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Université Nice - Sophia Antipolis

Activity Report 2012

Team MCTAO

Mathematics for Control, Transport and Applications

IN COLLABORATION WITH: Laboratoire Jean-Alexandre Dieudonné (JAD)

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Modeling, Optimization, and Control of Dynamic Systems

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Team MCTAO

Keywords: Control Theory, Nonlinear Control, Optimal Control, Optimal Transport

Creation of the Team: January 01, 2012 *, Updated into Project-Team:* January 01, 2013 .

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2. Overall Objectives

2.1. Overall Objectives

The core endeavor of this team is to develop methods in control theory for finite-dimensional nonlinear systems, as well as in optimal transport, and to be involved in applications of these techniques. Some mathematical fields like dynamical systems and optimal transport may benefit from control theory techniques. Our primary domain of industrial applications will be space engineering, namely designing trajectories in space mechanics using optimal control and stabilization techniques: transfer of a satellite between two Keplerian orbits, rendez-vous problem, transfer of a satellite from the Earth to the Moon or more complicated space missions. A second field of applications is quantum control with applications to Nuclear Magnetic Resonance and medical image processing.

2.2. Highlights of the Year

- The team started this year.
- Bernard Bonnard publishes, with Dominique Sugny from University of Bourgogne, a reference book on control applications to Quantum Dynamics and Space Dynamics [18].

3. Scientific Foundations

3.1. Control Systems

Our effort is directed toward efficient methods for the *control* of real (physical) systems, based on a *model* of the system to be controlled. *System* refers to the physical plant or device, whereas *model* refers to a mathematical representation of it.

We mostly investigate nonlinear systems whose nonlinearities admit a strong structure derived from the physics; the equations governing their behavior is then rather well known, and the modeling part consists in choosing what phenomena are to be retained in the model used for control design; the other phenomena being treated as perturbations; a more complete model may be used for simulations, for instance. We focus on systems that admit a reliable finite-dimensional model, in continuous time; this means that models are ordinary differential equations, often nonlinear.

Choosing accurate models yet simple enough to allow control design is in itself a key issue; however, modeling or identification as a theory is not per se in the scope of our project.

The extreme generality and versatility of linear control do not contradict the often heard sentence "most real life systems are nonlinear". Indeed, for many control problems, a linear model is sufficient to capture the important features for control. The reason is that most control objectives are local, first order variations around an operating point or a trajectory are governed by a linear control model, and except in degenerate situations (non-controllability of this linear model), the local behavior of a nonlinear dynamic phenomenon is dictated by the behavior of first order variations. Linear control is the hard core of control theory and practice; it has been pushed to a high degree of achievement –see for instance some classics: [56], [42]– that leads to big successes in industrial applications (PID, Kalman filtering, frequency domain design, H^∞ robust control, etc...). It must be taught to future engineers, and it is still a topic of ongoing research.

Linear control by itself however reaches its limits in some important situations:

1. **Non local control objectives.** For instance, steering the system from a region to a reasonably remote other one (path planning and optimal control); in this case, local linear approximation cannot be sufficient.
   It is also the case when some domain of validity (e.g. stability) is prescribed and larger than the region where the linear approximation is dominant.
2. **Local control at degenerate equilibria.** Linear control yields local stabilization of an equilibrium point based on the tangent linear approximation if the latter is controllable. When it is *not*, and this occurs in some physical systems at interesting operating points, linear control is irrelevant and specific nonlinear techniques have to be designed.
   This is in a sense an extreme case of the second paragraph in point 1: the region where the linear approximation is dominant vanishes.
3. **Small controls.** In some situations, actuators only allow a very small magnitude of the effect of control compared to the effect of other phenomena. Then the behavior of the system without control plays a major role and we are again outside the scope of linear control methods.
4. **Local control around a trajectory.** Sometimes a trajectory has been selected (this appeals to point 1), and local regulation around this reference is to be performed. Linearization in general yields, when the trajectory is not a single equilibrium point, a *time-varying* linear system. Even if it is controllable, time-varying linear systems are not in the scope of most classical linear control methods, and it is better to incorporate this local regulation in the nonlinear design, all the more so as the linear approximation along optimal trajectories is, by nature, often non controllable.

Let us discuss in more details some specific problems that we are studying or plan to study: classification and structure of control systems in section 3.2, optimal control, and its links with feedback, in section 3.3, the problem of optimal transport in section 3.4, and finally problems relevent to a specific class of systems where the control is "small" in section 3.5.

