

Optimal control with discontinuous running cost: eikonal equation and shape-from-shading

Pierpaolo Soravia

Dipartimento di Matematica Pura e Applicata, Università di Padova ¹

Abstract

We consider a class of Hamilton-Jacobi equations with discontinuous coefficients that contains as examples the eikonal equation with discontinuous refraction index, or the Hamilton-Jacobi equation of shape-from-shading with discontinuous intensity function. In general the Dirichlet problem for such equations does not have unique solution, however we can characterize the minimal and maximal solution and, under appropriate compatibility conditions, prove existence of a unique solution in the sense of viscosity solutions.

1 Introduction

In this paper we want to discuss the following Dirichlet problem for the Bellman equation of optimal control

$$\begin{aligned} \lambda u(x) + \sup_{\alpha \in \mathcal{A}} \{-f(x, \alpha) \cdot Du(x) - h(x, \alpha)\} &= g(x), \\ x \in \Omega \\ u(x) = 0, & \quad x \in \partial\Omega \end{aligned} \quad (1.1)$$

where Ω is an open subset of \mathbb{R}^N , $\lambda \geq 0$ and $g : \Omega \rightarrow [0, +\infty[$ will always be locally bounded and Borel measurable, hence possibly discontinuous. In the study of (1.1) it is fundamental to consider the following control system

$$\begin{cases} \dot{y}(t) = f(y(t), \alpha(t)) \\ y(0) = x \end{cases} \quad (1.2)$$

where $f : \mathbb{R}^N \times \mathcal{A} \rightarrow \mathbb{R}^N$ is a continuous function and \mathcal{A} is a compact subset of a metric space. In order to simplify the assumptions and avoid some technical difficulties, the set of admissible controls \mathcal{A} in (1.2) is chosen to be the set of relaxed controls, i.e.

$$\mathcal{A} = \{\alpha(\cdot) : \alpha : \mathbb{R}_+ \rightarrow P(D) \text{ measurable}\},$$

and $P(D)$ is the set of Radon probability measures on $D \subset \mathbb{R}^N$ a compact set (see the book by Warga [11]). Optimal control problems for the system (1.2) will be defined with respect to a running cost function $h : \mathbb{R}^N \times \mathcal{A} \rightarrow \mathbb{R}$ and the functional

$$J(t, x, \alpha) = \int_t^\infty e^{-\lambda s} [h(y_s(s), \alpha(s)) + g(y_s(s))] ds. \quad (1.3)$$

¹via Belzoni 7, 35131 Padova, Italy. Partially supported by ERC-TMR network project "Viscosity Solutions and their Applications". email: soravia@math.unipd.it

In the following $h : \mathbb{R}^N \times \mathcal{A} \rightarrow [0, +\infty[$ will be supposed to be at least continuous. In fact, some more stringent assumptions are needed on the data h, f , and throughout the paper we will suppose that, for all $R > 0$, they satisfy

$$\begin{cases} |f(x, \alpha) - f(y, \alpha)| \leq L|x - y|, & x, y \in \mathbb{R}^N, \alpha \in \mathcal{A}, \\ |h(x, \alpha) - h(y, \alpha)| \leq L_R|x - y|, & |x|, |y| \leq R, \alpha \in \mathcal{A}, \end{cases} \quad (1.4)$$

where L, L_R, C are positive constants. As a consequence, for given $\alpha \in \mathcal{A}$ and $x \in \mathbb{R}^N$, there is a unique global solution of (1.2), that we denote by $y_\alpha(t; \alpha) \equiv y(\cdot)$.

A motivation for studying equation (1.1) with discontinuous coefficient g can be found in the applications. For instance in geometric optics, to describe the propagation of light, the eikonal equation appears

$$\sum_{i,j=1}^N a_{ij}(x) u_{x_i x_j}(x) = g(x),$$

where $u = \sigma x^t$ and g has the meaning of the refraction index of the medium. As well known, refraction law applies across surfaces of discontinuity of g . Another example can be found in image processing and the shape-from-shading model. In this case we come up with the equation

$$\sqrt{1 + |Dw(x)|^2} = \frac{1}{f(x)} (\equiv g(x))$$

and the object to reconstruct is the graph of the unknown function w . In this case $f(x) \in]0, 1]$ represents the intensity of light reflected by the object and it is discontinuous when the object has ledges. With a bit of convex analysis, both equations above can be rewritten in the form (1.1). Further motivation appears directly in control theory when discontinuous functions are used to represent targets (in this case g will be a characteristic function) or state constraints (when g is instead an indicator functions).

