Symposium to Honor Bill Wolovich

Simposio Técnico en Honor a Bill Wolovich

December 7, 2008

Cancun, Mexico

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Una Fiesta para Wolovich

Sunday, December 7, 2008

Welcome Message from the Symposium Chairs

It is wonderful to be here in Cancun with all of you to celebrate and honor Bill's many accomplishments. Welcome!

This Symposium is to honor Bill Wolovich, who is turning 70 (ish) this year. Bill has contributed to many research areas including Multivariable Control, Robotics, Computer Vision and this event covers all of these and more. As you know Bill retired from Brown University a few years back, in 2001, but he continues teaching Brown's freshman engineering course. A detailed description of Bill's career and extensive accomplishments may be found in the article at the end of this book of abstracts.

Planning for the symposium has been very rewarding as it gave us the opportunity to revive old friendships and start new ones. We decided to have this Symposium just before the 2008 CDC in a warm place, at the beach in Cancun. The alternative was to have it on the campus of Brown University, a fine location, but at the end we opted for the more exotic destination. Steve and I are the symposium organizers, general chairs, program chairs, and chairs for local arrangements, registration, publicity, publications and finance. We have put together a strong technical program and we believe an interesting social program as well.

We would like to thank the 2008 CDC organizing committee, particularly Chaouki Abdallah, the General Chair, and Rafael Sandoval, the Local Arrangements Chair, for their continuous help and enthusiastic support.

Our special thanks go to you, the participants, for making this Symposium possible and we hope, memorable.

Welcome and thank you for coming!

Panos Antsaklis
University of Notre Dame

Steve Morse
Yale University

Speakers

Brian Anderson
Australian National University, Australia

Panos Antsaklis
University of Notre Dame

Shankar Bhattacharyya
Texas A & M University

Manolis A. Christodoulou
Technical University of Crete, Greece

G. Conte
Università Politecnica delle Marche, Ancona, Italy

Edward Davison
University of Toronto, Canada

Jean-Michel Dion
Institut Polytechnique de Grenoble, France

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SC Solutions Inc. and Stanford University

Mike Grimble
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Peter Kazanzides
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Vladimir Kucera
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Frank Lewis
University of Texas at Arlington

Steve Morse
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Hitay Özbay
Bilkent University, Ankara, Turkey

Thomas Parisini
University of Trieste, Italy

A.M. Perdon
Università Politecnica delle Marche, Ancona, Italy

Anders Rantzer
Lund University, Sweden

Michael Sebek
Czech Technical University, Prague, Czech Republic

Eduardo D. Sontag
Rutgers University

Mustafa Ünel
Sabanci University, Istanbul, Turkey

Program

8:15 – 8:30 Welcome and Opening Remarks

8:30 – 10:30 Presentations

Deadbeat Response is l_2 Optimal

Vladimir Kucera

A Simple Polynomial Approach to Nonlinear Control

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Numerical Algorithms for Polynomial Plus/Minus Factorization

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Hitay Özbay

Medical Robots and their Control Paradigms

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Rotational Motion with Almost Global Stability

Jose Vasconcelos, Carlos Silvestre, Paulo Oliveira and Anders Rantzer

10:30 – 11:00 Coffee Break

11:00 – 12:00 Presentations

Multivariable Zero-free Transfer Functions, and Their Application in Economic Modeling
Brian Anderson and Manfred Deistler

Zeros and Zero Dynamics for Linear, Time-delay Systems
G. Conte and A.M. Perdon

A Study of Feedback Fundamentals
Panos Antsaklis

12:00 – 12:30 Discussion – Then and Now in Control
Panos Antsaklis – Moderator

12:30 – 2:00 Lunch

2:00 – 4:00 Presentations
Some Notes on Realization Theory
Shankar Bhattacharyya

Recent Advances in Positive Systems: Evolution to the Servo Problem
Bartek Rosak and Edward Davison

Neural Network-Based Adaptive Optimal Controller — A Continuous-Time Formulation
D. Vrabie, Frank Lewis and D. Levine

Some Results on Input Classes for Identifiability
Eduardo D. Sontag

Control in Semiconductor Wafer Manufacturing
Abbas Emami-Naeini

Micromanipulation Using Vision and Force Feedback
Hakan Bilen and Mustafa Ünel

4:00 – 4:30 Coffee Break

4:30 – 5:30 Presentations
New Trends in Neuro-Fuzzy Adaptive Control Schemes
Manolis A. Christodoulou and Yiannis S. Boutalis

Sensor Classification for Control and Diagnosis Problems, A Structural Approach

Jean-Michel Dion and C. Commault

From Centralized to Distributed Fault Detection: An Adaptive Approximation Approach

