

Advanced Tools for Nonlinear Sampled-Data Systems' Analysis and Control

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It is shown that the formalism of asymptotic series expansions recently developed by the authors for computing the solutions of non autonomous differential equations, can be profitably employed to obtain the equivalent model to a nonlinear continuous system under generalized sampling procedures. Tools and insights for the design of sampled-data control systems are derived.

Keywords: Nonlinear sampled-data systems; discrete-time systems; digital control; asymptotic series expansions

1. Introduction

Several reasons motivate the renewed interest in sampled-data systems, among them:

- the highly demanding performances for computer controlled systems;
- the remarkable technological advances which push forward the limits of applications and make real theoretical research transfer;
- the fact that sampled-data systems are inherent components of hybrid processes and embedded systems: pervasive technologies which are present in the most challenging research programmes of the international scientific community.

In the attempt to stress a rather schematic classification of the methodologies, even though too simplistic for specialists, let us introduce the different ways to attack sampled-data control problems. These comments, valid in general, will essentially focus on nonlinear systems.

The continual evolution of digital technologies in terms of speed, costs and precision is at the basis of the increasing diffusion of digital control. A control system is, in this context, characterized by the digital computation of a control law from sampled measures performed on the given continuous plant. Two kinds of phenomena are therefore present : sampling of the measures and restoring of the continuous-time inputs of the plant; analog-to-digital and digital-to-analog conversions of the signals involved in the computation of the control law. The designer of a digital control scheme must therefore take into account, from the very beginning, problems linked to sampling, continuous-time restoring and quantization.

To study the effects of different sampling devices over the analysis and control properties of a given continuous-time dynamics is thus of major interest. The questions are: what about the properties of a given, open loop or closed loop, continuous-time system under sampling? Is it possible to preserve/to improve the performances of the control system? What about the behaviours in the inter-sample? Digital control design should answer these purposes.

The difficulties, already present in the linear context, give rise to increasing complexity in a nonlinear setting. To cite a few we note the appearance of critical zero dynamics and the loss of control properties like non-interaction or feedback linearization.

As rather usual in the digital control literature, this paper is concerned only with sampling and continuous-time restoring. Quantization effects, often represented by an additive noise with statistical characteristics depending on the device, raise up nowadays a renewed interest in the context of hybrid systems. These aspects, investigated in [2], will not be discussed in this paper which is focused on sampled-data control systems. Sampling and holding are assumed to be synchronized and the sampled equivalent model of the plant represents the link between the input to the holder device and the state or output sampled values of the plant. As far as the continuous-time reconstruction of the signals is concerned, we make use of zero-order holding devices ‘usual sampling’ or higher-order and/or multirate holding devices, ‘generalized sampling’.

As well known, the following three approaches, extensively developed in the linear context starting from the early 1950s, see [6], can be pursued for the design of digital controllers.

- *Continuous-time design (CTD)* The continuous-time controller is designed and then implemented in discrete time. When dealing with static feedback on a nonlinear plant, the most common approach consists in the direct implementation through zero-order holder of the continuous control computed at the sampling instants; this procedure is denoted as ‘emulation’. To compensate the effects of sampling and holding devices, a modified continuous model plant or a modified design procedure can be used, ‘indirect digital control’ or ‘redesign methods’. First results in the nonlinear context in these lines are in [11,24,25,27,35,42] where some new insights are given.

Emulation and redesign techniques have been extensively employed in the more recent nonlinear literature. The investigations are usually confined to understand up to what extent the continuous-time performances are maintained by the resulting sampled-data control scheme and to pursue a quantitative analysis for guaranteeing a safe sampling range. Referring to the sampling period length, the question is: up to what extent is it possible to guarantee, through emulated control, the performances of a continuous-time control design? The most accurate quantitative analysis on the limits of emulation make use of tools and methods developed in the area of robust control Lyapunov’s type techniques in the wide framework of input-to-state-stability [23,36,53,54,56,61].

- *Discrete-time design (DTD)* The controller is directly designed on the exact or approximate equivalent sampled model of the plant. This appears to be the natural framework for studying digital control but, in the nonlinear context, difficult problems must be faced : in general the usual sampled model does not admit a closed form representation ([41,62]), and the problem is still more complicated if not standard holding devices are used; properties of the plant which are relevant for the controller design may be lost under sampling; only a few number of design procedures involving rather complex computational aspects are available in discrete time. To quote a few, among the most traditional drawbacks of sampled models, put in light in a linear context too, let us recall that : minimum phase property is lost under usual sampling with the appearance of critical sampling zeroes [5,44,65]; the sampling period length is a crucial parameter of sampled-data systems [57,60]; structural or control properties can be lost depending on the sampling procedure and/or the order of approximation performed in the computation [7]. All these aspects request ad hoc analysis and control methodologies as well as non standard sampling procedures and devices [11,20,45,46,48,50].

Once a sampled equivalent model is assumed available, its practical computation being discussed lateron, direct digital and discrete-time control can be merged. Notable progresses have been done over the last years about nonlinear discrete-time control theory pursuing various different approaches either algebraic or geometric ones in the lines of consolidated mathematical frameworks set in the continuous-time theory. Results regarding controllability and observability, invariance, decoupling, regulation and observer design, are proposed and confronted with realistic examples. Nowadays, we can say that the available knowledge about discrete-time control theory in a nonlinear context covers a large variety of problems satisfactorily worked out on examples (see [3,4,7,8,12,16,19,29,33,34,36–39,43,47,64]).

To conclude about this aspect let us say that: significant progresses have been made regarding nonlinear discrete-time control theory over the last years so providing techniques and tools for solving nonlinear discrete-time control problems; important problems remain the choice of the sampling procedure, the computation of the sampled equivalent model and/or the accuracy of the approximated sampled model also in relation with the properties that must be maintained.

In spite of this, exact sampled models are still difficult to compute so that the Euler approximation is the most popular sampled model over which digital

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