Being nonsmooth in general, solutions of (1.1) will be defined in the sense of the theory of viscosity solutions. An important point to analyze then comes up. Indeed with this notion of solution, when an equation has a discontinuous coefficient, we cannot interpret g in a pointwise sense. This is due to the fact that value functions

Discontinuous Optimal Control

Malo L. J. Hautus



Discontinuous Optimal Control:

Existence of Discontinuous Optimal Solutions for Infinite Horizon Problems in Optimal Control and Calculus of Variations Zengxiang Tong,1991 Discontinuous and Optimal Control Irmgard Flügge-Lotz,1968 *Convex Optimal Control Problems with Discontinuous Dynamics* J. M. Murray,1990

Nonsmooth and Discontinuous Problems of Control and Optimization (NDPCO'98) Valentin Dmitrievich Batukhtin,Faina Mikhaïlovna Kirillova,V. I.

Ukhobotov,International Federation of Automatic Control,1999-01-01 This workshop was divided into three sections optimal control problems extremal problems of finite measures and applications The section on optimal control contains papers on differential gains synthesis evaluation and system control under conditions of uncertain information stability and qualitative optimal control problems The second section describes problems of finite measures under extreme conditions and numerical methods for solving such problems for non smooth and discontinuous functions The third section contains applications

Impulsive Control in Continuous and Discrete-Continuous Systems Boris M. Miller,Evgeny Y.

Rubinovich,2012-12-06 Impulsive Control in Continuous and Discrete Continuous Systems is an up to date introduction to the theory of impulsive control in nonlinear systems This is a new branch of the Optimal Control Theory which is tightly connected to the Theory of Hybrid Systems The text introduces the reader to the interesting area of optimal control problems with discontinuous solutions discussing the application of a new and effective method of discontinuous time transformation With a large number of examples illustrations and applied problems arising in the area of observation control this book is excellent as a textbook or reference for a senior or graduate level course on the subject as well as a reference for researchers in related fields Optimization of Dynamical Systems with Impulse Controls and Shocks Boris Miller,Evgeny

Rubinovich,2024-09-19 This text explores the state of the art in the rapidly developing theory of impulse control and introduces the theory of singular space time transformations a new method for studying shock mechanical systems Two approaches in the theory of impulse control are presented The first more traditional approach defines the impulsive action as a discontinuity of phase coordinates depending on the current time the state preceding the action and its magnitude The second requires the use of modern methods for describing dynamical systems differential equations with measures The impulse is treated as an idealization of a very short action of high magnitude which produces an almost abrupt change of phase coordinates The relation between these two approaches is also discussed and several applications both traditional and emerging are considered This text is intended for graduate students and researchers in control engineering and optimal control theory for dynamical systems Readers are assumed to be familiar with the theory of ODEs optimal control and functional analysis though an appendix is included that covers many of the necessary mathematical concepts **Modeling,**

Estimation and Control of Systems with Uncertainty G.B. DiMasi,A. Gombani,A.B. Kurzhanski,2013-03-12 This volume contains the papers that have been presented at the Conference on Modeling and Control of Uncertain Systems held in