3.2. Structure of nonlinear control systems

In most problems, choosing the adapted coordinates, or the right quantities that describe a phenomenon, sheds light on a path to the solution. In control systems, it is often crucial to analyze the structure of the model, deduced from physical principles, of the plant of be controlled; this may lead to putting it via some transformations in a simpler form, or a form that is most suitable for control design. For instance, equivalence to a linear system may allow to use linear control; also, the so-called "flatness" property drastically simplifies path planning [48], [63].

A better understanding of the "set of nonlinear models", partly classifying them, has another motivation than facilitating control design for a given system and its model: it may also be a necessary step towards a theory of "nonlinear identification" and modeling. Linear identification is a mature area of control science; its success is mostly due to a very fine knowledge of the structure of the class of linear models: similarly, any progress in the understanding of the structure of the class of nonlinear models would be a contribution to a possible theory of nonlinear identification.

These topics are central in control theory, but raise very difficult mathematical questions: static feedback classification is a geometric problem feasible in principle, although describing invariants explicitly is technically very difficult; and conditions for dynamic feedback equivalence and linearization raise unsolved mathematical problems, that make one wonder about decidability [1].

3.3. Optimal control and feedback control, stabilization

3.3.1. Optimal control.

Mathematically speaking, optimal control is the modern branch of the calculus of variations, rather well established and mature [24], [60], [34], [72]. Relying on Hamiltonian dynamics is now prevalent, instead of the standard Lagrangian formalism of the calculus of variations. Also, coming from control engineering, constraints on the control (for instance the control is a force or a torque, naturally bounded) or the state (for example in the shuttle atmospheric re-entry problem there is a constraint on the thermal flux) are imposed; the ones on the state are usual but these on the state yield more complicated necessary optimality conditions and an increased intrinsic complexity of the optimal solutions. Also, in the modern treatment, adapted numerical schemes have to be derived for effective computations of the optimal solutions.

What makes optimal control an applied field is the necessity of computing these optimal trajectories, or rather the controls that produce these trajectories (or, of course, close-by trajectories). Computing a given optimal trajectory and its control as a function of time is a demanding task, with non trivial numerical difficulties: roughly speaking, the Pontryagin Maximum Principle gives candidate optimal trajectories as solutions of a two point boundary value problem (for an ODE) which can be analyzed using mathematical tools from geometric control theory or solved numerically using shooting methods. Obtaining the *optimal synthesis* –the optimal control as a function of the state– is of course a more intricate problem [34], [37]. On the other hand the *value function* –the minimum of the criteria at each point– would give the solution to both questions if it were differentiable, but it is usually not, and is only a viscosity solution of the Hamilton-Jacobi-Bellman (**HJB**) equation (a PDE), whose study requires sophisticated non-smooth and singularity analysis.

[1] Consider the simple system with state $(x, y, z) \in I\!R^3$ and two controls that reads $\dot{z} = (\dot{y} - z\dot{x})^2\dot{x}$ after elimination of the controls; it is not known whether it is equivalent to a linear system, or flat; this is because the property amounts to existence of a formula giving the general solution as a function of two arbitrary functions of time and their derivatives up to a certain order, but no bound on this order is known a priori, even for this very particular example.

These questions are not only academic for minimizing a cost is *very* relevant in many control engineering problems. However, modern engineering textbooks in nonlinear control systems like the “best-seller” [51] hardly mention optimal control, and rather put the emphasis on designing a feedback control, as regular and explicit as possible, satisfying some qualitative (and extremely important!) objectives: disturbance attenuation, decoupling, output regulation or stabilization. Optimal control is sometimes viewed as disconnected from automatic control... we shall come back to this unfortunate point.

3.3.2. Feedback, control Lyapunov functions, stabilization.

A control Lyapunov function **(CLF)** is a function that can be made a Lyapunov function (roughly speaking, a function that decreases along all trajectories, some call this an “artificial potential”) for the closed-loop system corresponding to *some* feedback law. This can be translated into a partial differential relation sometimes called “Artstein’s (in)equation” [27]. There is a definite parallel between a CLF for stabilization, solution of this differential inequation on the one hand, and the value function of an optimal control problem for the system, solution of a HJB equation on the other hand. Now, optimal control is a quantitative objective while stabilization is a qualitative objective; it is not surprising that Artstein (in)equation is very under-determined and has many more solutions than HJB equation, and that it may (although not always) even have smooth ones.

