Preface

The present monograph contains new results and findings on control and estimation problems for financial systems and for statistical validation of computational tools used for financial decision-making. The use of state-space models in financial engineering will allow to eliminate heuristics and empirical methods currently in use in decision-making procedures for finance. On the other side, it will permit to establish methods of fault-free performance and optimality in the management of assets and capitals and methods assuring stability in the functioning of financial systems (e.g. of several financial institutions and of the banking sector). As it can be confirmed from an overview of the relevant bibliography, the systems theory-based and machine learning methods developed by the monograph stand for a genuine and significant contribution to the field of financial engineering. First, the monograph solves in a conclusive manner problems associated with the control and stabilization of nonlinear and chaotic dynamics in financial systems, when these are described in the form of nonlinear ordinary differential equations. Next, it solves in a conclusive manner problems associated with the control and stabilization of financial systems governed by spatiotemporal dynamics, that is systems described by partial differential equations (e.g. the Black–Scholes PDE and its variants). Moreover, the monograph solves the problem of filtering for the aforementioned types of financial models, that is of estimation of the entire dynamics of the financial systems when using limited information (partial observations) obtained from them. Finally, the monograph solves in a conclusive and optimal manner the problem of statistical validation of computational models and tools used to support financial engineers in decision taking. Through the methods it develops, the monograph enables to identify inconsistent and inappropriately parameterized financial models and to take necessary actions for their update.

The monograph comes to address the need about decision-making in finance that will be no longer based on heuristics and intuition but will make use of computational methods and tools characterized by fault-free performance and optimality. Through the synergism of systems theory and machine learning methods, the monograph offers solutions, in a conclusive manner, to the following key problems met in financial engineering: (i) control and stabilization of financial systems exhibiting nonlinear and chaotic dynamics; (ii) control and stabilization of financial systems exhibiting spatiotemporal dynamics described by partial differential equations; (iii) solution to the associated filtering problems, that is estimation of the complete dynamics of the aforementioned complex types of financial models with the use of limited information extracted out of them; (iv) elaborated computational tools for the assessment of risk in financial systems and for the optimized management of capitals and assets; and (v) statistical validation of decision support tools used in finance, such as forecasting models and models of financial systems dynamics. The monograph is primarily addressed to the academic and research community of financial engineering as well as to tutors of relevant university courses. It can also be a useful reference for students of financial engineering, at both undergraduate and postgraduate level, helping them to get acquainted with established approaches for control, estimation and forecasting in finance as well as with methods for validating the precision of computational tools used in decision support. Finally, it is addressed to financial engineers working on practical problems of risk-free decision-making and aiming at profitable management of funds, commodities and financial resources.

The management of financial systems has to address the following issues: (i) stability, (ii) modelling and forecasting and (iii) validation and update of decision-making tools. About (i), it is noted that although the dynamics of financial systems has been described efficiently by the Black–Scholes PDE and its variants, little has been done about its stabilization. The problem of control and stabilization of diffusion PDEs of this type is a non-trivial one and has to be implemented using as control inputs only the PDEs boundary conditions. The monograph offers solution of assured convergence and performance for this difficult control problem. Additionally, there are several types of financial systems described by nonlinear ODEs which exhibit chaotic dynamics. The monograph provides stabilizing control methods for such systems too. About (ii), it is easy to understand that forecasting in financial systems is significant for risk assessment and successful decision-making. By being in position to predict future states of the financial system, early warning indications are handled and profitable actions are taken for asset and capital management. The monograph's method contributes to this direction. About (iii), it is apparent that the effectiveness of all decision-making processes in finance is dependent on the sufficiency of the information collected from the financial system and on the accuracy and credibility of decision support tools. The statistical validation of decision-making software and of the models used by it is important for the maximization of profits in financial systems management and for the minimization of risks. Clearly, the monograph solves the statistical validation problems in a conclusive manner.

