

Sensitivity Analysis for Linear Systems based on Reachability Sets

Daniel Silvestre, Paulo Rosa, João P. Hespanha, Carlos Silvestre

Abstract—The problem of deciding which inputs in a model influence the most the state or output is often of practical importance, especially in the cases in which the system can be over-parameterized. In this context, a designer is required to perform sensitivity analyses so as to select which inputs are the most relevant to the problem at hand and remove those with smaller or no impact. In this paper, we tackle this issue by constructing the exact reachable set of a linear system that relates the inputs with the state of that system. By means of projections and solutions of linear optimization programs, we are able to assess which inputs drive the most the state or the output of a linear system. Illustrative examples are presented in order to provide insights on the proposed method.

I. INTRODUCTION

Sensitivity analysis has been a long standing research topic addressed by multiple techniques. The problem relates to the identification of the inputs causing the largest variability of the state/output of a model. Different techniques have been proposed and lengthy discussions are presented in the books [1], [2], [3], while further information can be found in the review articles [4], [5].

The sensitivity analysis is typically conducted by defining a model, assigning probability density functions to each input, generating inputs, and assessing the output of the model. The view in this paper is centered on a worst-case scenario where, instead of considering the probability information, the sensitivity analysis is driven by the most extreme impact each input can have on the state/output of the model.

The main motivation of considering the sensitivity of a model is to find which inputs are the most successful in achieving a control strategy or which contribute the most to the outputs of the system. We envisage as particular case of interest a formation of agents with their own dynamics.

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Which nodes contribute the most for a final decision depends on their individual dynamics but also on the topology. The techniques designed for sensitivity analysis in this paper aim to answer the question of which inputs should be used or, in the opposite direction, which elements are the ones that can cause the final state to drift the most in the worst-case scenario. In a smart grid environment, such techniques would be useful to determine what is the worst operating point if one of the inputs is compromised or faulty following the concepts in [6].

The first group of methods that has been used to address the problem can be categorized as *direct methods* or *differential sensitivity analysis* because the model equations are differentiated (similarly computed the difference equations) with respect to the inputs. The impact of each input can then be described by these derivatives. Many formulations exist for continuous-time models that are surveyed in [5] and that have been more recently developed in the works [7], [8], and also for the discrete-time case in [9], by exploiting the case of a Kalman filter.

The variance-based methods in [7], [8] determine the sensitivity of each input by computing the variance on the output caused by the inputs through an approximation model, by using Taylor series expansions. These methods have the advantage of considering a general nonlinear model of the type $Y = f(X_1, \dots, X_k)$, whereas the focus of this paper is on the linear case and with the main difference that only the variance is being used to compute the sensitivity. Our proposal is to leverage on recent developments in reachability sets computational approaches as a measurement of the uncertainty or variability caused by a given input.

Additional methods exist that estimate the variance using for example FAST (Fourier Amplitude Sensitivity Test) [10], which resorts to the Fourier series to represent the ANOVA decomposition of the nonlinear model. Similarly, some also use the WASP (Walsh Amplitude Sensitivity Procedure) [11]. The main objective is to compute the ratio between the variance of Y given X for all possible values of X and the variance of Y as a measure of the sensitivity. Examples range from [12], in which a transformation is used to reduce the computational cost, to [13] for a general sensitivity analysis independent of the model and also [14] where different methods based on variance using FAST are compared with direct methods. All such techniques consider the sensitivity from a variance point-of-view, trying to identify which inputs cause the most variability. Another interesting question arises when focusing on the support of the distribution where finding which input generates the worst possible scenario among all the plant inputs.

In [15], the authors show how the sensitivity can also be

Sensitivity Analysis In Linear Systems

Loren Kerry Platzman, Michael Athans



Sensitivity Analysis In Linear Systems:

Sensitivity Analysis in Linear Systems Assem Deif, 2012-12-06 A text surveying perturbation techniques and sensitivity analysis of linear systems is an ambitious undertaking considering the lack of basic comprehensive texts on the subject A wide ranging and global coverage of the topic is as yet missing despite the existence of numerous monographs dealing with specific topics but generally of use to only a narrow category of people In fact most works approach this subject from the numerical analysis point of view Indeed researchers in this field have been most concerned with this topic although engineers and scholars in all fields may find it equally interesting One can state without great exaggeration that a great deal of engineering work is devoted to testing systems sensitivity to changes in design parameters As a rule high sensitivity elements are those which should be designed with utmost care On the other hand as the mathematical modelling serving for the design process is usually idealized and often inaccurately formulated some unforeseen alterations may cause the system to behave in a slightly different manner Sensitivity analysis can help the engineer innovate ways to minimize such system discrepancy since it starts from the assumption of such a discrepancy between the ideal and the actual system