Sopron Hungary on September 3-7 1990 organised within the framework of the activities of the System and Decision Sciences Program of IIASA the International Institute for Applied Systems Analysis The importance of the subject has drawn the attention of researchers all over the world since several years In fact in most actual applications the knowledge about the system under investigation presents aspects of uncertainty due to measurement errors or poor understanding of the relevant underlying mechanisms For this reason models that take into account these intrinsic uncertainties have been used and techniques for the analysis of their behavior as well as for their estimation and control have been developed The main ways to deal with uncertainty consist in its description by stochastic processes or in terms of set valued dynamics and this volume collects relevant contributions in both directions However in order to avoid undesirable distinctions between these approaches but on the contrary to stress the unity of ideas we decided to organize the papers according to the alphabetical order of their authors We should like to take this opportunity to thank IIASA for supporting the Conference and the Hungarian National Member Organization for the kind hospitality in Sopron Finally we would like to express our gratitude to Ms Donna Huchthausen for her valuable secretarial assistance Vienna February 20 1991 GIOVANNI B Chaos and Complex Systems Stavros G. Stavrinos, Santo Banerjee, Suleyman Hikmet Caglar, Mehmet Ozer, 2013-03-19 Complexity Science and Chaos Theory are fascinating areas of scientific research with wide ranging applications The interdisciplinary nature and ubiquity of complexity and chaos are features that provides scientists with a motivation to pursue general theoretical tools and frameworks Complex systems give rise to emergent behaviors which in turn produce novel and interesting phenomena in science engineering as well as in the socio economic sciences The aim of all Symposia on Chaos and Complex Systems CCS is to bring together scientists engineers economists and social scientists and to discuss the latest insights and results obtained in the area of corresponding nonlinear system complex chaotic behavior Especially for the 4th International Interdisciplinary Chaos Symposium on Chaos and Complex Systems which took place April 29th to May 2nd 2012 in Antalya Turkey the scope of the symposium had been further enlarged so as to encompass the presentation of work from circuits to econophysics and from nonlinear analysis to the history of chaos theory The corresponding proceedings collected in this volume address a broad spectrum of contemporary topics including but not limited to networks circuits systems biology evolution and ecology nonlinear dynamics and pattern formation as well as neural psychological psycho social socio economic management complexity and global systems Multiple Shooting and Time Domain Decomposition Methods Thomas Carraro, Michael Geiger, Stefan Körkel, Rolf Rannacher, 2015-10-26 This book offers a comprehensive collection of the most advanced numerical techniques for the efficient and effective solution of simulation and optimization problems governed by systems of time dependent differential equations The contributions present various approaches to time domain decomposition focusing on multiple shooting and parareal algorithms The range of topics covers theoretical analysis of the methods as well as their algorithmic formulation and guidelines for practical implementation Selected examples show

that the discussed approaches are mandatory for the solution of challenging practical problems The practicability and efficiency of the presented methods is illustrated by several case studies from fluid dynamics data compression image processing and computational biology giving rise to possible new research topics This volume resulting from the workshop Multiple Shooting and Time Domain Decomposition Methods held in Heidelberg in May 2013 will be of great interest to applied mathematicians computer scientists and all scientists using mathematical methods [An Introduction to Optimal Control Theory](#) Onésimo Hernández-Lerma, Leonardo R. Laura-Guarachi, Saul Mendoza-Palacios, David González-Sánchez, 2023-02-21 This book introduces optimal control problems for large families of deterministic and stochastic systems with discrete or continuous time parameter These families include most of the systems studied in many disciplines including Economics Engineering Operations Research and Management Science among many others The main objective is to give a concise systematic and reasonably self contained presentation of some key topics in optimal control theory To this end most of the analyses are based on the dynamic programming DP technique This technique is applicable to almost all control problems that appear in theory and applications They include for instance finite and infinite horizon control problems in which the underlying dynamic system follows either a deterministic or stochastic difference or differential equation In the infinite horizon case it also uses DP to study undiscounted problems such as the ergodic or long run average cost After a general introduction to control problems the book covers the topic dividing into four parts with different dynamical systems control of discrete time deterministic systems discrete time stochastic systems ordinary differential equations and finally a general continuous time MCP with applications for stochastic differential equations The first and second part should be accessible to undergraduate students with some knowledge of elementary calculus linear algebra and some concepts from probability theory random variables expectations and so forth Whereas the third and fourth part would be appropriate for advanced undergraduates or graduate students who have a working knowledge of mathematical analysis derivatives integrals and stochastic processes *Optimality Conditions for Convex State Constrained Optimal Control Problems with Discontinuous States* Anton Schiela, 2007 **Discrete-Time Optimal Control and Games on Large Intervals** Alexander J. Zaslavski, 2017-05-03 Devoted to the structure of approximate solutions of discrete time optimal control problems and approximate solutions of dynamic discrete time two player zero sum games this book presents results on properties of approximate solutions in an interval that is independent lengthwise for all sufficiently large intervals Results concerning the so called turnpike property of optimal control problems and zero sum games in the regions close to the endpoints of the time intervals are the main focus of this book The description of the structure of approximate solutions on sufficiently large intervals and its stability will interest graduate students and mathematicians in optimal control and game theory engineering and economics This book begins with a brief overview and moves on to analyze the structure of approximate solutions of autonomous nonconcave discrete time optimal control Lagrange problems Next the structures of

