

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

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