Chris Byrnes's Work on Feedback Design for Nonlinear Systems

Alberto Isidori

I first met Chris at a Conference organized by Rudy Kalman in 1977. At that time, our research interests were quite apart. I met him again in 1979, at a Conference he had co-organized at Harvard University, and then subsequently at a Conference that I had co-organized in Rome in 1981. This were opportunities for deeper exchanges of ideas on various open issues in system theory and, above all, on a topic that at that time was attracting the interest of many researchers: feedback design for nonlinear systems. We both realized to have a number of viewpoints in common. I eventually invited him for a sabbatical at the University of Rome, that took place in the spring 1983. This visit marked the beginning of a mutually rewarding scientific collaboration, which continued for almost thirty years.

In 1983, one of my major interests was the development of the nonlinear analogue of the notion of zero of a system. I had a fresh experience in developing differential geometric methods of analysis of such systems and I knew that zeros for linear systems can be properly identified by means of geometric methods. Chris, on the other hand, had a fresh experience in studying stabilization of multivariable linear systems via output feedback, and was looking of ways to find a nonlinear analogue of the property that a linear system having all zeros with negative real part can be stabilized by "high gain" output feedback. We found out that the differential geometric setting provided an elegant framework for the extension of the concept of zero to nonlinear systems. We introduced the concept which we called the "zero dynamics" of a system, which are the dynamics characterizing the motions internally arising in a system when input and initial conditions are chosen so as to force the output to remain identically zeros. These dynamics can be explicitly identified by bringing, via suitable changes of coordinates, the state space description of the system into a form where the dynamics in question appear a subsystem. This form eventually become known as "Byrnes-Isidori" normal form. This form was instrumental, in our work and in the work of many others, for proving various versions of the original intuition: systems having a globally asymptotically stable zero dynamics can be stabilized (in a semi-global sense, that is with a guaranteed domain of attraction) by means of output feedback.

One day in 1988, while attending a Conference in southern France, Chris and I started talking of the opportunity of using the newly developed notion of zero dynamics in problems of asymptotically tracking/rejecting exogenous inputs. Aware of the fundaments results developed for linear systems by Davison, Francis and Wonham, we both knew that, in this problem, the notion of zeros plays a fundamental role. In fact, in a linear system the role of the control is precisely that of fixing transmission zeros so as to block exogenous inputs. To make this intuition work, we needed to develop a reasonable setting to investigate how a nonlinear system responds, in steady state, to persistent exogenous inputs. In this respect, Chris observed that a convenient mathematical tool for the analysis of the steady state response of nonlinear systems was the Center Manifold Theorem. This was an intuition full of consequences. In fact, center manifold theory proved instrumental in deriving necessary conditions for the existence of a (local) controller solving a problem of asymptotic tracking. These conditions eventually became known as the "nonlinear regulator equations" and nicknamed "FBI equations", after Francis, Byrnes and Isidori. Again, this conceptual framework became the starting point for numerous contributions, in our work and in the work of others, that eventually brought the theory of output regulation for nonlinear systems to a high degree of sophistication.

In 1989 Chris moved to Washington University and two years later he become Dean of Engineering of that University. This inevitably had an impact of the amount of our scientific collaboration, which anyway continued, at an obviously lesser level. In the early 1990's, motivated by the early work of Willems on the notion of passivity of systems, we investigated the problem of when a nonlinear system can be made passive by means of (state) feedback. As in the case of linear systems, it turned out that this is possible if the system has relative degree one and its zero dynamics are stable in the sense of Lyapunov. The result found in this way provided a robust alternative to the popular, but non robust, methods based on feedback linearization. In the early 2000's, it was again Chris' intuition the prime mover behind a joint research in which we proposed to review the concept of "steady state" in a nonlinear system. Reviewing and comparing numerous problems of analysis and design, we came to the conclusion that the most appropriate notion in this respect was the notion of "limit set of a set", which had been developed earlier by Hale and co-authors for autonomous, possibly infinite dimensional, dynamical system. Using this concept in the setting of feedback design, it was possible to lay the foundations for a general, non local, non-equilibrium based, approach to the design of nonlinear regulators.

Chris' enthusiasm, passion and sense of humor were constantly the right catalyst in a series of scientific adventures. He has been part of my personal life for many years, scientifically and socially. In the words of his last student, he was "a great scholar, a gracious host, and a fine man". His untimely death has been a loss not just for his close friends but also for the entire systems and control community.

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