The monograph comprises the following chapters:

In Chap. 1, systems theory and stability concepts are overviewed. This chapter analyses the basics of systems theory which can be used in the modelling of nonlinear dynamics. To understand the oscillatory behaviour of nonlinear systems that can exhibit such dynamics, benchmark examples of oscillators are given. Moreover, using examples from state-space models, the following properties are analysed: phase diagram, isoclines, attractors, local stability, bifurcations of fixed points and chaos properties.

In Chap. 2, main approaches to nonlinear control with potential application to financial systems are analysed. In control and stabilization of the dynamics of financial systems, one can distinguish three main research axes: (i) methods based on global linearization, (ii) methods based on asymptotic linearization and (iii) Lyapunov methods. As far as approach (i) is concerned, these are methods for the transformation of the nonlinear dynamics of the system to equivalent linear state-space descriptions for which one can design controllers using state feedback and can also solve the associated state estimation (filtering) problem. One can classify here methods based on the theory of differentially flat systems and methods based on Lie algebra. As far as approach (ii) is concerned, solutions are pursued to the problem of nonlinear control with the use of local linear models (obtained at local equilibria). For such local linear models, feedback controllers of proven stability can be developed. One can select the parameters of such local controllers in a manner that assures the robustness of the control loop to both external perturbations and model parametric uncertainty. As far as approach (iii) is concerned, that is methods of nonlinear control of the Lyapunov type, one comes against the problems of minimization of Lyapunov functions so as to assure the asymptotic stability of the control loop. For the development of Lyapunov-type controllers, one can either exploit a model about the financial systems dynamics or proceed in a model-free manner, as in the case of indirect adaptive control.

In Chap. 3, main approaches to nonlinear estimation with potential application to financial systems are analysed. To treat the filtering problem for nonlinear dynamics in financial systems, the Extended Kalman Filter is an established approach. However, since this is based on approximate linearization of the system's state-space description and in the truncation of higher order terms in the associated Taylor series expansion, the Unscented Kalman Filter is frequently used in its place. The latter filter performs state estimation by averaging on state vectors that are selected at each iteration of the filtering algorithm and being defined by the columns of the estimation error vector covariance matrix. Additionally, to handle the case of non-Gaussian noises in the filtering procedure, the particle filter has been proposed. A number of potential state vector values (particles) are updated in time through elitism criteria, and out of this set, the estimate of the state vector is computed. The topic of nonlinear estimation is completed by a new nonlinear filtering approach under the name Derivative-free nonlinear Kalman Filter. This filter based on linearizing transformation of the monitored financial system is proven to conditionally maintain the optimality features of the standard Kalman Filter and to be computationally faster than other nonlinear estimation methods. Moreover, to treat the distributed filtering and state estimation in financial systems, one can apply established methods for decentralized state estimation, such as the Extended Information Filter (EIF) and the Unscented Information Filter (UIF). EIF stands for the distributed implementation of the Extended Kalman Filter, while UIF stands for the distributed implementation of the Unscented Kalman Filter. Additionally, to obtain a distributed filtering scheme in this monograph, the Derivative-free

Extended Information Filter (DEIF) is implemented. This stands for the distributed implementation of a differential flatness theory-based filtering method under the name Derivative-free distributed nonlinear Kalman Filter. The improved performance of DEIF compared to the EIF and UIF is confirmed both in terms of improved estimation accuracy and in terms of improved speed of computation. Finally, one can note distributed filtering with the use of the distributed particle filter. This consists of multiple particle filters running at distributed computation units, while a consensus criterion is used to fuse the local state estimates.

