

# ALGEBRAIC ANALYSIS OF CONTROL SYSTEMS DEFINED BY PARTIAL DIFFERENTIAL EQUATIONS

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The present chapter contains the material taught within the module P2 of EAP 2004. The purpose of this intensive course is first to provide an introduction to “algebraic analysis”. This fashionable though quite difficult domain of pure mathematics today has been pioneered by V.P. Palamodov, M. Kashiwara and B. Malgrange around 1970, after the work of D.C. Spencer on the formal theory of systems of partial differential equations. We shall then focus on its application to control theory in order to study linear control systems defined by partial differential equations with constant or variable coefficients, also called multidimensional control systems, by means of new methods from module theory and homological algebra. We shall revisit a few basic concepts and prove, in particular, that controllability, contrary to a well established engineering tradition or intuition, is an intrinsic structural property of a control system, not depending on the choice of inputs and outputs among the control variables or even on the presentation of the control system. Our exposition will be rather elementary as we shall insist on the main ideas and methods while illustrating them through explicit examples. Meanwhile, we want to stress out the fact that these new techniques bring striking results even on classical control systems of Kalman type I.

*Key-Words:* Algebraic Analysis, Partial Differential Equations, Module Theory, Torsion Module, Projective Module, Projective Equivalence, Homological Algebra, Extension Functor, Control Theory, Controllability, Observability, Characteristic Set.

## 1.1 INTRODUCTION

We start recalling and revisiting the important controllability concept in classical control theory. For this, we shall adopt standard notations for the input  $u = (u^1, \dots, u^p)$ , the state  $x = (x^1, \dots, x^n)$  and the output  $y = (y^1, \dots, y^m)$ , the dot indicating time derivative.

A control system with coefficients in a constant field  $k$  (say  $\mathbb{Q}, \mathbb{R}, \mathbb{C}$  in general) is said to be in “Kalman form” if it can be written as  $\dot{x} = Ax + Bu$ , where  $A$  is a constant  $n \times n$  matrix and  $B$  is a constant  $n \times p$  matrix with maximum rank  $p$ , where we understand that  $A$  and  $B$  have coefficients in  $k$ . If we should like to characterize such a system of ordinary differential (OD) equations, we could say that it is linear, first order, with no equation of order zero and with no derivative of  $u$  appearing in the OD equations.

**Definition 1.1:** The above control system is said to be *controllable* if, starting from any initial point  $x_0$  at time  $t = 0$ , it is possible to find an input such that the corresponding trajectory is passing through an arbitrary final point  $x_T$  at a final time  $T$ .

The following celebrated test has been given by E.R. Kalman in 1963 [6]:

**Theorem 1.2:** The above control system is controllable if and only if the *controllability matrix*  $(B, AB, A^2B, \dots, A^{n-1}B)$  has maximum rank  $n$ .

Of course, in general, starting with  $\text{rk}(B) = l_0 = p$ , the rank will increase successively and we may set  $\text{rk}(B, AB) = l_0 + l_1, \dots, \text{rk}(B, AB, \dots, A^{n-1}B) = l_0 + \dots + l_{n-1}$  as the rank will not increase anymore because of the Cayley-Hamilton theorem saying that  $A^n$  is a linear combination of the previous lower powers of  $A$ .

In order to provide a preview of the type of techniques that will be used in the sequel, we provide a new short