Thomas Parisini and Marios M. Polycarpou

5:30 – 6:30	In Bill's Honor *Steve Morse* – Moderator *Peter Kazanzides*
7:30	Dinner

Abstracts

Brian D. O. Anderson
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Manfred Deistler
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Multivariable Zero-free Transfer Functions, and Their Application in Economic Modeling

Central banks and funds investment managers work with mathematical models. In recent years, a new class of model has come into prominence—generalized dynamic factor models. These are characterized by having a modest number of inputs, corresponding to key economic variables and industry-sector-wide variables for central banks and funds managers respectively, and a large number of outputs, economic time series data or individual stock price movements for example. It is common to postulate that the input variables are linked to the output variables by a finite-dimensional linear discrete-time dynamic model, the outputs of which are corrupted by noise to yield the measured data. The key problems faced by central banks or funds managers are model fitting given the output data (but not the input data), and using the model for prediction purposes. These are essentially tasks usually considered by those practicing identification and time series modelling. Nevertheless there is considerable underlying linear system theory. This flows from the fact that the underlying transfer function matrix is tall. This talk will describe a number of consequences of this seemingly trivial fact. For example, a tall transfer function of known McMillan degree but otherwise generic has no zeros, finite or infinite. A finite sequence of output data in the discrete time case allows recovery of a finite sequence of input data, without knowledge of the initial state. Canonical state-variable forms take on a special format.

Key references outlining this work are as follows:

Anderson, B.D.O., Deistler, M., Generalized linear dynamic factor models—a structure theory, CDC 2008, to appear.
Anderson, B.D.O. and Deistler, M., Properties of zero-free transfer function matrices. SICE Journal of Control, Measurement and System Integration, to appear.

Panos Antsaklis
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A Study of Feedback Fundamentals

In the area of Systems and Control theory, the emphasis has been on designing feedback controllers given a model of the process to be controlled and a number of control specifications. Many powerful methodologies have been introduced in the past half century to design controllers that stabilize and achieve desired performance in a robust way, being tolerant to certain class of plant parameter variations and external disturbances. Feedback or closed loop control, instead of feed-forward or open loop control, is used because of uncertainties in the plant and its environment. Significantly less effort has been spent in the past half century on understanding exactly how and why feedback works so well not only in the control of engineered systems but in natural systems as well. What are the fundamental principles, the fundamental mechanisms, which make feedback control so powerfully effective? These fundamental mechanisms should be independent of the particular type of mathematical models used, that is the system may be described by differential equations, by automata, by logic expressions, by natural language since we do know that feedback is ubiquitous and works! What are these fundamental properties that are present everywhere? This talk will raise many questions and I hope will provide a few answers as well.

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Some Notes on Realization Theory

In this talk, prepared in honor of Prof. Wolovich's 70th birthday, we discuss some issues related to minimal and non-minimal realizations and their role in controller synthesis. In particular, it is pointed out that realizations may be generically minimal or fragile with respect to system parameters. The latter class of systems are minimal only on an algebraic variety. Reliable control and stabilization can be achieved in such cases by first perturbing the system away from this variety to restore its locally maximal order and to base controller design based on this perturbed model. Examples illustrating this departure from the conventional wisdom of always using minimal realizations, will be included in the talk.

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New Trends in Neuro-Fuzzy Adaptive Control Schemes

We use a new definition of Neuro-Fuzzy Dynamical Systems, using the concept of Fuzzy Dynamical Systems (FDS) in conjunction with High Order Neural Network Functions (F-HONNFs). The dynamical system is assumed nonlinear and totally unknown. We first propose its approximation by a special form of a fuzzy dynamical system (FDS) and in the sequel the fuzzy rules are approximated by appropriate HONNF's. Thus the identification scheme leads to a Recurrent High Order Neural Network, which however, takes into account the fuzzy output partitions of the initial FDS. The proposed scheme does not require a priori experts' information on the number and type of input variable membership functions, making it less vulnerable to initial design assumptions. After the identification process we adaptively control the system either directly or indirectly. By doing so, we present weight updating laws for the involved HONNs. With rigorous proofs we guarantee that the errors converge to zero exponentially fast, or at least become uniformly ultimately bounded. At the same time we guarantee stability by proving that all signals in the closed loop remain bounded. During both the identification and control process we assume, first that we know the centers and shapes of membership functions, and we identify the HONN parameters in which case we get a directional variation. Thus in order to guarantee existence of the control law, we define a new method replacing the well known projection, which is termed parameter hopping and thus we rigorously prove existence of the control law, guaranteeing stability properties. In the sequel we also assume, that both membership function centers and HONN parameters are identifiable, ending up with a bilinear multivariable adaptive control problem which is solved for the first time in the adaptive controls literature. In this last case we are able to adaptively controlling the system, while the updating laws automatically update the parameters as well as the centers of the membership functions, placing them optimally in space. The only requirement is that we know the signs of the centers, a condition that may be relaxed in our future research work using a method similar to the Nussbaum gain for scalar-vector bilinear cases. Simulations illustrate the potency of the method and comparisons with conventional approaches are given. The simulation tests are based on benchmark examples. Also, the applicability of the method is tested on a DC Motor system where it is shown that by following the proposed procedure one can obtain asymptotic regulation.

