MY RECENT RESEARCH INTERESTS

1 Modeling and Realization of Stochastic Systems

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This has been one of my main research interests since about thirty years. *Stochastic Realization Theory* has emerged from this work as a fundamental contribution to Stochastic model building and Stochastic Systems Theory, which has developed over the years and is now been collected in a monograph co-authored with Anders Lindquist entitled *Linear Stochastic Systems: a Geometric Approach.* Stochastic Realization Theory is centered around the original idea of *Markovian Splitting Subspace* and *Markovian representation* of a random signal, which is a natural probabilistic analog of the notion of *state* and state-space model in deterministic dynamical systems and is rooted on the Bayesian notion of sufficient statistics. This new theoretical framework has provided a mathematical theory of model building which has provided the conceptual basis for later work on subspace identification and has led for the first time to the understanding of structural properties of stochastic systems like minimality, which are important in applications to filtering and recursive estimation algorithms of minimal dimension. For example a new minimal–complexity solution of a class of noncausal estimation problems has been found and a new role of the family of *all* solutions of the Algebraic Riccati Equation in the computation of the optimal noncausal estimator has been discovered.

The idea of stochastic state (splitting) has been applied to various types of signals, e.g. to finite-state processes. Stochastic realization in this context has the purpose of finding algorithms for modelling finite-state signals as functions of a finite state Markov Chain (what is now called a "hidden Markov Chain"). This problem is being now recognized as a key problem in signal processing with many potential applications to source coding, speech recognition etc.. Work in this area has started in the 70's and has continued until recently in collaboration with Jan van Schuppen.

Below we list the papers where the concept of splitting was shown to be the natural counterpart of the idea of "state" in the stochastic setting and the basic ideas of stochastic realization theory were introduced.

1. G. Picci: Stochastic realization of Gaussian processes *Proceedings of the IEEE* Vol.**64**, No. 1, pp 112-122, 1976.

2. G. Picci: Some connections between the theory of sufficient statistics and the identifiability problem *SIAM Journal on Applied Mathematics* Vol.**33**, No. 3, pp 383-398, 1977.

3. G. Picci: On the internal structure of finite-state stochastic processes in *Recent developements in Variable Structure Systems* R. Mohler and A. Ruberti eds.(Proceedings of the third Italy-USA symposium on Variable-Structure Systems, Taormina, Italy, September 1977),*Springer Lecture Notes in Economics andMathematical Systems*, Vol **162**, pp. 288-304, 1978.

4. A. Lindquist, G. Picci and G. Ruckebusch: On minimal splitting subspaces and Markovian representation *Mathematical Systems Theory* Vol. **12**, pp. 271-279, 1979.

5. A. Lindquist and G. Picci: On the stochastic realization problem *SIAM Journal on Control and Optimization* Vol. **17**, No. 3, pp. 365-389, 1979.

6. L. Finesso and G. Picci: A characterization of minimal square spectral factors *IEEE Transactions on Automatic Control* Vol.**AC-27**, No. 1, pp. 122-127, 1982.

7. A. Lindquist and G. Picci: On a condition for minimality of Markovian splitting subspaces *Systems And Control Letters* Vol. **1**, No. 4, pp. 264-269, 1982.

8. A. Lindquist, S. K. Mitter and G. Picci: Toward a theory of nonlinear stochastic realization in *Feedback and Control of Linear and Nonlinear Systems* D. Hinrichsen and A. Isidori eds. *Springer Lecture Notes on Control and Information Sciences*, Vol **39**, pp. 175-189, 1982.

9. A. Lindquist and G. Picci: Forward and backward semimartingale models for stationary increments processes *Stochastics*, Vol. **15**, No. 5 ,pp. 1-50, 1985.

10. A. Lindquist and G. Picci: Realization theory for multivariate stationary Gaussian processes *SIAM Journal on Control and Optimization* Vol.**23**, No. 6 pp. 809-857, 1985 (invited paper).

11. A. Lindquist and G. Picci: A geometric approach to modeling and estimation of linear stochastic systems *Journal of Math. Systems, Estimation and Control* vol.**1**, pp. 241–333, 1991.

12. G. Picci: Stochastic modeling and stochastic realization theory in *Mathematical System Theory: the influence of R.E. Kalman*, R.E. Kalman Festschrift voume, A. Antoulas ed., Springer Verlag, pp. 213–229, 1991.