In Chap. 4, linearizing control and filtering for nonlinear dynamics in financial systems is explained. A flatness-based adaptive fuzzy control is applied to the problem of stabilization of the dynamics of a chaotic finance system, describing interaction between the interest rate, the investment demand and the price exponent. First, it is proven that the system is differentially flat. This implies that all its state variables and its control inputs can be expressed as differential functions of a specific state variable, which is a so-called flat output. It also implies that the flat output and its derivatives are differentially independent which means that they are not connected to each other through an ordinary differential equation. By proving that the finance system is differentially flat and by applying differential flatness diffeomorphisms, its transformation to the linear canonical (Brunovsky) is performed. For the latter description of the system, the design of a stabilizing state feedback controller becomes possible. A first problem in the design of such a controller is that the dynamic model of the finance system is unknown, and thus, it has to be identified with the use neurofuzzy approximators. The estimated dynamics provided by the approximators is used in the computation of the control input, thus establishing an indirect adaptive control scheme. The learning rate of the approximators is chosen from the requirement the system's Lyapunov function to have always a negative first-order derivative. Another problem that has to be dealt with is that the control loop is implemented only with the use of output feedback. To estimate the non-measurable state vector elements of the finance system, a state observer is implemented in the control loop. The computation of the feedback control signal requires the solution of two algebraic Riccati equations at each iteration of the control algorithm. Lyapunov stability analysis demonstrates first that an H-infinity tracking performance criterion is satisfied. This signifies elevated robustness against modelling errors and external perturbations. Moreover, global asymptotic stability is proven for the control loop.

In Chap. 5, nonlinear optimal control and filtering for financial systems is explained. A new nonlinear optimal control approach is proposed for the stabilization of the dynamics of a chaotic finance model. The dynamic model of the financial system, which expresses interaction between the interest rate, the investment demand, the price exponent and the profit margin, undergoes approximate linearization round local operating points. These local equilibria are defined at each iteration of the control algorithm and consist of the present value of the system's state vector and the last value of the control inputs vector that was exerted on it. The approximate linearization makes use of Taylor series expansion and of the computation of the associated Jacobian matrices. The truncation of higher order terms in the Taylor series expansion is considered to be a modelling error that is compensated by the robustness of the control loop. As the control algorithm runs, the temporary equilibrium is shifted towards the reference trajectory and finally converges to it. The control method needs to compute an H-infinity feedback control law at each iteration and requires the repetitive solution of an algebraic Riccati equation. Through Lyapunov stability analysis, it is shown that an H-infinity tracking performance criterion holds for the control loop. This implies elevated robustness against model approximations and external perturbations. Moreover, under moderate conditions, the global asymptotic stability of the finance system's feedback control is proven.

In Chap. 6, a Kalman Filtering approach for the detection of option mispricing in the Black–Scholes PDE is introduced. Financial derivatives and option pricing models are usually described with the use of stochastic differential equations and diffusion-type partial differential equations (e.g. Black–Scholes models). Considering the latter case in this chapter, a new filtering method for distributed parameter systems is developed for estimating option price variations without the knowledge of initial conditions. The proposed filtering method is the so-called Derivative-free nonlinear Kalman Filter and is based on a decomposition of the nonlinear partial differential equation model into a set of ordinary differential equations with respect to time. Next, each one of the local models associated with the ordinary differential equations is transformed into a model of the linear canonical (Brunovsky) form through a change of coordinates (diffeomorphism) which is based on differential flatness theory. This transformation provides an extended model of the nonlinear dynamics of the option pricing model for which state estimation is possible by applying the standard Kalman Filter recursion. Based on the provided state estimate, validation of the Black–Scholes PDE model can be performed and the existence of inconsistent parameters in the Black–Scholes PDE model can be concluded.

In Chap. 7, a Kalman Filtering approach to the detection of option mispricing in electric power markets is analysed. As mentioned in the previous chapter, option pricing models are usually described with the use of stochastic differential equations and diffusion-type partial differential equations (e.g. Black–Scholes models). In case of electric power markets these models are complemented with integral terms which describe the effects of jumps and changes in the diffusion process and which are associated with variations in the production rates, in the condition of the transmission and distribution system, in the pay-off capability, etc. Considering the latter case, that is a partial integrodifferential equation for the option's price, a new filtering method, is developed for estimating option price variations without knowledge of initial conditions. The proposed filtering method is the so-called Derivative-free nonlinear Kalman Filter and is based on a transformation of the initial option price dynamics into a state-space model of the linear canonical form. The transformation is shown to be based on differential flatness theory and finally provides a model of the option price dynamics for which state estimation is possible by applying the standard Kalman Filter recursion. Based on the provided state estimate, validation of the Black–Scholes partial integrodifferential equation can be performed and the existence of inconsistent parameters in the electricity market pricing model can be concluded.