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Zeros and Zero Dynamics for Linear, Time-delay Systems

The notion of zero of a linear, dynamical system can be investigated and studied from many different points of view. In particular, the algebraic approach proposed some time ago by M. Sain and B. Wyman provides conceptual and practical tools for generalizing the notion of zero to several classes of dynamical systems, notably to systems with coefficients in a ring. By representing time delay systems as systems with coefficients in a ring, it is possible to introduce a suitable notion of zeros and of zero dynamics in the time delay framework, that turns out to be useful for studying interesting control problems. In this paper, we discuss such notions and their features, both from an algebraic point of view and from a geometric one, highlighting the relationship between zeros and controlled invariance subspaces of the state space. In addition, we investigate the role of zeros and zero dynamics in the design of feedback control loops and in inversion problems involving time delay systems and we show the practical use of those notions in dealing with tracking problems in the time-delay framework.

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Recent Advances in Positive Systems: Evolution to the Servo Problem

The servomechanism problem has been of importance in the emergence of LTI systems over the span of several decades. However for the class of "positive systems" , there is a gap in the research literature in that the tracking and disturbance rejection problem, although of great importance, has been ignored. Thus the goal of this talk is to give an overview of recent results obtained for the tracking and disturbance problem for positive LTI systems.

A positive LTI system is an LTI system with the imposed constraints that the state, output and/or input variables be nonnegative for all time. The motivation for studying these systems is that the nonnegative property occurs quite frequently in various applications and in nature, e.g. they immediately arise in hydrology, engineering stocking, baking ovens, furnace systems, building temperature control systems, in almost all areas of biology.

The talk will present various results discussing the servomechanism problem under measurable or unmeasurable disturbances for both known (or unknown) positive LTI systems.

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Sensor Classification for Control and Diagnosis Problems: A Structural Approach

Control and diagnosis of dynamical systems require measures or estimation of system variables via sensors. In this paper we consider the sensor network design problem. This problem amounts to finding sets of variables to be measured by sensors for observation or control purposes as observability, disturbance rejection or diagnosis for example.

In this paper we address the sensor classification problem in the following sense. Given a system with its sensor network and a property P which is satisfied by this system with the existing sensors, we will classify the sensors with respect to their importance relative to the preservation of the property P in case of failure. More precisely we will characterize the sensors which are critical, i.e. which failure leads to property loss and those which are useless for the property. We will also quantify the relative importance of the sensors which are neither useless nor critical.

We consider here linear structured system models, they represent a large class of parameter dependent linear systems. This allows us to use graph theory in order to easily exploit the structure of the process irrespective of the parameter values. The properties which will be studied here are observability and Fault Detection and Isolation (FDI), we will then provide the sensor classification for these properties in case of sensor failure. The complexity of the classification algorithms is polynomial with respect to the dimension of the system.

The contribution of this approach is to provide with a unified framework allowing, with only a structural knowledge on the system, to determine which sensors are compulsory to use or useless to preserve a given property. Furthermore we propose a quantification of the respective importance of the useful sensors. The proposed graph approach is visual, easy to handle and close to the physical structure of the system. The underlying ideas are general and can be applied to other classes of models and properties.

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Control in Semiconductor Wafer Manufacturing

A semiconductor wafer undergoes a wide range of processes before it is transformed from a bare silicon wafer to one populated with millions of transistor circuits. Such processes include Physical or Chemical Vapor Deposition, (PVD, CVD), Chemical-Mechanical Planarization (CMP), Plasma Etch, Rapid Thermal Processing (RTP), and photolithography. As feature sizes keep shrinking, process control plays an increasingly important role in each of these processes. Model-based approach is an effective means of designing commercial controllers for advanced semiconductor equipment. We will give an overview of the applications of advanced control in the semiconductor industry. It is our experience that the best models for control design borrow heavily from the physics of the process. The manner in which these models are used for a specific control application depends on the performance goals. In some cases such as RTP and lithography, the closed-loop control depends entirely on having very good physical models of the system. For other processes such as CMP, physical models have to be combined with empirical models or are entirely empirical. The resulting multivariable controllers may be *in-situ* feedforward-feedback or run-to-run controllers, or a combination thereof. The three case studies that are presented in this paper (RTP, CMP, and lithography) are representative of the leading edge applications of advanced control in the semiconductor industry.