We have, in the team, a longstanding research record on the topic, construction of CLFs and stabilizing feedback controls. This is all the more interesting as our line of research has been pointing in almost opposite directions. [43], [52], [53], [67], [68], [70], [71], [44] insist on the construction of continuous feedback, hence smooth CLFs whereas, on the contrary, [41], [74], [75], [76], [77] proceed with a very fine study of non-smooth CLFs, yet good enough (semi-concave) that they can produce a reasonable discontinuous feedback with reasonable properties.

3.4. Optimal Transport

The study of optimal mass transport problems in the Euclidean or Riemannian setting has a long history which goes from the pioneer works of Monge [65] and Kantorovitch [57] to the recent revival initiated by fundamental contributions due to Brenier [38], [39] and McCann [64]. However, the study of the same transportation problems in the presence of non-holonomic constraints –(like being an admissible trajectory for a control system– is quite new. The first contributors were Ambrosio and Rigot [25] who proved the existence and uniqueness of an optimal transport map for the Monge problem associated with the squared canonical sub-Riemannian distance on the Heisenberg groups. This result was extended later by Agrachev and Lee [22], then by Figalli and Rifford [46] who showed that the Ambrosio-Rigot theorem holds indeed true on many sub-Riemannian manifolds satisfying reasonable assumptions. The problem of existence and uniqueness of an optimal transport map for the squared sub-Riemannian distance on a general complete sub-Riemannian manifold remains open; it is strictly related to the regularity of the sub-Riemannian distance in the product space, and remains a formidable challenge. Generalized notions of Ricci curvatures (bounded from below) in metric spaces have been developed recently by Lott and Villani [61] and Sturm [79], [80]. A pioneer work has been work in the Heisenberg group by Juillet [54] who captured the right notion of curvature in this setting. Agrachev and Lee [23] have elaborated on this work to define new notions of curvatures in three dimensional sub-Riemannian structures. The optimal transport approach happened to be very fruitful in this context. Many things remain to do in a more general context.

One of the results of A. Hindawi’s PhD under the supervision of L. Rifford and J.-B. Pomet was to extend regularity theory established in the Euclidean case to the more general quadratic costs associated with linear optimal control problems (LQR), see [50]. This successful result opens a new range of optimal transport problems associated with cost coming from optimal control problems. We can nowadays expect regularity properties for optimal transport maps associated with reasonable optimal control problems with constraints on the state or on the velocities.

We believe that matching optimal transport with geometric control theory is one originality of our team. We expect interactions in both ways.

3.5. Small controls and conservative systems, averaging

Using averaging techniques to study small perturbations of integrable Hamiltonian systems dates back to H. Poincaré or earlier; it gives an approximation of the (slow) evolution of quantities that are preserved in the non-perturbed system. It is very subtle in the case of multiple periods but more elementary in the single period case, here it boils down to taking the average of the perturbation along each periodic orbit; see for instance [26], [78].

When the "perturbation" is a control, these techniques may be used after deciding how the control will depend on time and state and other quantities, for instance it may be used after applying the Pontryagin Maximum Principle as in [30], [31], [40], [49]. Without deciding the control a priori, an "average control system" may be defined as in [2].

The focus is then on studying into details this simpler "averaged" problem, that can often be described by a Riemannian metric for quadratic costs or by a Finsler metric for costs lime minimum time.

This line of research stemmed out of applications to space engineering, see section 4.1. For orbit transfer in the two-body problem, an important contribution was made by B. Bonnard, J.-B. Caillau and J. Gergaud [31] in explicitly computing the solutions of the average system obtained after applying Pontryagin Maximum Principle to minimizing a quadratic integral cost; this yields an explicit calculation of the optimal control law itself. Studying the Finsler metric issued form the time-minimal case is in progress.

4. Application Domains

4.1. Space engineering, satellites, low thrust control

Space engineering is very demanding in terms of safe and high-performance (for instance in terms of fuel consumption, because only a finte amount of fuel is onborad a sattelite for all its "life") control laws. It is therefore prone to real industrial collaborations.

We are especially interested in trajectory control of space vehicles using their own propulsion devices, outside the atmosphere. Here we discuss "non-local" control problems (in the sense of section 3.1 point 1): in the geocentric case, orbit transfer rather than station keeping; also we do not discuss attitude control.