Structural Sensitivity Analysis and Optimization 1 Kyung K. Choi, Nam-Ho Kim, 2004-12-08 Extensive numerical methods for computing design sensitivity are included in the text for practical application and software development The numerical method allows integration of CAD FEA DSA software tools so that design optimization can be carried out using CAD geometric models instead of FEA models This capability allows integration of CAD CAE CAM so that optimized designs can be manufactured effectively Performance Sensitivity Analysis for Linear Systems with Stable Feedback Perturbations Gao Zhiwei, 2018 The performance sensitivity of linear systems with stable feedback perturbations both on the plant and the feedback controller is discussed Using norm the sufficient condition for the robust stability is derived Also the upper bounds for the sensitivity function matrix and the closed loop transfer function matrix of the perturbed system are presented

Explicit Cost Sensitivity Analysis for Linear Systems with Quadratic Criteria Loren Kerry Platzman, Michael Athans, 1974 **Multiparameter Sensitivity Analysis for Linear Systems** Ranendra Narayan Biswas, Ernest S. Kuh, 1965

System Sensitivity Analysis Jose Behar Cruz, 1973 Theory of Sensitivity in Dynamic Systems Mansour Eslami, 2013-11-09 This book provides a comprehensive treatment of the development and present state of the theory of sensitivity of dynamic systems It is intended as a textbook and reference for researchers and scientists in electrical engineering control and information theory as well as for mathematicians The extensive and structured bibliography provides an overview of the literature in the field and points out directions for further research *Mathematical Computation with Maple V: Ideas and Applications* Thomas Lee, 2012-12-06 Developments in both computer hardware and Perhaps the greatest impact has been felt by the software over the decades have fundamentally education community Today it is nearly changed the way people solve problems impossible to find a college or university that has Technical professionals have greatly

benefited not introduced mathematical computation in from new tools and techniques that have allowed some form into the curriculum Students now them to be more efficient accurate and creative have regular access to the amount of in their work computational power that were available to a very exclusive set of researchers five years ago This Maple V and the new generation of mathematical has produced tremendous pedagogical computation systems have the potential of challenges and opportunities having the same kind of revolutionary impact as high level general purpose programming Comparisons to the calculator revolution of the languages e g FORTRAN BASIC C 70 s are inescapable Calculators have application software e g spreadsheets extended the average person s ability to solve Computer Aided Design CAD and even common problems more efficiently and calculators have had Maple V has amplified our arguably in better ways Today one needs at mathematical abilities we can solve more least a calculator to deal with standard problems problems more accurately and more often In life budgets mortgages gas mileage etc specific disciplines this amplification has taken For business people or professionals the excitingly different forms

Advanced Design of Mechanical Systems: From Analysis to Optimization Jorge A.C. Ambrosio, Peter Eberhard, 2009-11-25 Multibody systems are used extensively in the investigation of mechanical systems including structural and non structural applications It can be argued that among all the areas in solid mechanics the methodologies and applications associated to multibody dynamics are those that provide an ideal framework to aggregate different disciplines This idea is clearly reflected e g in the multidisciplinary applications in biomechanics that use multibody dynamics to describe the motion of the biological entities in finite elements where multibody dynamics provides werful tools to describe large motion and kinematic restrictions between system components in system control where the methodologies used in multibody dynamics are the prime form of describing the systems under analysis or even in many plications that involve fluid structure interaction or aero elasticity The development of industrial products or the development of analysis tools using multibody dynamics methodologies requires that the final result of the devel ments are the best possible within some limitations i e they must be optimal Furthermore the performance of the developed systems must either be relatively insensitive to some of their design parameters or be sensitive in a controlled manner to other variables Therefore the sensitivity analysis of such systems is fundamental to support the decision making process This book presents a broad range of tools for designing mechanical systems ranging from the kinematic and dynamic analysis of rigid and flexible multibody systems to their advanced optimization

Sensitivity Analysis of Suboptimal Controllers of Linear Systems Derived from Models of Lower Dimension Philippe Charles Pezet, 1974

Fundamentals of Ordinary Differential Equations Mohit Chatterjee, 2025-02-20 Fundamentals of Ordinary Differential Equations is a comprehensive guide designed for students researchers and professionals to master ODE theory and applications We cover essential principles advanced techniques and practical applications providing a well rounded resource for understanding differential equations and their real world impact The book offers a multifaceted approach from basic principles to advanced concepts catering to fields like

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Murray-Smith,2012-12-06 obtained by simulation more quickly effec Computer simulation of dynamic systems is a topic which is growing steadily in importance tively and cheaply than by experimentation and testing of the real system System perfor in the physical sciences engineering biology and medicine The reasons for this trend mance can also be investigated using simula relate not only to the steadily increasing tion for a much wider range of conditions than can be contemplated for the real system power of computers and the rapidly falling costs of hardware but also to the availability because of operating constraints or safety of appropriate software tools in the form of requirements Similar factors can apply in simulation languages Problem oriented lan other fields such as biomedical systems guages of this kind assist those who are not engineering specialists in computational methods to trans System simulation using digital computers can relate either to models based on continu late a mathematical description into a simula tion program in a simple and straightforward ous variables or to discrete event descriptions fashion They can also provide useful diag Continuous system simulation techniques are applied to systems described by sets of differ nostic information when difficulties are encountered Therefore a simulation lan ential equations and algebraic equations **Fundamentals of Numerical Methods & Analysis** Dr. Swati