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Pawel Majecki
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A Simple Polynomial Approach to Nonlinear Control

Although engineering systems are nonlinear most can be controlled adequately by linear control techniques. However, there is a class of systems for which linear control design methods are inadequate and the number of applications where this is occurring is increasing. This is due to increasingly stringent demands on the required performance of some high performance control systems. Such systems have to operate in zones where severe nonlinearities often dominate. In this case reliable and simple nonlinear control design methods are essential.

One of the simplest possible optimal control methods for linear systems is the so called generalized minimum variance controller on which the proposed nonlinear method builds. The main benefits of the so called NGMV approach lie in the simplicity of the concepts and in the straightforward structure of the algorithm. Since the introduction of NGMV designs a family of controllers has been introduced to deal with the different needs of stochastic or uncertain systems. These relate to their linear counterparts of factorised GMV, LQG, Generalised H_∞ and more recently generalized predictive controls.
In certain limiting cases, all of these algorithms revert to the basic NGMV design but in asymptotic cases for linear plant models the algorithms become identical to the well known linear versions. The polynomial operator versions of these algorithms are particularly easy to use and understand. The predictive controller is the most recent to be developed and seems to have great potential. The presentation will focus mostly on the predictive NGMV control which has been evaluated on reheat furnace controls and other potential applications.

Peter Kazanzides
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Medical Robots and Their Control Paradigms

In this talk, I will provide an overview of my work in medical robotics, which began at IBM Research in 1989 with the development of the ROBODOC System for orthopaedic surgery and continued at a startup company that commercialized the technology. ROBODOC was used for over 20,000 hip and knee surgeries and recently received FDA approval. I will also describe several medical robots developed since I joined Johns Hopkins University in 2002.

The talk will then highlight the different high-level control paradigms employed in these systems, which vary from full automation to shared or cooperative control methods. In the medical environment, robot control must often balance the task goals with constraints imposed by the surgeon, the patient, or by intraoperative feedback from other devices. For example, the robot can create a virtual fixture to guide the surgeon or enforce a safety boundary; this fixture may need to be updated in real time to account for patient motion. The hope is that mechanical assistance, when coupled with appropriate control strategies, will enable surgeons to perform their tasks with greater safety and efficiency, thereby improving patient care.

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Deadbeat Response is l_2 Optimal

A typical linear control strategy in discrete-time systems, deadbeat control, produces transients that vanish in finite time. On the other hand, the linear-quadratic control stabilizes the system and minimizes the l_2 norm of its transient response. Quite surprisingly, it is shown that deadbeat systems are l_2 optimal, at least for reachable systems.

The proof makes use of polynomial matrix fractions and structure theorem for linear time-invariant multivariable systems, the notions introduced by W.A. Wolovich in the early seventies. The result demonstrates the flexibility offered by the linear-quadratic regulator design and is an exercise in inverse optimality. The linear-quadratic regulator gain is unique, whereas the deadbeat feedback gains are not. Only one deadbeat gain is linear-quadratic optimal. An alternative construction of such a gain, based on solving an algebraic Riccati equation, is thus available.

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D. Levine
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Neural Network-Based Adaptive Optimal Controller – A Continuous-Time Formulation

In this paper new online adaptive control scheme is presented for partially unknown nonlinear systems, which converges to the optimal state-feedback control solution for affine in the input nonlinear systems. The main features of the algorithm map on the characteristics of the rewards-based decision making process in the mammal brain.

The derivation of the optimal adaptive control algorithm is presented in a continuous-time framework. The optimal control solution will be obtained in a direct fashion, without system identification. The algorithm is an online approach to policy iterations based on an adaptive critic structure to find an approximate solution to the state feedback, infinite-horizon, optimal control problem.

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On Strongly Stabilizing Controller Synthesis

We present a small-gain based design method for synthesizing strongly stabilizing controllers (i.e. stable controllers stabilizing the feedback system) for various classes of linear time invariant plants. First, we consider multi-input-multi-output (MIMO) finite dimensional plants in our discussion. Next, extension of this technique to systems with time delays is illustrated. Furthermore, as a special case of stable controllers, we consider proportional plus derivative (PD) controller design for MIMO plants with input-output time delays.

