfamily is selected such that its convex hull is also very representative of a large cone, encompassing in the most favorable cases all the given gradients. By this change in the definition of the algorithm, we were able to reformulate the QP formulation, now stated in a suitable basis, in a way that is well-suited for the treatment of cases where the number of gradients exceeds, possibly vastly, the dimension of the vector space. This revision makes the algorithm much more general and robust [43].

## 6.9. Multi-point optimization of a time-periodic system of pulsating jets

**Participants:** Jean-Antoine Désidéri, Régis Duvigneau.

A multi-point optimization exercise governed by the time-dependent compressible Navier-Stokes equations has been solved based on the sensitivity analysis (see above). A system was considered consisting of three pulsating jets acting on a flat-plate boundary layer. As it is well-known, the flow mixing by the jets has the effect of reducing the drag, as this was confirmed by the simulation of the flow in the somewhat arbitrary initial setting of the jets. Then, positions and pulsation frequencies of the jets have been maintained fixed, while their amplitudes and phases, six parameters in total, have been optimized to minimize the drag force. The finite-volume simulation of the time-periodic flow provides the drag force as a function of time over a large number of timesteps (800 for an accurate description of a period). The sensitivity analysis simultaneously provides the derivatives of drag with respect to the six design parameters. These derivatives were averaged over 20 distinct time-intervals, thus yielding 20 averaged gradient vectors of dimension 6. The MGDA was then used to define a descent direction common to the 20 vectors, a descent step was applied to the design parameters, and the process was continued iteratively.

The experiment confirmed the possibility to reduce the drag force at all times of the period, and not only in the average. In contrast, using the average gradient to define the direction of search resulted in a more important reduction of the average drag but at the cost of an increase of drag in a critical portion of the time period. Hence our optimization algorithm is more versatile and powerful than one aiming at minimizing purely statistical functions obtained by time averaging. We also demonstrated the possibility to optimize over a subinterval of the time interval.

## 6.10. Quasi-Riemannian approach to constrained optimization

**Participants:** Didier Bailly [Research Engineer, ONERA Department of Applied Aerodynamics, Meudon], Gérald Carrier [Research Engineer, ONERA Department of Applied Aerodynamics, Meudon], Jean-Antoine Désidéri.

In differentiable optimization, the Broyden-Fletcher-Goldfarb-Shanno (BFGS) method is one of the most efficient methods for unconstrained problems. Besides function values, it only requires the specification of the gradient. An approximate Hessian is calculated by successive approximations as part of the iteration, using rank-1 correction matrices. As a result, the iteration has superlinear convergence : when minimizing a quadratic function in  $n$  variables, if the one-dimensional minimizations in the calculated directions of search are done exactly, the Hessian matrix approximation is exact after  $n$  iterations, and from this, the iteration identifies to Newton's iteration, and produces the exact local optimum in only one additional iteration ( $n + 1$  in total).

However the BFGS method does not extend to constrained problems very simply. Following Gabay [95] and other authors, Chunhong Qi *et al* [128] have proposed a "Riemannian" variant, RBFGS that indeed incorporates equality constraints in the formulation and actually demonstrates superior convergence rates for problems with a large number of variables. However these Riemannian formulations are non trivial to implement since they require procedures implementing non-trivial differential-geometry operators ('retraction' and 'metric transport') to be developed. In their paper, they assume a formal expression of the constraint to be known. But, in PDE-constrained optimization, many constraints are functional, and it is not clear how the metric transport operator in particular can be defined.

We are investigating how can a quasi-Riemannian method can be defined based on the sole definition of evaluation procedures for the gradients. By condensing all the equality constraints in one, a purely-explicit approximate retraction operator has been defined that yields a point whose distance to the constraint surface is fourth-order at least. The associated transport operator is currently being examined formally. These techniques will be experimented in the context of constrained optimum-shape design in aerodynamics.

### 6.11. Unstructured mesh adaptation using an adjoint-based sensor

**Participants:** Sébastien Bourasseau [Doctoral student, ONERA Department of Computational Fluid Dynamics, Châtillon], Jacques Peter [Research Engineer, ONERA Department of Computational Fluid Dynamics, Châtillon], Jean-Antoine Désidéri.