13. A. Lindquist, S. K. Mitter and G. Picci: Toward a theory of nonlinear stochastic realization in *Feedback and Control of Linear and Nonlinear Systems* D. Hinrichsen and A. Isidori eds. *Springer Lecture Notes on Control and Information Sciences*, Vol **39**, pp. 175-189, 1982.

14. G. Picci and S. Pinzoni: Acausal Models and Balanced realizations of stationary processes *Linear Algebra and its Applications* (special issue on Systems Theory), vol. **205-206**, pp. 957-1003, 1994.

15. A. Lindquist, G. Michaletzky and G. Picci Zeros of Spectral Factors,the geometry of Splitting Subspaces and the Algebraic Riccati Inequality, *SIAM J. on Control and Optimization*,**33**, pp. 365-401, March 1995.

16. G. Picci, "Geometric methods in Stochastic Realization and System Identification", *CWI Quarterly* (invited paper), **9**, pp. 205-240, 1996.

17. A Ferrante and G. Picci, "Minimal Realization and Dynamic Properties of Optimal Smoothers" *IEEE Transactions on Automatic Control*, vol. **45**, 2000, pp. 2028-2046.

18. A. Ferrante, G. Picci, and S. Pinzoni "Silverman algorithm and the structure of discrete-time stochastic systems, *Linear Algebra and its Applications* special issue on systems and control, **351-352**, pp. 219-242 (2002).

19. A. Lindquist and G. Picci, *Linear Stochastic Systems: A Geometric Approach*, book in preparation.

2 Identification and Subspace identification

Early work in the field of identification was on identifiability and parametrization of multivariable models. Recent works has mostly been on *subspace identification*. There are basically two different approaches to the problem of fitting a model to observed data. The first, the *optimization approach*, is based on the principle of minimizing a suitable distance function between the data and the chosen model class. Well-known and widely accepted examples of distance functions are the likelihood function and the average squared prediction-error of the observed data. For multivariable models the optimization approach has several drawbacks. First there are rather subtle identifiability and parametrization issues which are traditionally solved by use of canonical forms. These however tend to lead to ill-conditioned estimation problems. Next, the likelihood (or prediction error) minimization can, except in trivial cases, only be done numerically by iterative algorithms in the parameter space, say in the space of minimal (A, B, C, D) matrix quadruples. For this reason there is no guarantee of reaching a true minimum and often a time-consuming random search in the parameter space is necessary to validate the estimates.

The subspace identification approach is not based on optimization. It may be described as a two steps procedure by which one first constructs a *state* for the observed process, and then does regression on a state space model. The successive noise model identification step requires the solution of a Riccati equation. This is a system-theoretic paradigm essentially rooted on stochastic realization theory. It is well-known that subspace methods do not require the a priori choice of identifiable parametrizations and can be implemented by fast and reliable numerical schemes. A statistical assessment of these methods has been an open problem for some time. Work in collaboration with A. Chiuso has lead to substantial progress on the statistical analysis of subspace methods.

1. G. Picci: Some connections between the theory of sufficient statistics and the identifiability problem *SIAM Journal on Applied Mathematics* Vol.**33**, No. 3, pp 383-398, 1977.

2. G. Picci: Some numerical aspects of multivariable system identification *Mathematical Programming Studies*, Vol. **18**, pp. 76-101, 1982.

3. A. Lindquist and G. Picci, "Geometric Methods for State-Space Iden-

tification", in *Identification, Adaptation, Learning*, *NATO-ASI: From Identifiation to Learning* Como, Italy Aug. 1994), S. Bittanti and G. Picci. eds, Springer Verlag, pp. 1-69, 1996.

4. G. Picci and T. Katayama, "Stochastic realization with exogenous inputs and subspace methods identification", *Signal Processing*, special issue on subspace methods, Part II: System Identification, **52**, n.2, pp. 145-160, 1996.

5. A. Lindquist and G. Picci, Canonical correlation analysis , approximate covariance extension and identification of stationary time-series, *Automatica*, vol **32**, pp. 709-733, 1996.