A space vehicle is subject to
- gravitational forces, from one or more central bodies (the corresponding acceleration is denoted by $F_{\text{grav.}}$ below),
- other forces of small amplitude (the corresponding acceleration is denoted by F_2 below),
- a thrust, the control, produced by a propelling device; it is the $G\,u$ term below; assume for simplicity that control in all directions is allowed, *i.e.* G is an invertible matrix.
In position-velocity coordinates, its dynamics can be written as

$$\ddot{x} \;=\; F_{\text{grav.}}(x,t)\;\Big[+\;F_2(x,\dot{x},t)\Big]\;+\;G(x,\dot{x})\,u\;,\qquad \|u\|\leq u_{\max}. \tag{1}$$

The second term is often neglected in the design of the control. Time-dependence reflects the movement of attracting celestial bodies if there is more than one (see below).

4.1.1. Low thrust

means that $u_{\max}$ is small, or more precisely that the maximum magnitude of $G\,u$ is small with respect to the one of $F_{\text{grav.}}$ (but is usually large compared to F_2). Hence the influence of the control is very weak instantaneously, and trajectories can only be significantly modified by accumulating the effect of this low thrust on a long time. Obviously this is possible only because the free system is somehow conservative. This was "abstracted" in section 3.5.

Why low thrust ? The common principle to all propulsion devices is to eject particles, with some relative speed with respect to the vehicle; conservation of momentum then induces, from the point of view of the vehicle alone, an external force, the “thrust” (and a mass decrease). Ejecting the same mass of particles with a higher relative speed results in a proportionally higher thrust; this relative speed (specific impulse, I_{sp}) is a characteristic of the engine; the higher the I_{sp}, the smaller the mass of particles needed for the same change in the vehicle momentum. Engines with a higher I_{sp} are highly desirable because, for the same maneuvers, they reduce the mass of "fuel" to be taken on-board the satellite, hence leaving more room (mass) for the payload. “Classical” chemical engines use combustion to eject particles, at a somehow limited speed even with very efficient fuel; the more recent electric engines use a magnetic field to accelerate particles and eject them at a considerably higher speed; however electrical power is limited (solar cells), and only a small amount of particles can be accelerated per unit of time, inducing the limitation on thrust magnitude.

Electric engines theoretically allow many more maneuvers with the same amount of particles, with the drawback that the instant force is very small; sophisticated control design is necessary to circumvent this drawback. High thrust engines allow simpler control procedures because they almost allow instant maneuvers (strategies consist in a few burns at precise instants).

4.1.2. Typical problems

Let us mention two.

- *Orbit transfer or rendez-vous*. It is the classical problem of bringing a satellite to its operating position from the orbit where it is delivered by the launcher; for instance from a GTO orbit to the geostationary orbit at a prescribed longitude (one says rendez-vous when the longitude, or the position on the orbit, is prescribed, and transfer if it is free). In equation (1) for the dynamics, $F_{\text{grav.}}$ is the Newtonian gravitation force of the earth (it then does not depend on time); F_2 contains all the terms coming either from the perturbations to the Newtonian potential or from external forces like radiation pressure, and the control is usually allowed in all directions, or with some restrictions to be made precise.
- *Three body problem*. This is about missions in the solar system leaving the region where the attraction of the earth, or another single body, is preponderant. We are then no longer in the situation of a single central body, $F_{\text{grav.}}$ contains the attraction of different planets and the sun. In regions where two central bodies have an influence, say the earth and the moon, or the sun and a planet, the term $F_{\text{grav.}}$ in (1) is the one of the restricted three body problem and dependence on time reflects the movement of the two “big” attracting bodies.

  In the 2003 mission SMART-1, the project was to send a small observation vehicle from the Earth to the Moon using low-thrust propulsion. The vehicle was launched and reached the moon: the goal was achieved; precise reports on the control used can be found in [73]. There was no attempt to minimize fuel consumption, or transfer time, and it is not a surprise that the implemented solution is far from optimal with respect to these criteria. In a recent work in the Dijon team, and in collaboration with J. Gergaud from APO team at IRIT- ENSEEIHT (Toulouse) we have computed optimal trajectories for the Earth-Moon transfer according to the energy minimization problem, the time minimal transfer or the propellant minimization consumption. These results combine geometric optimal control and numerical simulations with adapted numerical codes. The contributions are described in G. Picot Phd thesis, (Dijon November 2010), B. Daoud (Phd thesis defended at Dijon in October 2011) and the numerical codes are developed by O. Cots (Phd thesis to be defended at Dijon in June 2012). Our previous work [29] gives a *feedback* solution for this problem, divided in three phases, the design being based on a two-body model in the first and last phase, where the effect of the primaries is preponderant and the second phase is in the neighborhood of the L2 Lagrange point. This opens perspectives in trajectory optimization; see the recent work [32]. For a state of the art, the reader may refer to [62] or [28].