# Algebraic Analysis

**Josiah Willard Gibbs**



## **Algebraic Analysis:**

**Algebraic Analysis of Differential Equations** T. Aoki,H. Majima,Y. Takei,N. Tose,2009-03-15 This volume contains 23 articles on algebraic analysis of differential equations and related topics most of which were presented as papers at the conference Algebraic Analysis of Differential Equations from Microlocal Analysis to Exponential Asymptotics at Kyoto University in 2005 This volume is dedicated to Professor Takahiro Kawai who is one of the creators of microlocal analysis and who introduced the technique of microlocal analysis into exponential asymptotics *Foundations of Algebraic Analysis* Masaki Kashiwara,Takahiro Kawai,Tatsuo Kimura,1986 The use of algebraic methods for studying analysts is an important theme in modern mathematics The most significant development in this field is microlocal analysis that is the local study of differential equations on cotangent bundles This treatise provides a thorough description of microlocal analysis starting from its foundations The book begins with the definition of a hyperfunction It then carefully develops the microfunction theory and its applications to differential equations and theoretical physics It also provides a description of microdifferential equations the microlocalization of linear differential equations Finally the authors present the structure theorems for systems of microdifferential equations where the quantized contact transformations are used as a fundamental device The microfunction theory together with the quantized contact transformation theory constitutes a valuable new viewpoint in linear partial differential equations Originally published in 1986 The Princeton Legacy Library uses the latest print on demand technology to again make available previously out of print books from the distinguished backlist of Princeton University Press These editions preserve the original texts of these important books while presenting them in durable paperback and hardcover editions The goal of the Princeton Legacy Library is to vastly increase access to the rich scholarly heritage found in the thousands of books published by Princeton University Press since its founding in 1905 [Algebraic Analysis](#) G A Wentworth,2023-07-18 This classic text on algebraic analysis has been the standard reference for generations of students and mathematicians G A Wentworth presents a rigorous and comprehensive treatment of the subject from basic algebraic operations to complex analyses of polynomials and equations This book remains an indispensable resource for students and professionals seeking a deep understanding of abstract algebraic principles This work has been selected by scholars as being culturally important and is part of the knowledge base of civilization as we know it This work is in the public domain in the United States of America and possibly other nations Within the United States you may freely copy and distribute this work as no entity individual or corporate has a copyright on the body of the work Scholars believe and we concur that this work is important enough to be preserved reproduced and made generally available to the public We appreciate your support of the preservation process and thank you for being an important part of keeping this knowledge alive and relevant **Algebraic Analysis** ,1988 [Algebraic Analysis](#) George Albert Wentworth,James Alexander McLellan,John Cadenhead Glashan,1889 *Algebraic Analysis of Social Networks* J. Antonio R. Ostoic,2021-02-17 Presented in a comprehensive manner this book

provides a comprehensive foundation in algebraic approaches for the analysis of different types of social networks such as multiple signed and affiliation networks. The study of such configurations corresponds to the structural analysis within the social sciences and the methods applied for the analysis are in the areas of abstract algebra, combinatorics and graph theory. Current research in social networks has moved toward the examination of more realistic but also more complex social relations by which agents or actors are connected in multiple ways. Addressing this trend, this book offers hands on training of the algebraic procedures presented along with the computer package *multiplex* written by the book's author specifically to perform analyses of multiple social networks. An introductory section on both complex networks and for R will feature however the subjects themselves correspond to advanced courses on social network analysis with the specialization on algebraic models and methods. *Functor Categories, Model Theory, Algebraic Analysis and Constructive Methods*

Alexander Martsinkovsky, 2024-05-04. This volume comprises selected contributions by the participants of the second Functor Categories Model Theory Algebraic Analysis and Constructive Methods conference which took place at the University of Almer, Spain in July 2022. The conference was devoted to several seemingly unrelated fields: functor categories, model theory of modules, algebraic analysis including linear control systems and constructive category theory to mention just a few. The fact that these fields are actually related is a very recent realization. The connections between these disciplines are changing in real time and the goal of this volume is to provide an initial reference point for this emerging interdisciplinary field. Besides research articles, the volume includes two extended lectures: one on constructive methods in algebraic analysis and the other on the functorial approach to algebraic systems theory. Hence, in addition to its interest for researchers, the volume will also be an invaluable resource for newcomers.

**B-Series** John C. Butcher, 2022-04-02. B-series, also known as Butcher series, are an algebraic tool for analysing solutions to ordinary differential equations including approximate solutions. Through the formulation and manipulation of these series, properties of numerical methods can be assessed. Runge-Kutta methods in particular depend on B-series for a clean and elegant approach to the derivation of high-order and efficient methods. However, the utility of B-series goes much further and opens a path to the design and construction of highly accurate and efficient multivalued methods. This book offers a self-contained introduction to B-series by a pioneer of the subject. After a preliminary chapter providing background on differential equations and numerical methods, a broad exposition of graphs and trees is presented. This is essential preparation for the third chapter in which the main ideas of B-series are introduced and developed. In chapter four, algebraic aspects are further analysed in the context of integration methods, a generalization of Runge-Kutta methods to infinite index sets. Chapter five on explicit and implicit Runge-Kutta methods contrasts the B-series and classical approaches. Chapter six on multivalued methods gives a traditional review of linear multistep methods and expands this to general linear methods for which the B-series approach is both natural and essential. The final chapter introduces some aspects of geometric integration from a B-series point of view, placing B-series at the centre of its most important applications.

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