Mesh adaptation is a powerful tool to obtain accurate aerodynamic simulations at limited cost. When the simulation is aimed at the accurate calculation of aerodynamic outputs (forces, moments) goal-oriented methods based on the adjoint vector of the output of interest are often advocated. The calculation of the total derivative  $dJ/dX$  of the aerodynamic function of interest,  $J$ , with respect to the volume mesh coordinates,  $X$ , has been extended to the case of an unstructured grid. The software developments have been validated for inviscid and laminar viscous flows, and implemented in the ONERA code (elsA). Then a local sensor  $\theta$  based on  $dJ/dX$  was devised to identify areas where the location of the volume mesh nodes has a strong impact on the evaluation of the output  $J$ . The sensor has been shown to be adequate in different flow regimes (subsonic, transonic, supersonic), for internal (blade and nozzle) and external (airfoils, wings) aerodynamic configurations. The proposed method has been compared to a well-known goal-oriented method (Darmofal and Venditti, 2001) and to a feature-based method; it yields comparable results at lower cost in simple configurations. A publication is currently subject to minor revisions.

### 6.12. Multi-fidelity surrogate modeling with application to the optimization of nanophotonic devices

**Participants:** Cédric Durantin [Doctoral student, CEA LETI Grenoble], Alain Glière [Research Engineer, CEA LETI Grenoble], Jean-Antoine Désidéri.

Multiple models of a physical phenomenon are sometimes available with different levels of approximation, the high fidelity model being more demanding in terms of computational time than the coarse approximation. In this context, including information from the lower fidelity model to build a surrogate model is desirable. A new multi-fidelity metamodeling method, based on Radial Basis Function, the co-RBF, is proposed. The new method is compared with the classical co-kriging on two analytical benchmarks and a realistic validation test, namely the design of a miniaturized photoacoustic gas sensor. The co-RBF method brings better results on high dimensional problem and could be considered as an alternative to co-kriging for multi-fidelity metamodeling.

## 7. Partnerships and Cooperations

### 7.1. National Initiatives

#### 7.1.1. Project BOUM

G. Costeseque holds a BOUM (SMAI) project on “*Homogeneization mathematical methods for traffic flow models*” with W. Salazar and M. Zaydan (LMI, INSA Rouen) and J.A. Firozaly (CERMICS, Ecole des Ponts ParisTech and LAMA, Univeristé Paris-Est Créteil).

#### 7.1.2. Project SOKA

R. Duvingneau is coordinator of the project SOKA, funded by INSEP for 2014-2015. The objective is the modeling and optimization of racing canoes in the perspective of 2016 Olympic Games in Rio. Other partners are the Ecole Centrale de Nantes and FFCK (French Federation of Canoe-Kayak).

## 7.2. European Initiatives

### 7.2.1. FP7 & H2020 Projects

#### 7.2.1.1. TraM3

Type: FP7

Defi: NC

Instrument: ERC Starting Grant

Objectif: NC

Duration: October 2010 - March 2016

Coordinator: Inria

Inria contact: Paola Goatin

Abstract: The project intends to investigate traffic phenomena from the macroscopic point of view, using models derived from fluid-dynamics consisting in hyperbolic conservation laws. The scope is to develop a rigorous analytical framework and fast and efficient numerical tools for solving optimization and control problems, such as queues lengths control or buildings exits design. See also: <http://www-sop.inria.fr/members/Paola.Goatin/tram3.html>

## 7.3. International Initiatives

### 7.3.1. Inria International Labs

#### **Inria@SiliconValley**

Associate Team involved in the International Lab:

#### 7.3.1.1. ORESTE

Title: Optimal RERoute Strategies for Traffic managEment

International Partner (Institution - Laboratory - Researcher):

University of California Berkeley (United States) - Electrical Engineering and Computer Science (EECS) (EECS) - Alexandre M. Bayen

Start year: 2015

See also: <http://www-sop.inria.fr/members/Paola.Goatin/ORESTE/index.html>

This project focuses on traffic flow modeling and optimal management on road networks. Based on the results obtained during the first three years, we aim at further develop a unified macroscopic approach for traffic monitoring, prediction and control. In particular, we aim at investigating user equilibrium inference and Lagrangian controls actuations using macroscopic models consisting of conservation laws or Hamilton-Jacobi equations.