approximate solutions of autonomous discrete time optimal control problems that are discrete time analogs of Bolza problems in calculus of variations are studied The structures of approximate solutions of two player zero sum games are analyzed through standard convexity concavity assumptions Finally turnpike properties for approximate solutions in a class of nonautonomous dynamic discrete time games with convexity concavity assumptions are examined *Optimal Control of Differential Systems with Discontinuous Right-hand Side* Malo L. J. Hautus,1970 **Discrete and Continuous Dynamical Systems** ,2007 *Dynamics of Continuous, Discrete & Impulsive Systems* ,2005 **Developments in Model-Based Optimization and Control** Sorin Olaru,Alexandra Grancharova,Fernando Lobo Pereira,2015-12-23 This book deals with optimization methods as tools for decision making and control in the presence of model uncertainty It is oriented to the use of these tools in engineering specifically in automatic control design with all its components analysis of dynamical systems identification problems and feedback control design Developments in Model Based Optimization and Control takes advantage of optimization based formulations for such classical feedback design objectives as stability performance and feasibility afforded by the established body of results and methodologies constituting optimal control theory It makes particular use of the popular formulation known as predictive control or receding horizon optimization The individual contributions in this volume are wide ranging in subject matter but coordinated within a five part structure covering material on complexity and structure in model predictive control MPC collaborative MPC distributed MPC optimization based analysis and design and applications to bioprocesses multivehicle systems or energy management The various contributions cover a subject spectrum including inverse optimality and more modern decentralized and cooperative formulations of receding horizon optimal control Readers will find fourteen chapters dedicated to optimization based tools for robustness analysis and decision making in relation to feedback mechanisms fault detection for example and three chapters putting forward applications where the model based optimization brings a novel perspective Developments in Model Based Optimization and Control is a selection of contributions expanded and updated from the Optimisation based Control and Estimation workshops held in November 2013 and November 2014 It forms a useful resource for academic researchers and graduate students interested in the state of the art in predictive control Control engineers working in model based optimization and control particularly in its bioprocess applications will also find this collection instructive **Infinite-Horizon Optimal Control in the Discrete-Time Framework** Joël Blot,Naïla Hayek,2013-11-08 In this book the authors take a rigorous look at the infinite horizon discrete time optimal control theory from the viewpoint of Pontryagin s principles Several Pontryagin principles are described which govern systems and various criteria which define the notions of optimality along with a detailed analysis of how each Pontryagin principle relate to each other The Pontryagin principle is examined in a stochastic setting and results are given which generalize Pontryagin s principles to multi criteria problems Infinite Horizon Optimal Control in the Discrete Time Framework is aimed toward researchers and PhD students in various scientific fields such as mathematics applied

mathematics economics management sustainable development such as of fisheries and of forests and Bio medical sciences who are drawn to infinite horizon discrete time optimal control problems

Dynamic Optimization of a Singular-nonlinear System with a Discontinuous Optimal Control Paul George Gothier,1981

Discrete-Time Inverse Optimal Control for Nonlinear Systems Edgar N. Sanchez,Fernando Ornelas-Tellez,2013-04-08

Discrete Time Inverse Optimal Control for Nonlinear Systems proposes a novel inverse optimal control scheme for stabilization and trajectory tracking of discrete time nonlinear systems This avoids the need to solve the associated Hamilton Jacobi Bellman equation and minimizes a cost functional resulting in a more efficient controller Design More Efficient Controllers for Stabilization and Trajectory Tracking of Discrete Time Nonlinear Systems The book presents two approaches for controller synthesis the first based on passivity theory and the second on a control Lyapunov function CLF The synthesized discrete time optimal controller can be directly implemented in real time systems The book also proposes the use of recurrent neural networks to model discrete time nonlinear systems Combined with the inverse optimal control approach such models constitute a powerful tool to deal with uncertainties such as unmodeled dynamics and disturbances Learn from Simulations and an In Depth Case Study The authors include a variety of simulations to illustrate the effectiveness of the synthesized controllers for stabilization and trajectory tracking of discrete time nonlinear systems An in depth case study applies the control schemes to glycemic control in patients with type 1 diabetes mellitus to calculate the adequate insulin delivery rate required to prevent hyperglycemia and hypoglycemia levels The discrete time optimal and robust control techniques proposed can be used in a range of industrial applications from aerospace and energy to biomedical and electromechanical systems Highlighting optimal and efficient control algorithms this is a valuable resource for researchers engineers and students working in nonlinear system control

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