6. T. Katayama and G. Picci, " Realization of Stochastic Systems with Exogenous Inputs and Subspace Identification Methods", *Automatica*, vol. **35**, no. 10, pp. 1635-1652, 1999.

7. Chiuso, A. and Picci G. "Some Algorithmic aspects of Subspace Identification with Inputs", *Applied Mathematics and Computer Sciences*, **11**, 1, pp. 55-76 (2001).

8. A. Chiuso and G. Picci (2004), "Asymptotic Variance of Subspace Estimates". *Journal of Econometrics*, **118**(1-2), pp. 257–291.

9. A. Chiuso, G. Picci (2004), "On the Ill-conditioning of subspace identification with inputs". *Automatica*, **40**(4), pp. 575-589.

10. A. Chiuso, G. Picci (2004), "Numerical conditioning and asymptotic variance of subspace estimates". *Automatica*, **40**(4), pp. 677-683.

11. A. Chiuso and G. Picci (2004), , "Subspace identification by data orthogonalization and model decoupling", *Automatica*, **40**(4), pp. 1689-1703.

12. A. Chiuso and G. Picci (2004), "Asymptotic Variance of Subspace Methods by Data Orthogonalization and Model Decoupling: a Comparative Analysis", *Automatica*, **40**(4), pp. 1705–1717.

13. A. Chiuso and G. Picci (2005), "Consistency Analysis of some Closed-loop Subspace Identification Methods", *Automatica: special issue on System Identification*, **41** pp. 377-391.

14. T. Katayama, H. Kawauchi and G. Picci (2005), "Subspace Identification of Closed Loop Systems by Orthogonal Decomposition", *Automatica* **41** pp. 863-872.

15. A. Chiuso, G. Picci (2005), "Prediction Error vs. Subspace Methods in Closed Loop Identification". *Proc of the 16th IFAC World Congress*, Prague.

16. A. Chiuso and G. Picci (2006) "Estimating the Asymptotic Variance of Closed-Loop Subspace Estimators," in *Proc. of SYSID 2006*, Newcastle, Australia, March 2006.

3 Factor Analysis and Errors-in-Variables Modeling

It is well-known that ARMAX models treat the observed variables in an asymmetric manner, since a distinction is made from the outset of which varibles in the model are "inputs" and which are "outputs". In particular input variables are assumed to be observed without error. As much argued by Kalman, these models may be inappropriate ("prejudiced") descriptions to impose to real data coming from economic time series or industrial processes involving feedback.
"Unprjudiced" models like Error–in Variables (EIV) or Factor–Analysis (FA) models, have been around for several years in the statistical literature but serious identifiability problems for these models have hampered their application. Solving the intrinsic "unidentifiability", or better the inherent non–uniqueness of these models has been an open problem for decades. The unidentifiability problem for a class of FA models (for the so–called "two–blocks" models), both static and dynamic, has been thoroughly studied in a paper appeared in the *Journal of Econometrics* in 1989. There it shown that the continuum of minimal FA models describing two given random signals can be parametrized explicitly by a certain projection matrix. The choice of a particular model (i.e. projection matrix) results in *exact* (i.e. with no modelling error) representation of a particular subset of the output variables while the complementary subset is instead represented with a maximal modelling error variance. A uniquely identifiable model can be selected by choosing how much representaton error variance one is willing to tolerate on each out-

put vector. The identifiability of EIV models with white measurement errors (the so-called Frisch scheme) has been also addressed recently

1. G. Picci and S. Pinzoni: Dynamic Factor-Analysis models for stationary processes *IMA Journal on Mathematics of Control and Information* Vol.**3**, No. 2 , pp. 185-210, 1986.

2. G. Picci: Parametrization of Factor Analysis models *Journal of Econometrics* Vol. **41**, No. 1 pp. 17-38, 1989.

3. G. Picci, F Gei and S. Pinzoni: Errors–in–Variables models with white measurement errors, *Proc. 2nd European Control Conference (ECC)*, p. 2154-2158, Groningen the Netherlands, 1993.

4. G. Bottegal, G. Picci and S.Pinzoni (2010), On the identifiability of errors-in-variables models with white measurement errors, *Automatica* to appear.