#### **LIRIMA**

Associate Team involved in the IIL :

#### 7.3.1.2. ANO

The LIRIMA team ANO : Numerical analysis of PDEs and Optimization is a partnership between Opale project and the EMI engineering college, Rabat / National Centre for Scientific and Technical Research (CNRST) Morocco. The Team leader is Prof. Rajae Aboulaïch, EMI. Other french participants are the Project Commands at Saclay, Palaiseau and the team-project DRACULA at Inria Lyon.

The ANO team is composed of ten senior researchers from Morocco and ten senior researchers from France and more than fifteen PhD students.

The themes investigated are biomathematics (Models for plants growth, cardiovascular and cerebral diseases, cardio image segmentation), mathematical finance (optimal portfolio, risk management, Islamic finance), and multiobjective optimization in structural mechanics.

### 7.3.2. Participation In other International Programs

- PHC PROCOPE Team *Transport Networks Modeling and Analysis*  
Duration : Jan. 2014- Dec. 2015  
Coordinator: P. Goatin (France), S. Göttlich (Germany)  
Other partner: University of Mannheim (Germany)  
Abstract: The proposed research cooperation focuses on the development and analysis of methods for time-dependent transport phenomena in complex systems. Such systems are given for example by traffic flow networks, production lines, gas and water networks, or chemical reactions. Our particular importance is to model physical processes according to their scale by suitable mathematical means. To this end a model hierarchy using a discrete description for the small scale effects and a continuous model to describe large scale phenomena is investigated. These novel and nonstandard approaches allow to incorporate detailed nonlinear dynamic behavior, which is currently not possible with the widely used classical mixed?integer linear approaches. Through the coupling of discrete and continuous models, both on the theoretical and the applied level, we will contribute to the quantification of uncertainty as well as on control problems for these systems. The modeling is achieved by first considering transport phenomena such as traffic, production, gas and water before controlling the systems. We analyze system properties and derive and implement efficient numerical algorithms for simulation and optimization purposes. In this setting, the proposed project yields a significant contribution for tackling large dynamical problems not only restricted to traffic management but also in other engineering areas.

## 7.4. International Research Visitors

### 7.4.1. Visits of International Scientists

#### 7.4.1.1. Internships

- H. Yoldas (May 2015, L'Aquila University): numerical study of a non-local version of Hughes' model for pedestrian flows.
- M. Pfirsching (September 2015): numerical schemes for non-local conservation laws.
- S. Villa (March-June 2015, Milano - Bicocca): moving bottlenecks in traffic flow.
- Z. Tabbakh (15 november- 15 december, EMI, Rabat) Modeling and optimization of lakes aeration process.

## 8. Dissemination

### 8.1. Promoting Scientific Activities

#### 8.1.1. Scientific events organisation

##### 8.1.1.1. General chair, scientific chair

- J.-A. Désidéri and A. Habbal jointly held the chairs of the 27th IFIP TC7 Conference 2015 on System Modelling and Optimization, SophiaTech Campus Sophia Antipolis, France June 29 - July 3, 2015.
- A. Habbal was general co-chair of the LIRIMA Biomathematics workshop, 11-12 November 2015, In LERMA - Mohammadia Engineering School, Mohammed V University - Rabat, Morocco.

##### 8.1.1.2. Member of the organizing committees

- P. Goatin was member of the Organizing Committee of the workshop "*Mathematical Foundations of Traffic*" at IPAM (UCLA), Los Angeles (USA). Sept. - Oct. 2015. <http://www.ipam.ucla.edu/programs/workshops/workshop-i-mathematical-foundations-of-traffic/>

- P. Goatin co-organized with J. Härri (EURECOM) the Labex UCN@Sophia thematic day “*Intelligent Transport Systems*”. March 2015.
- J.-A. Désidéri and A. Habbal directed the Organizing Committee of the 27th IFIP TC7 Conference 2015 on System Modelling and Optimization, SophiaTech Campus Sophia Antipolis, France June 29 - July 3, 2015