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Marios M. Polycarpou
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From Centralized to Distributed Fault Detection: An Adaptive Approximation Approach

This talk deals with the problem of designing a distributed fault detection methodology for distributed (and possibly large-scale) nonlinear dynamical systems. The adaptive approximation technique extends well-known results regarding nonlinear uncertain systems to the case of distributed nonlinear systems that are modelled as the interconnection of several subsystems. The subsystems are allowed to overlap, thus sharing some state components. For each subsystem, a Local Fault Detector is designed, based on the measured local state of the subsystem as well as the transmitted variables of neighboring states that define the subsystem interconnections. The local detection decision is made on the basis of the knowledge of the local subsystem dynamic model and of an adaptive approximation of the interconnection with neighboring subsystems. The use of a specially-designed consensus-based estimator is proposed in order to improve the detectability of faults affecting variables shared among different subsystems.

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Anders Rantzer
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Rotational Motion with Almost Global Stability

Global stability is usually a highly desirable property in schemes for control and estimation. However, for rotational motion there are topological constraints preventing solutions with fully global stability. The best one could hope for is an equilibrium that is “almost globally stable” in the sense that for all initial states except for a set of zero measure, the dynamics converge to the equilibrium. In this presentation, we show how Lyapunov functions can be combined with the so called density functions to prove the desirable stability property. In fact, combination of the two concepts turns out to be more powerful than any one of them on its own.

Results are illustrated on a special type of rotational dynamics where almost globally stability can be proved with density functions of a simple analytical form. In attitude estimation for rotational bodies, the argument can be extended to also prove that the stability property is robust to measurement noise.

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Numerical Algorithms for Polynomial Plus/Minus Factorization

Two new algorithms are presented in the paper for the plus/minus factorization of a scalar discrete-time polynomial. The first method is based on the discrete Fourier transform theory (DFT) and its relationship to the Z-transform. Involving DFT computational techniques and the famous fast Fourier transform routine brings high computational efficiency and reliability. The method is applied in the case-study of H_2-optimal inverse dynamic filter to an audio equipment. The second numerical procedure originates in a symmetric spectral factorization routine, namely the Bauer’s method of the 1950s. As a byproduct, a recursive LU factorization procedure for Toeplitz matrices is devised that is of more general impact and can be of use in other areas of applied mathematics as well. Performance of the method is demonstrated by an l_1 optimal controller design example.

Eduardo Sontag
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Some Results on Input Classes for Identifiability

This talk discusses what classes of input signals are sufficient in order to completely identify (in the absence of noise) the input/output behavior of generic bilinear systems. The main results are that step inputs are not sufficient, nor are single pulses, but the family of all pulses (of a fixed amplitude but varying widths) do suffice for identifiability. The work is joint with Yuan Wang and Alexandre Megretski.

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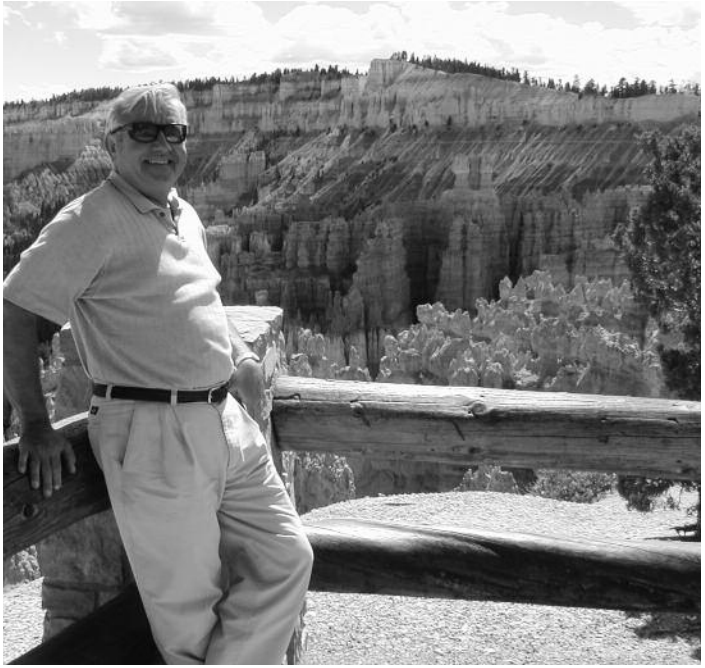
Micromanipulation Using Vision and Force Feedback

With the recent advances in the fields of micro and nanotechnology there has been growing interest in complex micromanipulation and microassembly strategies. Despite the fact that many commercially available micro devices such as the key components in automobile airbags, ink-jet printers and projection display systems are currently produced in a batch technique with little assembly, many other products such as read/write heads for hard disks and fiber optics assemblies require flexible precision assemblies. Furthermore, many biological micromanipulations such as invitro-fertilization, cell characterization and treatment rely on the ability of human operators. Requirement of high-precision, repeatable and financially viable operations in these tasks have given rise to the elimination of direct human involvement, and autonomy in micromanipulation and microassembly.