In Chap. 8, corporations' default probability forecasting using the Derivative-free nonlinear Kalman Filter is explained. This chapter proposes a systematic method for forecasting default probabilities for financial firms with particular interest in electric power corporations. According to the credit risk theory, a company's closeness to default is determined by the distance of its assets' value from its debts. The assets' value depends primarily on the company's market (option) value through a complex nonlinear relation. By forecasting with accuracy the enterprise's option value, it becomes also possible to estimate the future value of the enterprise's assets and the associated probability of default. This chapter proposes a systematic method for forecasting the proximity to default for companies (option/asset value forecasting methods) using the new nonlinear Kalman Filtering method under the name Derivative-free nonlinear Kalman Filter. The firm's option value is considered to be described by the Black–Scholes nonlinear partial differential equation. Using differential flatness theory, the partial differential equation is transformed into an equivalent state-space model in the so-called canonical form. Using the latter model and by redesigning the Derivative-free nonlinear Kalman Filter as a m-step ahead predictor, estimates are obtained of the company's future option values. By forecasting the company's market (option) values, it becomes finally possible to forecast the associated asset value and volatility and also to estimate the company's future default risk.

In Chap. 9, validation of financial options models using neural networks with invariance to Fourier transform is explained. It is known that numerical solution of the Black–Scholes PDE enables to compute with precision the values of financial options, within a finite-time horizon. It is also known that solutions to the option pricing problem can be obtained in closed form using Fourier methods, such as the Fast Fourier Transform, the expansion in Fourier-cosine series or the expansion in Fourier–Hermite series. In this chapter, modelling of financial options' dynamics is performed, using a neural network with 2D Gauss-Hermite basis functions that remain invariant to Fourier transform. Knowing that the Gauss-Hermite basis functions satisfy the orthogonality property and remain unchanged under the Fourier transform, subjected only to a change of scale, one has that the considered neural network provides the spectral analysis of the options' dynamics model. Actually, the squares of the weights of the output layer of the neural network denote the spectral components for the monitored options' dynamics. By observing changes in the amplitude of the aforementioned spectral components, one can have also an indication about deviations from nominal values, for parameters that affect the options' dynamics, such as interest rate, dividend payment and volatility. Moreover, since specific parametric changes are associated with amplitude changes of specific spectral components of the options' model, isolation of the distorted parameters can be also performed.

In Chap. 10, statistical validation of financial forecasting tools with generalized likelihood ratio approaches is analysed. The local statistical approach for fault detection and isolation is applied to the problem of validation of a fuzzy model which can be used in forecasting. The method detects the inconsistencies between a fuzzy rule base and the modelled system. It can also identify which are the faulty parameters of the fuzzy model. The Fisher information matrix explains the detectability of changes in the parameters of the fuzzy model. Simulation tests illustrate the method's credibility. As a case study, statistical validation of a neurofuzzy model of chaotic time series is considered.

In Chap. 11, distributed Kalman Filtering for risk assessment in interconnected financial markets is analysed. In financial decision-making, such as in the trading of options, it is important to regularly validate the accuracy and reliability of decision support tools. In this context, this chapter introduces a distributed scheme for the validation of option price forecasting models enabling early diagnosis of options mispricing. It is considered that N independent agents monitor and forecast the variation of option prices through locally parameterized Kalman Filters. It is also assumed that final decision about the options' price is taken through a fuzzy consensus scheme, that is the individual forecasts of the distributed agents, provided by local Kalman Filters are fused with a fuzzy weighting process. Thus, forecasting is finally performed by a fuzzy Kalman Filter. It is likely, though, that some of the distributed models are improperly parametrized and fail to describe accurately the real dynamics of the option's market. To this end, a statistical method is developed capable of (i) detecting if the estimation about the options's price that is provided by the multi-agent system is sufficiently precise or not and (ii) isolating the ith agent that makes use of an improperly parameterized model. This chapter provides one of the few approaches for testing the accuracy of distributed Kalman Filters for financial decision-making and the only one that permits to detect parametric changes that are of magnitude of less than 1% of the nominal value of the monitored financial system.