### 8.1.2. Journal

#### 8.1.2.1. Reviewer - Reviewing activities

- R. Duvigneau is reviewers for the following international journals : Computers & Fluids, International Journal for Numerical Methods in Fluids, Computer Methods for Applied Mechanical Engineering, Computer Aided Geometric Design, Applied Mathematics & Mechanics, Engineering Optimization.
- P. Goatin is reviewers for the following international journals: Acta Applicandæ Mathematicæ ; African Journal of Mathematics and Computer Science Research; Algorithms; Annales de l’Institut Henri Poincaré (C) Analyse Non Linéaire; Applied Mathematics and Computation; Computer-aided Civil and Infrastructure Engineering; Discrete and Continuous Dynamical Systems; European Journal of Operational Research; IEEE Transactions on Automatic Control; IEEE Transactions on Intelligent Transportation Systems; International Journal of Dynamical Systems and Differential Equations; Journal of Computational Physics; Journal of Flow, Turbulence and Combustion; Mathematical Models and Methods in Applied Sciences; Mathematics of Computation; Networks and Heterogeneous Media; New Journal of Physics; Nonlinear Analysis Ser. B: Real World Applications; SIAM Journal of Mathematical Analysis; SIAM Journal of Applied Mathematics; SIAM Journal of Numerical Analysis; SIAM Journal on Scientific Computing.
- A. Habbal is reviewer for the following international journals: Applied Mathematics (AM), Scientific Research Publishing ; Journal of Structural and Multidisciplinary Optimization ; Journal of Math. Model. Nat. Phenom. ; International Journal of Mechanical Sciences ; Modern Applied Science ; Asian Journal of Control ; Applied Mathematics and Computation ; Computer Methods in Applied Mechanics and Engineering.

#### 8.1.3. Invited talks

- J.-A. Désidéri: Contributions to PDE for Applications, Univ. Paris 6, Aug. 31-Sept. 1 2015. “Multiple-Gradient Descent Algorithm (MGDA) applied to the parametric optimization of pulsating jets in unsteady flow”.
- P. Goatin: 8th International Congress on Industrial and Applied Mathematics, Beijing (China), August 2015. Mini-symposium: “Data-driven mathematical models for production and traffic flow”. Invited talk: “*Uncertainty quantification in traffic flow models calibration from GPS data*”.
- P. Goatin: 13th Viennese Workshop on Optimal Control and Dynamic Games, Vienna (Austria), May 2015. Special session: “Mean-field models and control of multi-agent systems”. Invited talk: “*Conservation laws with non-local flux in traffic flow modeling*”.
- P. Goatin: CoToCoLa - Conference on Contemporary topics in conservation laws, Besançon (France), February 2015. Invited talk: “*Conservation laws with non-local flux in traffic flow modeling*”.
- A. Habbal: 1st Summer School Labex MS2T - Multi-objective design and optimisation of technological systems, Cap Hornu, August 2015. Invited lecture: *Multidisciplinary Optimization and Game Theory*.

#### 8.1.4. Research administration

- P. Goatin is member of BCP (“Bureau du Comité des Projets”) at Inria Sophia Antipolis Méditerranée.

- R. Duvigneau is member of the "Conseil National des Universités" (CNU) for the 26th section (applied mathematics).

## 8.2. Teaching - Supervision - Juries

### 8.2.1. Teaching

Master: Advanced Optimization, 40.5 hrs, M2, Ecole Polytechnique Universitaire (EPU), Nice Sophia Antipolis (J.-A. Désidéri, R. Duvigneau).

Master: Conservation laws and finite volume scheme, 30 hrs, M2, Ecole Polytechnique Universitaire (EPU), Nice Sophia Antipolis (P. Goatin).

Master: Multidisciplinary Optimization, 22.5 hrs, joint *Institut Supérieur de l'Aéronautique et de l'Espace* (ISAE Supaéro, "Complex Systems") and M2 (Mathematics), Toulouse (J.-A. Désidéri, R. Duvigneau).

Licence: Numerical Methods I, 76hrs, Ecole Polytechnique Universitaire (EPU), Nice Sophia Antipolis (A. Habbal).

Licence: Summer Project in Mathematical Modeling, 36 hrs, L3, Ecole Polytechnique Universitaire (EPU), Nice Sophia Antipolis (A. Habbal).

Master: Numerical Methods for Partial Differential Equations, 66 hrs, M1, Ecole Polytechnique Universitaire (EPU), Nice Sophia Antipolis (A. Habbal).

Master: Concurrent design in building structures, M2 Students Project, Ecole Polytechnique Universitaire (EPU), Nice Sophia Antipolis (A. Habbal).

### 8.2.2. Supervision

PhD : Sébastien Bourasseau, *Contribution to a mesh refinement method based on the adjoint vector for the computation of aerodynamic outputs*, December 2015. Supervisors : J.-A. Désidéri and J. Peter (ONERA).