  An issue for future experimental missions in the solar system is interplanetary flight planning with gravitational assistance. Tackling this global problem, that even contains some combinatorial problems (itinerary), goes beyond the methodology developed here, but the above considerations are a brick in this puzzle.

4.1.3. Properties of the control system.

If there are no restrictions on the thrust direction, i.e., in equation (1), if the control u has dimension 3 with an invertible matrix G, then the control system is "static feedback linearizable", and a fortiori flat, see section 3.2. However, implementing the static feedback transformation would consist in using the control to "cancel" the gravitation; this is obviously impossible since the available thrust is very small. As mentioned in section 3.1, point 3, the problem remains fully nonlinear in spite of this "linearizable" structure [2].

4.1.4. Context for these applications

The geographic proximity of Thales Alenia Space, in conjunction with the "Pole de compétitivité" PEGASE in PACA region is an asset for a long term collaboration between Inria - Sophia Antipolis and Thales Alenia Space (Thales Alenia Space site located in Cannes hosts one of the very few European facilities for assembly, integration and tests of satellites).

B. Bonnard and J.-B. Caillau in Dijon have had a strong activity in optimal control for space, in collaboration with the APO Team from IRIT at ENSEEIHT (Toulouse), and sometimes with EADS, for development of geometric methods in numerical algorithms.

4.2. Quantum Control

The activity of B. Bonnard in quantum control started as a collaboration with D. Sugny (a physicist from ICB) in the ANR project Comoc, localized mainly at the University of Dijon; the problem was the control of the orientation of a molecule using a laser field, with a model that does take into account the dissipation due to the interaction with the environment, molecular collisions for instance. The model is a dissipative generalization of the finite dimensional Schrödinger equation, known as Lindblad equation. In particular we have computed the minimum time control and the minimum energy control for the orientation or a two-level system, using geometric optimal control and adapted numerical methods (shooting and numeric continuation) [36], [35]. The model is a 3-dimensional system depending upon 3 parameters, yielding a very complicated optimal control problem that we have solved for prescribed boundary conditions.

More recently, based on this project, we have reoriented our control activity towards Nuclear Magnetic Resonance (MNR). In MNR medical imaging, the contrast problem is the one of designing a variation of the magnetic field with respect to time that maximizes the difference, on the resulting image, between two different chemical species; this research is conducted with Prof. S. Glaser (TU-München); it was evidenced experimentally that the current contrast of the image is significantly improved by using "our" exact optimal control methods. The model is the Bloch equation for spin $\frac{1}{2}$ particles, that can be interpreted as a sub-case of Lindblad equation for a two-level system; the control problem to solve amounts to driving in minimum time the magnetization vector of the spin to zero (for parameters of the system corresponding to one of the species), and generalizations where such spin $\frac{1}{2}$ particles are coupled: double spin inversion for instance. This research project is supported on the french side by a PEPS INSIS (Control-Image).

4.3. Applications of optimal transport

Optimal Transportation in general has many applications. Image processing, biology, fluid mechanics, mathematical physics, game theory, traffic planning, financial mathematics, economics are among the most popular fields of application of the general theory of optimal transport. Many developments have been made in all these fields recently. Two more specific fields:
- In image processing, since a grey-scale image may be viewed as a measure, optimal transportation has been used because it gives a distance between measures corresponding to the optimal cost of moving densities from one to the other, see e.g. the work of J.-M. Morel and co-workers [66].

[2] However, the linear approximation around *any* feasible trajectory is controllable (a periodic time-varying linear system); optimal control problems will have no singular or abnormal trajectories.

- In representation and approximation of geometric shapes, say by point-cloud sampling, it is also interesting to associate a measure, rather than just a geometric locus, to a distribution of points (this gives a small importance to exceptional "outlier" mistaken points); this was developed in Q. Mérigot's PhD [69] in the GEOMETRICA project-team. The relevant distance between measures is again the one coming from optimal transportation. Such approach, combined with evolution of densities mentioned above, may help to perform robust stabilization of set of particles.