In Chap. 12, stabilization of financial systems dynamics through feedback control of the Black–Scholes PDE is analysed. The objective of this chapter was to develop a boundary control method for the Black–Scholes PDE which describes option dynamics. It is shown that the procedure for numerical solution of Black–Scholes PDE results in a set of nonlinear ordinary differential equations (ODEs) and an associated state equations model. For the local subsystems, into which a Black–Scholes PDE is decomposed, it becomes possible to apply boundary-based feedback control. The controller design proceeds by showing that the state-space model of the Black–Scholes PDE stands for a differentially flat system. Next, for each subsystem which is related to a nonlinear ODE, a virtual control input is computed, which can invert the subsystem's dynamics and can eliminate the subsystem's tracking error. From the last row of the state-space description, the control input (boundary condition) that is actually applied to the Black–Scholes PDE is found. This control input contains recursively all virtual control inputs which were computed for the individual ODE subsystems associated with the previous rows of the state-space equation. Thus, by tracing the rows of the state-space model backwards, at each iteration of the control algorithm, one can finally obtain the control input that should be applied to the Black–Scholes PDE so as to assure that all its state variables will converge to the desirable setpoints.

In Chap. 13, stabilization of the multi-asset Black–Scholes PDE using differential flatness theory is analysed. A method for feedback control of the multi-asset Black–Scholes PDE is developed. By applying once more semi-discretization and a finite differences scheme, the multi-asset Black–Scholes PDE is transformed into a state-space model consisting of ordinary nonlinear differential equations. For this set of differential equations, it is shown that differential flatness properties hold. This enables to solve the associated control problem and to succeed stabilization of the options' dynamics. It is shown that the previous procedure results in a set of nonlinear ordinary differential equations (ODEs) and to an associated state equations model. For the local subsystems, into which a multi-asset Black–Scholes PDE is decomposed, it becomes possible to apply boundary-based feedback control. The controller design proceeds by showing that the state-space model of the multi-asset Black–Scholes PDE stands for a differentially flat system. Next, for each subsystem which is related to a nonlinear ODE, a virtual control input is computed, which can invert the subsystem's dynamics and can eliminate the subsystem's tracking error. From the last row of the state-space description, the control input (boundary condition) that is actually applied to the multi-asset Black–Scholes PDE system is found. This control input contains recursively all virtual control inputs which were computed for the individual ODE subsystems associated with the previous rows of the state-space equation. Thus, by tracing the rows of the state-space model backwards, at each iteration of the control algorithm, one can finally obtain the control input that should be applied to the multi-asset Black–Scholes PDE so as to assure that all its state variables will converge to the desirable setpoints.

In Chap. 14, stabilization of commodities pricing PDE using differential flatness theory is explained. Pricing of commodities (e.g. oil, carbon, mining products, electric power and agricultural crops) is vital for the majority of transactions taking place in financial markets. A method for feedback control of commodities pricing dynamics is developed. The PDE model of the commodities price dynamics is shown to be equivalent to a multi-asset Black–Scholes PDE. Actually, it is a diffusion process evolving in a 2D assets space, where the first asset is the commodity's spot price and the second asset is the convenience yield. As in the previous chapters, by applying semi-discretization and a finite differences scheme, this multi-asset PDE is transformed into a state-space model consisting of ordinary nonlinear differential equations. For the local subsystems, into which the commodities PDE is decomposed, it becomes possible to apply boundary-based feedback control. The controller design proceeds by showing that the state-space model of the commodities PDE stands for a differentially flat system. Next, for each subsystem which is related to a nonlinear ODE, a virtual control input is computed, which can invert the subsystem's dynamics and can eliminate the subsystem's tracking error. From the last row of the state-space description, the control input (boundary condition) that is actually applied to the multi-factor commodities' PDE system is found. This control input contains recursively all virtual control inputs which were computed for the individual ODE subsystems associated with the previous rows of the state-space equation. Thus, by tracing the rows of the state-space model backwards, at each iteration of the control algorithm, one can finally obtain the control input that should be applied to the commodities PDE system so as to assure that all its state variables will converge to the desirable setpoints. By demonstrating the feasibility of such a control method it is also proven that through selected purchase and sales during the trading procedure, the price of the negotiated commodities can be made to converge and stabilize at specific reference values.