PhD : Matthias Mimault, *Crowd motion modeling by conservation laws*, University of Nice Sophia Antipolis, December 2015. Supervisor: P. Goatin.

PhD in progress : Cédric Durantin, *Meta-modelling for the optimization of nanophotonic devices*, October 2014. Supervisors : J.-A. Désidéri and A. Glière (CEA LETI).

PhD in progress : Quentin Mercier, *Multicriterion optimization under uncertainties : the stochastic multiple gradient approach. Application to aerelasticity*, October 2015. Supervisors : J.-A. Désidéri and F. Poirion.

PhD in progress : Maroua Mokni, *Development, analysis and numerical evaluation of MGDA*, October 2013. Supervisors : J.-A. Désidéri and M. Ayadi (LAMSIN-ENIT, Tunisia).

PhD in progress : Sosina Mengistu-Gashaw (EURECOM), *Mobility and connectivity modelling of 2-wheels traffic for ITS applications*, March 2015. Supervisors: P. Goatin and J. Härrri (EURECOM).

PhD in progress: Boutheina Yahyaoui, *Validation of mecano-chemo-biological models for cell sheet wound closure*, Jan 2013, Supervisors: A. Habbal, Mekki Ayadi (LAMSIN, ENIT, Tunis)

PhD in progress: Rabeb Chamekh, *Game strategies for thermo-elasticity*, Jan 2015, Supervisors: A. Habbal, Moez Kallel (LAMSIN, ENIT, Tunis)

PhD in progress: Kelthoum Chahour, *Modeling and optimal design of coronary angioplastic stents*, Nov 2015, Supervisors: A. Habbal, Rajae Aboulaich (LERMA, EMI, Rabat)

PhD in progress: A. Gdhami, *isogeometric analysis methods for hyperbolic systems*, University of Tunis / University of Nice - Sophia Antipolis, Oct. 2013, supervisors: R. Duvigneau and M. Moakher (ENIT).



PhD in progress: M. Sacher, *advanced methods for numerical optimization of yacht performance*, Ecole Navale, Oct. 2014, supervisors: R. Duvigneau, O. Le Maître (LIMSI), F. Hauville and J.-A. Astolfi (Ecole Navale).

### 8.2.3. Juries

- P. Goatin was member of the selection (Inria Sophia Antipolis) committee for the competitive selection of young graduate scientists (CR2).
- P. Goatin was member of the committee of Y. Tang's PhD thesis "*Stability analysis and Tikhonov approximation for linear singularly perturbed hyperbolic systems*", Université de Grenoble, September 18th, 2015.
- P. Goatin was referee of U. Razafiston's Habilitation thesis "*Contribution à l'analyse théorique de problèmes elliptiques en domaine non borné, à la simulation numérique d'équations hyperboliques et aux méthodes de bases réduites*", Université de Besançon, December 3rd, 2015.
- A. Habbal was referee of M.F. Frabolot PhD thesis *optimisation de forme avec detection automatique de parametres* (Mécanique avancée, UT Compiègne), March 2015
- A. Habbal was referee of R.F. Coelho Habilitation HDR *Optimisation structurale et multidisciplinaire en mécanique et en Génie civil* (UT Compiègne), April 2015
- J.-A. Désidéri was referee of Gwladys Ravon's PhD thesis *Inverse problems for heart optical cartography*, December 18th, 2015.
- R. Duvigneau was reviewer of the PhD manuscript of D. Valizadeh ("Development and analysis of a discrete adjoint operator for incompressible Navier-Stokes equations for low Reynolds number", Ecole Centrale de Nantes).

## 9. Bibliography

### Major publications by the team in recent years

- [1] A. AGGARWAL, R. M. COLOMBO, P. GOATIN. *Nonlocal systems of conservation laws in several space dimensions*, in "SIAM Journal on Numerical Analysis", 2015, vol. 52, n<sup>o</sup> 2, pp. 963-983, <https://hal.inria.fr/hal-01016784>
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- [5] L. BLANCHARD, R. DUUVIGNEAU, A.-V. VUONG, B. SIMEON. *Shape gradient for isogeometric structural design*, in "J. Optimization Theory and Applications", 2014, vol. 161, n<sup>o</sup> 2
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## Publications of the year

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