McTAO is not directly involved in applications of transport. A starting point may be Alice Erlinger's PhD, in co-supervision with Ludovic Rifford and Robert McCann from the University of Toronto, that will comprehend applications of optimal transportation to the modeling of markets in economy; it is starting in september, 2012.

Applications that would be *specific to the type of costs that we consider*, i.e. these coming from optimal control are concerned with evolutions of densities under state or velocity constraints. A fluid motion or a crowd movement can be seen as the evolution of a density in a given space. If constraints are given on the directions in which these these densities can evolve, we are in the framework of non-holonomic transport problems. Such approach could be useful to stabilize a large set of particles.

4.4. Applications to some domains of mathematics.

Control theory (in particular thinking in terms of inputs and reachable set) has brought novel ideas and progresses to mathematics. For instance, some problems from classical calculus of variations have been revisited in terms of optimal control and Pontryagin's Maximum Principle [55]; also, closed geodesics for perturbed Riemannian metrics where constructed in [58], [59] with control techniques.

The work in progress [45] is definitely in this line, applying techniques from control to construct some perturbations under constraints of Hamiltonian systems to solve longstanding open questions in dynamical systems. Other work by Rifford and Ruggiero [13] applied successfully geometric control techniques to obtain genericity properties for Hamiltonian systems.

5. New Results

5.1. Optimal control for quantum systems: the contrast problem in NMR

These studies aim at optimizing the contrast in Nuclear Magnetic Resonance imaging using advanced optimal control.

5.1.1. Theoretical aspects

Participants: Bernard Bonnard, John Marriott, Monique Chyba [University of Hawaii], Gautier Picot [University of Hawaii], Olivier Cots, Jean-Baptiste Caillau.

This is done in collaboration with University of Hawaii, and deals with many theoretical aspects of the contrast problem in NMR: analysis of the optimal flow, feedback classification in relation with the relaxation times of the species. This activity has been the object of two publications [5], [4], and a conference talk [14] on feedback classification in the contrast problem, that will be followed by a journal article.

John Marriott will defend his Phd thesis on this topic, august 28, 2013; This will be followed by a two day conference on quantum control systems with applications, supported by a NSF grant and by the Engineering Department (P.E. Crouch).

5.1.2. Experimental aspects

Participants: Bernard Bonnard, Olivier Cots, Dominique Sugny [Univ. de Bourgogne], Steffan Glaser [TU München].

As said in section 4.2, our work on this problem is based on experiments conducted in Prof. S. Glaser in Munich. Experiments using our techniques and measuring the improvement between materials that have an importance in medicine, like oxygenated and de-oxygenated blood have been conducted successfully, see [7], [9].

5.1.3. Numerical aspects

Participants: Bernard Bonnard, Olivier Cots, Jean-Baptiste Caillau.

In december, Pierre Martinon and Mathieu Caeys visited our group. This launhes a collaboration whose objective is to compare the direct and indirect methods in the contrast problem (implemented in the Bocop and Hampath sofwares) and use LMI techniques to get a global bound on the problem (in the contrast problem there are many local optima and the global optimality is a complicated issue)-also O. Cots visited R. Zidani (COMMANDS team) to investigate the use of numerical HJB techniques in the problem. This collaboration will allow to compare in a physical important problem the various available numerical methods in optimal control.

5.2. Conjugate and cut loci computations and applications

Participants: Bernard Bonnard, Olivier Cots, Jean-Baptiste Caillau.

One of the most important results obtained by B. Bonnard and his collaborators concern the explicit computations of conjugate and cut loci on surfaces. This has applications in optimal control to compute the global optimum and in optimal transport where regularity properties of the map in the Monge problem is related to convexity properties of the tangent injectivity domains. This shows also the transverse part of the team: [3] complete the previous results obtained with Rifford [33] ; the paper [20] analyses the conjugate and cut loci in Serret-Andoyer metrics and dynamics of spin particles with Ising coupling, and is a first step towards the computation of conjugate and cut loci on left invariant Riemannian and SR- metrics in S0(3) with applications for instance to the attitude control problem of a spacecraft. The submitted paper [19] concerns the analysis of singular metrics on surfaces in relation with the average orbital transfer problem.

5.3. Averaging in control

Participants: Bernard Bonnard, Helen-Clare Henninger, Jean-Baptiste Pomet.

A reference paper on the construction and properties of an “average control system” [2] is to be published; it is based on Alex Bombrun’s doctoral work (2007). It connects solutions of highly oscillating control systems to those of an average control system, when the frequency of oscillation goes high.