4 Stochastic model reduction by aggregation

The papers listed below document a tentative of understanding how well a stochastic reduced order model could represent a "complicated " deterministic system. This work elaborates theoretically on the observation that in many practical situations stochastic models work well as thy are effectively *reduced–order descriptions* of large deterministic systems in which "parasitcs" and variables coupling with the environment are represented as additive "noise" in the dynamical equations. A well–known problem in many areas of control, but especially in adaptive control, is how to cope with unmodelled dynamics. There seems to be some evidence that control schemes which use *stochastic* models and stochastic description of the environment are more robust to unmodelled dynamics.

1. G.Picci: Application of stochastic realization theory to a fundamental problem of statistical physics (invited keynote address at MTNS-85) in *Modelling, Identification and Robust Control* C. I. Byrnes, A. Lindquist eds. North Holland, pp. 211-258 1986.

2. G. Picci: Aggregation of linear systems in a completely deterministic framework in *Three Decades of Mathematical System Theory. A Collection of Surveys at the Occasion of the Fiftieth Birthday of Jan C.*

Willems, H. Neijmeijer, J.M. Schumacher eds., *Springer Lecture Notes in Control and Information Sciences*, Vol.**135** pp. 358-381, 1989.

3. G.Picci Stochastic model reduction by aggregation in *Systems Models and Feedback: Theory and Applicatons*, A Isidori, T.J. Tarn eds., Proc. of a Workshop held in the occasion of the 65-th aniversary of A. Ruberti, Capri, italy, June 1992.

4. G. Picci and T.S.J. Taylor: Generation of Gaussian Processes and Linear Chaos. *Proc 31st IEEE Conf. on Decision and Control* Tucson Arizona, pp. 2125–2131, 1992.

5. G. Picci and T.S.J. Taylor: Stochastic aggregation of flexible mechanical structures *Recent advances in Mathematical Theory of Systems, Control,Networks and Signal Processing II*, H. Kimura, S. Kodama eds. (Proceedings of MTNS-91, Kobe 1991), pp. 203–207, Mita press, Tokyo, 1992.

6. G. Picci: Markovian representation of linear Hamiltonian systems, in *Probabilistic Methods in Mathematical Physics*, F. Guerra, M.I. Loffredo and C. Marchioro eds. World Scientific Singapore, pp. 358–373, 1992.

4.1 Stochastic Control and applications

Below is a list of representative papers addressing various issues related to LQG, H^∞ control and applications.

1. G.B. Di Masi, L. Finesso and G. Picci: Design of an LQG controller for single-point moored large tankers *Automatica* Vol.**22**, No. 2, pp. 155-169, 1986.

2. G. Picci and S. Pinzoni: On feedback-dissipative systems *Journal of Math. Systems, Estimation and Control* vol.**2**, No. 1, pp. 1–30, 1992.

3. R. Muradore and G. Picci (2005), "Mixed H^2/H^∞ control: the discrete-time case", *Systems and Control Letters*, **54**, pp. 1-13.

5 Vision-Based estimation and guidance

This last project is centered on Kalman filter-based motion and scene estimation from visual sensing. There is a close collaboration with the computer vision groups at UCLA (prof Soatto) and Caltech (prof Perona), and much joint work has resulted from the collaboration with these teams.

1. R.Frezza, G. Picci, P. Perona, S. Soatto, "System Theoretic Aspects of Dynamic Vision", in *Trends in Control*, A. Isidori ed., (invited paper presented at the 3rd European Control Conference, Rome, Italy, Sept. 1995), Springer Verlag, pp. 349 - 383 , 1995.

2. R.Frezza, G. Picci, "On line path following by recursive spline updating", (invited paper FP09) *Proceedings of the 34th Conference on Decision and Control*, New Orleans, IEEE Press, pp. 4047-4052, vol **4**, 1995.

3. G. Picci, "Dynamic Vision and Estimation on Spheres", *Proceedings of the 1997 Conference on Decision and Control*, San Diego Ca., p. 1140-1145, IEEE Press 1997.

4. R.Frezza, S. Soatto, G. Picci, "On-line path following by recursive spline updating", *Proceedings of the 1997 Conference on Decision and Control*, San Diego Ca, p. 1130-1135, IEEE Press, 1997.