In this work, a flexible micromanipulation strategy based on vision and force feedback is developed. More specifically, a robust vision based control architecture is proposed and implemented to compensate errors due to uncertainties in position and shape of the microobjects to be manipulated. Furthermore, novel estimators are developed to identify the optical system and to characterize the mechanical properties of the biological structures through a synthesis of concepts from computer vision, estimation and control theory. Estimated mechanical parameters are utilized to reconstruct the imposed force on a biomembrane and to provide the adequate information to control the position, velocity and acceleration of the probe without damaging the cell/tissue during an injection task.



Bill Wolovich was born October 15, 1937 in Hartford, Connecticut and spent his early years in Bristol, Connecticut where he attended the local elementary and secondary schools. He excelled in physics and mathematics, and was offered a full scholarship after high school to attend General Motors Institute and subsequently work at a local GM plant in Bristol, which he declined, choosing instead to attend the University of Connecticut as an engineering student in the Fall of 1955. He graduated with honors from U. Conn in 1959 as a member of both Tau Beta Pi and Eta Kappa Nu, engineering honor societies. He subsequently received his MSEE degree from Worcester Polytechnic Institute in 1961 and entered the U.S. Air Force as a Second Lieutenant shortly after graduation.

He served as a Ground Electronics Officer in the Air Force from 1961 to 1964 and was fortunate to be stationed at Hanscom Field In Bedford, Massachusetts upon his discharge in 1964 when the NASA Electronics Research Center opened next to MIT in Cambridge. He was offered a position there in the Control Systems Group which was headed by Dr. George Kovach. This group eventually evolved into the Office of Control Theory and Applications (OCTA), headed by Dr. Hugo Schuck, and employing a number of the leading control systems researchers at that time, including Michael Athans, Roger Brocket, Peter Falb, Steven Kahn, Harold Kushner, Steve Morse, Murray Wonham and George Zames. It was a truly dynamic and exciting environment that Bill found himself in and he started taking courses at MIT and collaborating with various members of OCTA, primarily Peter Falb, who became his mentor and Ph.D. advisor at Brown, where Peter was a Professor of Applied Mathematics.

During his stay at OCTA, from 1964-1970, Bill took a number of courses at MIT, including a course on State-Space Systems, taught by Roger Brocket. These courses, and conversations with various members of OCTA, prompted Bill to study the problem of decoupling the inputs and outputs of a multi-input, multi-output (MIMO) using linear state feedback. He "solved" this problem in 1966, but required the assistance of Peter Falb to insure that the condition he derived (the nonsingularity of a matrix B*) was necessary for decoupling as well as sufficient. The complete solution was subsequently presented at the 1966 ACC at the University of Pennsylvania by Peter Falb and published in Vol. AC-12, 1967 TAC ("Decoupling in the Design and Synthesis of Multivariable Control Systems.") This was Bill's first and probably best known contribution to control theory and by 1990 had been cited well over 100 times in various technical presentations and publications.

Bill then began to look at extending the observation that the coefficients of the numerator and denominator polynomials of a SISO transfer function of a linear system appeared as columns and rows in state-space canonical forms of the system. This led him to seek polynomial matrix factorizations of the transfer matrix of a MIMO system, motivated in large part by the research of numerous individuals, including Brian Anderson, Shankar Bhattacharyya, E.J. Davison, E.G. Gilbert, Michael Grimble, B.L. Ho, R.E. Kalman, Vladimir Kucera, D.G. Luenberger, D.Q. Mayne, Steve Morse, E. Polak, J.B. Pearson, H.H. Rosenbrock, Michael Sebek, Eduardo D. Sontag, L.M. Silverman, M.K. Sain and Murray Wonham. He eventually discovered that a direct correspondence exists between the coefficients of the numerator and denominator polynomials of a special factorization of a MIMO transfer matrix and the rows and columns of canonical state-space representations provided the denominator polynomial matrix was either “row proper” or “column proper.” These definitions first appeared in the 1968 paper “On the Structure of Multivariable Systems,” SIAM Journal on Control, Vol. AC-13.