This average system in the case of minimum time for low thrust orbit transfer in the two body problem is currently being explored, in particular the study of its inherent singularities. Helen Henninger’s PhD aims at going much further in this direction and then apply this local study to real missions, possibly in a three-body environment.

5.4. Optimal transport

Participants: Ludovic Rifford, Alice Erlinger, Ahed Hindawi, Alessio Figalli, Bernard Bonnard, Jean-Baptiste Caillau, Lionel Jassionesse, Robert Mc Cann [U. of Toronto].

This year has seen new results or starting directions in many areas of optimal cotrol.

- The very general condition for continuity of the transport map given in [47] motivated exploration of conditions for convexity of the tangent injectivity domain [10], [3] on. Lionel Jassionnesse’s PhD is in part devoted to Ma-Tudinger-Wang tensor that also plays an important role in this matter.
- In Ahed Hindawi’s PhD [1], defended this year, results in optimal transport for sub-Riemannian costs (see the survey [16]) are generalized to costs coming from optimal control problems with quadratic cost and a drift.
- Alice Erlinger’s PhD, joint with University of Toronto is exploring Optimal Transport’s application to modeling in economics

5.5. Applications of control methods to lDynamical systems

Participants: Ludovic Rifford, Ayadi Lazrag, Riccardo Ruggiero, Alessio Figalli, Rafael Ruggiero [PUC, Rio de Janeiro].

Ludovic Rifford and collaborators have been applying, with success, techniques from geometric control theory to open problems in dynamical systems. Mostly on genericity properties and using controllability methods to build suitable perturbations See [11], [13], [21].

Ayadi Lazrag's PhD also deals with such problems

6. Bilateral Contracts and Grants with Industry

6.1. Thales Alenia Space - Inria

"Transfert orbital dans le problème des deux et trois corps avec la technique de propulsion faible".

This contract starts October, 2012 for 3 years. It partially supports Helen Heninger's PhD.

The goal is to improve transfer strategies for guidance of a spacecraft in the gravitation field of one central body (the two-body problem) or two celestial bodies (three-body problem).

6.2. CNES - Inria - UPV/EHU

Contract (reference CNES: RS10/TG-0001-019) ending May, 2013. It involves CNES, University of Bilbao (UPV/EHU) and Inria; its objective is to set up a methodology for testing the stability of nonlinear amplifying devices via frequency optimization techniques.

On the Inria side, this contract concerns McTAO for 25% and APICS project-team for 75%.

7. Partnerships and Cooperations

7.1. Regional Initiatives

The "région *Provence Alpes Côte d'Azur*" partially supports Helen Heninger's PhD. The other part comse from Thales Alenia space, see section 6.1.

7.2. National Initiatives

7.2.1. IMB - Université de Bourgogne, Dijon

The team is officially a common team with University of Nice, but also has very strong links with Université de Bourgogne and IMB (Institute of Mathematics in Burgundy). Bernard Bonnard is currently in leave from Université de Bourgogne; Jean-Baptiste Caillau collaborates actively with us; there is also an active common seminar http://nolot.perso.math.cnrs.fr/JourneesControleTransport2.html .

7.2.2. GCM (ANR project)

This is a four year project ending in 2013, on Geometric Control Methods, Sub-Riemannian Geometry and Applications. It is organized in four "poles" and gathers people from Université du Sud Toulon-Var, Université de Bourgogne (Dijon), École Polytechnique (Paris), Nancy-Université, Université Joseph Fourier (Grenoble 1), Université Paris Sud, ParisTech ENSTA and Université Nice Sophia-Antipolis. Bernard Bonnard and Ludovic Rifford (leader of one pole) are members of this project. More details on the site; http://www-fourier.ujf-grenoble.fr/~charlot/GCM.html.

7.2.3. MOA (GDR)

Bernard Bonnard and Ludovic Rifford participate in this CNRS network on Mathematics of Optimization and Applications. http://gdrmoa.univ-perp.fr/.

7.3. European Initiatives

Collaborations with Major European Organizations

Technische Universität München, Department of Chemistry (Germany).

The applications of optimal control to MNR (see sections 4.2 and 5.1.2) are conducted with the group of Prof. Steffen Glaser in Munich.

7.4. International Initiatives

Inria International Partners

University of Hawaii, Department of Mathematics (U. S. A.)