5. A. Chiuso and G. Picci, "Visual Tracking of Points as Estimation on the Unit Sphere" in *The Confluence of Vision and Control*, D. Kriegman, G. Hager and S. Morse eds. Springer-Verlag Lecture Notes in Control and Information Systems (LNCIS) n. 237, pp. 90-105, 1998.

6. R Frezza, G. Picci and S. Soatto "A Lagrangian Formulation of Nonholonomic Path Following" in *The Confluence of Vision and Control*, D. Kriegman, G. Hager and S. Morse eds. Springer-Verlag Lecture Notes in Control and Information Systems (LNCIS) n. 237, pp. 118-133, 1998.

7. A. Chiuso and G. Picci, "A wide-sense estimation theory on the unit sphere", in *Proceedings of the 1998 Conference on Decision and Control*, Tampa, Florida, paper n. FM02-5, p. 3745-3750, 1998.

8. A. Chiuso, A. Ferrante, G. Picci (2005) Reciprocal realization and modeling of textured images" *Proc. of CDC-ECC05*, pp. 6059-6064, Sevilla, Spain.

9. A. Chiuso, G. Picci and S. Soatto (2008), Wide sense estimation on the orthogonal group, *Communications in Information and Systems (the Brockett legacy special issue)*, **8**, pp. 185-200.

10. A. Chiuso and G. Picci (2008), Some identification techniques in computer vision (invited paper), in *Proc. of the 47th IEEE Decision and Control Conference*, pp. 3935-3946, Cancun, Mex. Dec. 2008.

6 Applied projects and Grants

Applied work which has resulted from several contracts with industries and research agencies has led to the implementation of stochastic filtering and modern control algorithms to marine systems, electric drives, and more recently, to autonomous mobile robots based on computer vision. Principal industrial or applied scientific projects,

1. *Design of single–point mooring control systems for large tankers*, 1984, contract with TECNOMARE S.p.A., Venice, Italy. Co–investigators G.B. Di Masi and L. Finesso.

2. Project manager and team leader of the italian team (IT-LADSEB) for the European Research Network of Excellence *System Identification* (ERNSI), funded by the Commission of the European Communities through the Human Capital and Mobility Program (HCM), formerly SCIENCE Project, started in 1992 and concluded in 1996.

3. Principal investigator of *Guidance and Control of Autonomous Vehicles based on Computer Vision*, reserch grant funded by the Italian Space Agency, (A.S.I.), Rome, awarded in 1992-93-94-95-97-99, co-investigators R. Frezza, P. Perona and S. Soatto. Some papers describing the work done in this area are listed above.

4. *Control of an underwater manipulator based on local image features*, 1994, TECNOMARE and SAIPEM SpA contract, co-investigator R. Frezza.

5. Project manager and team leader of the italian team (IT–LADSEB) for the European Research Network of Excellence *System Identification* (ERNSI), funded by the Commission of the European Communities through the Training and Mobility of Researchers Program (TMR), 1997-2003.

6. National coordinator and principal investigator of the University of Padova team, of the national research project *Identification and Control of Industrial Systems* funded by the italian ministery of higher education (MURST), 1998-2000.

7. National coordinator and principal investigator of the University of Padova team, of the national research project *Identification and Adaptive Control of Industrial Systems* funded by the italian ministery of higher education (MURST), 2000-2002.

8. National coordinator and principal investigator of the University of Padova team, of the national research project *New Algorithms for the Identification and Adaptive Control of Industrial Systems* funded by the italian ministery of university research (MIUR), 2002-2004.

9. Consultant for various industrial groups, among which Tecnomare S.p.A. Venice, Italy; Ferrari S.p.A. Maranello, Italy; SATE S.r.L. Venice,Italy; Salvagnini S.p.A. Vicenza, Italy; and others.

10. General Coordinator and principal investigator of the University of Padova team, of the reasearch cluster *Robotic Vision* for the Italian Space Agency, (A.S.I.), Rome, 1999-2000-2001.

11. General Project Coordinator and University of Padova team leader, of the European Community IST project *Real-time Embedded Control of Mobile Systems with Distributed Sensing (RECSYS)*, V-th Framework Programme, 2002-2005.

12. National coordinator and principal investigator of the University of Padova team, of the national research project *New Algorithms for the Identification and Adaptive Control of Industrial Systems* funded by the italian ministery of university research (MIUR), 2006-2008 and 2008-2010.