Once this observation was made, it was relatively straightforward to determine how the coefficients of the denominator polynomial matrices of MIMO systems could be totally altered by linear state feedback, and that the numerator polynomial matrix remained invariant, as in the SISO case. These results appeared in the 1968 paper “On the Stabilization of Controllable Systems,” Vol. AC-13. This discovery also led to a precise formulation of the so-called “Exact Model Matching” problem, namely when can one use (say) linear state feedback in a MIMO system to transform the transfer matrix of the system to one that exactly matches that of a given, model system. A fairly complete solution to this problem appeared in the 1972 paper “The Use of State Feedback for Exact Model Matching,” SIAM Journal on Control, Vol. 10, No. 3. Most of these earlier results also formed a significant part of Bill’s Ph.D. dissertation under the guidance of Peter Falb, a Professor of Applied Mathematics at Brown University, where Bill received his degree in 1970. His Ph.D. dissertation was subsequently embellished and published as his first book, **Linear Multivariable Systems**, Springer Verlag, 1974.

Some other significant events happened in 1970, namely the replacement of NASA’s Electronics Research Center, and OCTA, by a U.S. Department of Transportation (DOT) Research Facility, the subsequent hiring of Bill as an Assistant Professor of Engineering at Brown University, and the birth of Bill’s second child, a boy, in December. He and his wife Nancy had a girl in 1966 who would eventually graduate from Brown in 1988 and write an honor’s thesis under the direction of none other than Peter Falb! After his arrival at Brown in the summer of 1970, Bill continued his work with Peter using polynomial matrix methods to solve a wide variety of linear systems questions, including those found in the following publications:

“Output Feedback Decoupling,” *IEEE Transactions on Automatic Co*ntrol, February 1975.

“On the Cancellation of Multivariable System Zeros by State Feedback,” *IEEE Transactions on Automatic Control*, Vol. AC-19, No. 3, June 1974.

“Composite System Controllability and Observability,” *Automatica*, Vol. 10, March 1974.

“On the Numerators and Zeros of Rational Transfer Matrices,” *IEEE Transactions on Automatic Control*, October 1973.

“On Determining the Zeros of State-Space Systems,” *IEEE Transactions on Automatic Control*, October 1973.

“Frequency Domain State Feedback and Estimation,” *International Journal on Control*, Vol. 17, No. 2, June 1973.

“The Determination of State-Space Representations for Linear Multivariable Systems,” *Automatica,* January 1973.

“On the Synthesis of Multivariable Systems,” Transactions on Automatic Control, Vol. AC-18, No. 1, February 1973.

The virtual “replacement” of the Laplace operators by the differential operator D led to "The Differential Operator Approach to Linear System Analysis and Design*," Journal of the Franklin Institute*, January, 1976, which established a more direct connection between linear systems defined in the time domain and those defined in the frequency domain.

By now, Bill's reputation in control systems was growing, as evidenced by his promotion to Associate Professor with tenure in 1973 and to full Professor 4 years later. His reputation led to his having some very promising young graduate students, including Panos Antsaklis, Howard Elliott, and Vasfi Eldem. He also hosted some prominent visitors and visited some prominent hosts from the mid-70's to the early 80's, resulting in numerous publications during this period, including:

Parameterization Issues in Multivariable Adaptive Control," *Automatica*, Vol. 20 1984. (with H. Elliott).

"Discrete Models for Linear Multivariable Systems," *International Journal on Control*, 38(2) 1983 (with H. Elliott).

"Arbitrary Adaptive Pole Placement for Linear Multivariable Systems," *IEEE Transactions on Automatic Control*, AC-29(2) February 1984. (with H. Elliott and M. Das).

"Parameter Insensitive Pole Assignment for Scalar Input Systems," *IEEE Transactions on Automatic Control*, AC-28 (2), February 1983 (with V. Eldem).

"Generic Pole Assignment: Preliminary Results," *IEEE Transactions on Automatic Control*, Vol. AC-28 (4) April 1983. (with A.S. Morse and B.D.O. Anderson).

"A Frequency Domain Model Reduction Procedure," *Automatica*, Vol. 16 March, 1980. (with H. Elliott).

"Parameter Adaptive Identification and Control," *IEEE Transactions on Automatic Control*, Vol. AC-24, No. 3, June 1979 (with H. Elliot).

"Output Regulation and Tracking in Linear Multivariable Systems," *IEEE Transactions on Automatic Control*, Vol. AC-24, No. 3, June 1979. (with Pedro Ferreira).

"Arbitrary Pole Placement Using Linear Output Feedback Compensation," *International Journal on Control*, Vol. 25(6), June 1977 (with P.J. Antsaklis).