There is a lon term collaboration on optimal control and control of quantum systems, see mostly section 5.1.1. Besides, Gautier Picot, a former Phd student from Dijon has a temporary position at the Math Department and collaborates with M. Chyba and G. Patterson (second Phd student from M. Chyba) in relation with the Laboratoire d'Astronomie de Paris, to apply the Hampath code to make rendez-vous with quasi-asteroids entering in the solar system near the L1-Lagrange point, in the continuation of the work developed by G. Picot and B. Daoud. This collaboration is very active and has to be emphasized.

University of Toronto, Department of Mathematics (Canada)

Optimal Transport. Alice Erlinger's PhD is co-supervised by Ludovic Rifford and John Mc Cann from University of Toronto. See section 5.4.

7.5. International Research Visitors

7.5.1. Visits of International Scientists

Alessio Figalli, from University of Texas at Austin, visited twice, for a total of slightly more than a month.

7.5.2. Visits to International Teams

There is a strong collaboration with the control group in the University of Hawaii around M. Chyba. B. Bonnard visited the group twice in 2012-2013 (a total of 3 months). The purpose of the collaboration is to study the aspects of the contrast problem in Nuclear Magnetic Resonance, see section 5.1.1.

8. Dissemination

8.1. Scientific Animation

Bernard Bonnard and Ludovic Rifford belong to the editorial board of Journal of Dynamical and Control Systems.

All members of the team are active reviewers in journals of the field.

The team organized two one-day seminars:
- June 19 in Sophia ANtipolis, invited speakers: Richard Epenoy (CNES, Toulouse) and Vincent Andrieu (LAGEP, Lyon),

- September 24, in Dijon http://nolot.perso.math.cnrs.fr/JourneesControleTransport.html.
To be continued in march, 2013 in dijon and in may, 2013 in Nice.

8.2. Community service within Inria

J.-B. Pomet is the president of the “Commission de Suivi Doctoral”, and in charge of “formation par la recherche”. This includes organising local visits for students, organising PhD candidates selection, managing PhD students working at Inria Sophia (that are from two different “écoles doctorales” from Université de Nice, not counting these in Montpellier).

8.3. Teaching - Supervision - Juries

8.3.1. Teaching

Licence: L. Rifford, “Analyse I” and “Option Maths”, 60 hours (equiv TD), Univ. de Nice Sophia Antipolis

8.3.2. Supervision

PhD: Ahed Hindawi, *Transport Optimal en Théorie du Contrôle*, Université de Nice Sophia Antipolis, defended June 27, 2012, advisors: Ludovic Rifford and Jean-Baptiste Pomet, see [1].

PhD in progress: Alice Erlinger, subject: *Economics and Optimal Transport*, Université de Nice Sophia Antipolis, started october, 2012, advisor: Ludovic Rifford.

PhD in progress: Helen Heninger, subject: , Université de Nice Sophia Antipolis, started october, 2012, advisors: Bernard Bonnard and Jean-Baptiste Pomet.

PhD in progress: Ayadi Lazrag, subject: *Control methods in dynamical systems*, Université de Nice Sophia Antipolis, started october, 2011, advisor: Ludovic Rifford.

PhD in progress: Lionel Jassionnesse, subject: *Convexité du domaine d’injectivité tangent sur le surfaces et transport optimal*, Université de Bourgogne, started october, 2010, advisor: Bernard Bonnard.

PhD in progress: John Marriott, subject: *Optimal control and the contrast problem in RMN*, University of Hawaii, started october, 2010, advisors: Monique Chyba and Bernard Bonnard, provisional defense date: August 28, 2013.

MsC: Alice Erlinger, *Problèmes de régularité en théorie du Transport Optimal*, Université de Nice Sophia Antipolis, supervisor: Ludovic Rifford.

MsC: Hamza Agli, *Etude numérique du moyenné pour le transfert orbital plan*, ENSEEIHT, supervisors: Jean-Baptiste Pomet and Bernard Bonnard.

MsC, 1st year: Ciro Duran-Santilli, *Flatness in control systems*, Ecole Polytechnique, supervisor: Jean-Baptiste Pomet.

MsC, 1st year: Igor Pontes-Duff-Pereira, *Transfert optimal d’un Satellite - Moyennation pour le temps minimum*, Ecole Polytechnique, supervisors: Jean-Baptiste Pomet and Bernard Bonnard.

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Articles in International Peer-Reviewed Journals

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