Maheshwari , Dr. Asha Rani , Dr. Rohit Kumar, Dr. Anita Dahiya,2025-08-26 Fundamentals of Numerical Methods Analysis provides a comprehensive introduction to essential computational techniques for solving mathematical problems Covering error analysis root finding interpolation numerical integration differentiation and differential equations the book bridges theory with practical applications It equips students and researchers with robust problem solving tools emphasizing accuracy stability and efficiency in numerical computations *Systems Analysis and Simulation in Ecology* Bernard C.

Patten,2013-09-11 Systems Analysis and Simulation in Ecology Volume IV continues the organization begun in Volume III to document a meeting Modeling and Analysis of Ecosystems held at the University of Georgia on 1 3 March 1973 Several chapters are considerably expanded over their original concept and several others are included which were not part of the symposium The book is organized into five parts Part I contains chapters on estuarine marine ecosystems Part II presents models of several terrestrial ecosystems Part III has chapters devoted to human aspects of ecology Part IV considers special problems of ecosystem modeling namely linear versus nonlinear models aggregation and validation Part V the most extensive

section describes theory in ecosystem analysis The book s chapters demonstrate the current scope of systems ecology its past and present emphasis on parts and mechanisms in simulation modeling and its movement toward systems analysis and new more formal consideration of wholes in theory They make clear that although the systems approach is young in ecology it has substantially enriched the science both methodologically and conceptually [Analysis of Dynamic Psychological Systems](#) H.E. Fitzgerald,R.L. Levine,2013-03-08 Drawing on sources from a wide range of disciplines this first volume of a two volume tutorial on systems theory focuses on non linear dynamical techniques for analysis of feedback processes information flow decision making control theory and modeling of human behavioral systems [Orthogonal Functions in Systems and Control](#) Kanti Bhushan Datta,B. M. Mohan,1995 This book provides a systematic and unified approach to the analysis identification and optimal control of continuous time dynamical systems via orthogonal polynomials such as Legendre Laguerre Hermite Tchebycheff Jacobi Gegenbauer and via orthogonal functions such as sine cosine block pulse and Walsh This is the first book devoted to the application of orthogonal polynomials in systems and control establishing the superiority of orthogonal polynomials to other orthogonal functions *Control Theory of Digitally Networked Dynamic Systems* Jan Lunze,2013-07-06 The book gives an introduction to networked control systems and describes new modeling paradigms analysis methods for event driven digitally networked systems and design methods for distributed estimation and control Networked model predictive control is developed as a means to tolerate time delays and packet loss brought about by the communication network In event based control the traditional periodic sampling is replaced by state dependent triggering schemes Novel methods for multi agent systems ensure complete or clustered synchrony of agents with identical or with individual dynamics The book includes numerous references to the most recent literature Many methods are illustrated by numerical examples or experimental results *The Finite Element Method for Engineers* Kenneth H. Huebner,Donald L. Dewhirst,Douglas E. Smith,Ted G. Byrom,2001-09-07 A useful balance of theory applications and real world examples The Finite Element Method for Engineers Fourth Edition presents a clear easy to understand explanation of finite element fundamentals and enables readers to use the method in research and in solving practical real life problems It develops the basic finite element method mathematical formulation beginning with physical considerations proceeding to the well established variation approach and placing a strong emphasis on the versatile method of weighted residuals which has shown itself to be important in nonstructural applications The authors demonstrate the tremendous power of the finite element method to solve problems that classical methods cannot handle including elasticity problems general field problems heat transfer problems and fluid mechanics problems They supply practical information on boundary conditions and mesh generation and they offer a fresh perspective on finite element analysis with an overview of the current state of finite element optimal design Supplemented with numerous real world problems and examples taken directly from the authors experience in industry and research The Finite Element Method for Engineers Fourth Edition gives readers the real insight needed to apply the method to challenging

problems and to reason out solutions that cannot be found in any textbook

Modelling and Simulation of Integrated Systems in Engineering D J Murray-Smith, 2012-05-30 This book places particular emphasis on issues of model quality and ideas of model testing and validation Mathematical and computer based models provide a foundation for explaining complex behaviour decision making engineering design and for real time simulators for research and training Many engineering design techniques depend on suitable models assessment of the adequacy of a given model for an intended application is therefore critically important Generic model structures and dependable libraries of sub models that can be applied repeatedly are increasingly important Applications are drawn from the fields of mechanical aeronautical and control engineering and involve non linear lumped parameter models described by ordinary differential equations Focuses on issues of model quality and the suitability of a given model for a specific application Multidisciplinary problems within engineering feature strongly in the applications The development and testing of nonlinear dynamic models is given very strong emphasis

Applied Mechanics Reviews ,1973

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