In Chap. 15, stabilization of mortgage price dynamics using differential flatness theory is analysed. Pricing of mortgages (loans for the purchase of residences, land or farms) is vital for the majority of transactions taking place in financial markets. In this chapter, a method for stabilization of mortgage price dynamics is developed. It is considered that mortgage prices follow a PDE model which is equivalent to a multi-asset Black–Scholes PDE. Actually, it is a diffusion process evolving in a 2D assets space, where the first asset is the residence price and the second asset is the interest rate. By applying semi-discretization and a finite differences scheme, this multi-asset PDE is transformed into a state-space model consisting of ordinary nonlinear differential equations. For the local subsystems, into which the mortgage PDE is decomposed, it becomes possible to apply boundary-based feedback control. The controller design proceeds by showing that the state-space model of the mortgage price PDE stands for a differentially flat system. Next, for each subsystem which is related to a nonlinear ODE, a virtual control input is computed, which can invert the subsystem's dynamics and can eliminate the subsystem’s tracking error. From the last row of the state-space description, the control input (boundary condition) that is actually applied to the multi-factor mortgage price PDE system is found. This control input contains recursively all virtual control inputs which were computed for the individual ODE subsystems associated with the previous rows of the state-space equation. Thus, by tracing the rows of the state-space model backwards, at each iteration of the control algorithm, one can finally obtain the control input that should be applied to the mortgage price PDE system so as to assure that all its state variables will converge to the desirable setpoints. By showing the feasibility of such a control method, it is also proven that through selected modification of the PDE boundary conditions, the price of the mortgage can be made to converge and stabilize at specific reference values.

The main purpose of this book was to disseminate new findings useful for academic teaching and research in the area of financial engineering and to develop systematic methods for management and risk minimization in financial systems. Methods for solving control and estimation problems in financial systems become progressively part of the curriculum of several academic departments at undergraduate level. This is because there is a need to acquaint future engineers with technologies that enable the functioning of financial systems according to the desirable specifications, even under uncertainty and partial information about their dynamic model. The present book contains teaching material which can be used for independent courses on financial engineering. This book can also serve perfectly the needs of postgraduate courses on financial engineering where more emphasis can be given to advanced computational and the mathematical techniques for the profitable and risk-free management of financial systems. The title of the course can be the same as the title of the book, i.e. state-space approaches to modelling and control in financial engineering: systems theory and machine learning methods. Starting from the analysis of dynamical systems theory and of established approaches for control and estimation in nonlinear dynamical systems, the monograph moves progressively to the solution of key problems met in financial engineering, such as (i) nonlinear control and filtering for financial systems exhibiting complex and chaotic dynamics, (ii) control and estimation for the PDE dynamics of financial systems, and (iii) statistical validation of decision support tools used in financial engineering. Through the balanced interaction between the theoretical and the application part, students can assimilate the new knowledge and can become efficient in control and estimation of financial systems and in methods for the optimized management of capitals and assets.

However, this book and is not only addressed to the academic community but also targets people working in practical problems and applications of financial engineering. There is continuous demand for developing elaborated software tools that will enable optimal decision-making about financial systems. To this end, there is a need to eliminate heuristics and intuition-based approaches in financial engineering and to establish methods that assure stabilization and convergence of financial systems to desirable performance indexes. The monograph's contribution to this direction is clear.

Athens, Greece
March 2017

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Springer

http://www.springer.com/978-3-319-52865-6

State-Space Approaches for Modelling and Control in Financial Engineering
Systems theory and machine learning methods
Rigatos, G.G.
2017, XXVIII, 310 p. 114 illus., 88 illus. in color., Hardcover
ISBN: 978-3-319-52865-6