"A General Algorithm for Determining State-Space Representations," *Automatica*, Vol. 13, May 1977 (with R. Guidorzi).

"On the Stability of Solutions to Minimal and Nonminimal Design Problems," *IEEE Transactions on Automatic Control*, Vol. AC-22, No. 1, February, 1977, (with P.J. Antsaklis and H. Elliott).

By this time Bill felt that he was ready for some new challenges beyond linear multivariable control systems, so he accepted a position with the *Automated Manufacturing (Robotics) Group* at the IBM T. J. Watson Research Laboratories in Yorktown Heights, New York during a nine-month sabbatical leave from the Summer of 1983 through the Spring of 1984 to study robotics and see if any of his control background could be applied to the field. He soon discovered that the study of robotics was a highly complex and interdisciplinary field that includes not only several scientific disciplines, but social, economic, and even political issues as well. He decided to limit his initial investigations to the vast majority of robots used in manufacturing, namely fixed-base, multiple link manipulators, which require a thorough understanding of the configuration and motion kinematics associated with open kinematic chains, the static force/torque relations between the links of a manipulator and their contact with the external world, the spatial trajectory planning necessary to achieve smooth, controlled motion of a robot in Cartesian space, the dynamical behavior of manipulators combining the link forces and torques with corresponding motion, the basic control principles required ensuring coordinated link motion, and the common features that all robotic programming languages should have in order to allow human operators to implement and modify the specific tasks that robots are required to perform. Needless to say, it took Bill a while to learn much that was lacking from his control systems background, but he did master much of this material in a relatively short period of time. After his return to Brown in the fall of 1984, he and Professor Ben Freund from the Mechanics Group, initiated a very popular robotics course which culminated with the Publication of Bill's second book: **Robotics: Basic Analysis and Design**, Holt Rinehart and Winston Publishing Company, 1987. One of the primary contributions of this text was the first complete published solution to the so-called "inverse kinematic problem" for a six-link robot with a spherical wrist.

This plunge into robotics would serve to motivate much of Bill's subsequent work with new graduate students, beginning with Peter Kazanzides, who programmed an IBM Cartesian robot loaned to Brown to track smoothly around an arbitrary shape using force feedback, as reported in the technical paper: "A Multiprocessor System for Real-time Robotic Control," *Information Sciences*, Vol. 44, No. 3, 1988 (with P. Kazanzides and H. Wasti). In a later report, his Ph.D. student Dalila Megherbi reported work on obstacle avoidance in the paper "Real-Time Velocity Feedback Obstacle Avoidance via Complex Variables and Conformal Mapping," *Proceedings of the 1992 IEEE International Conference on Robotics and Automation*, Nice, France, May 1992.

However, Bill never totally lost his interest in control systems, and continued to follow results on parameter uncertainty and various robust control techniques that were being developed to compensate for systems whose mathematical models were not totally known. He felt that there was a need to integrate uncertainty into basic control system analysis and design so he began to write an undergraduate text on the subject in which he proposed a two degree of freedom (2 DOF) controller for SISO systems which did not depend on an explicit error signal between the input and output to "drive" a traditional inner loop controller. His particular approach separated loop goals, such as closed loop stability, from response goals, such as minimum time, zero error tracking. His text "**Automatic Control Systems: Basic Analysis and Design**," Holt, Rinehart and Winston (1994) concentrates on the design of 2 DOF controllers to obtain robust closed loop stability with respect to both parameter uncertainty and unmodeled dynamics, disturbance elimination, noise attenuation and robust zero error tracking. His 2 DOF controller was shown to represent the most general possible type of linear controller for SISO systems that can simultaneously achieve a variety of desired response and loop performance goals, irrespective of any particular system description.

Always looking for new challenges, Bill began to investigate another subject associated with polynomials and their application in computer vision, namely the description of closed, bounded planar curves by implicit polynomials in x and y, such as $x^2 + y^2 = 1$, an implicit polynomial equation for a simple planar circle. With the able assistance of a new graduate student, Mustafa Ünel, he was able to derive a new expression for an implicit polynomial as a product of conic (second degree) factors with unique conic factor centers. In the special case of quartics (4th degree polynomials), this expression can be written as the sum-of-products of two monica conics and two corresponding parallel lines. This finding opened the door to much further investigations by Bill and Mustafa from 1997 through 2001.

Their primary focus during that time was the development of new and innovative ways of simplifying the modeling, identification, design and measurement of a large variety of objects, a fundamental problem in Computer Vision, Artificial Intelligence and Mechatronics. During that period of time, they produced at least six major journal articles, eight conference papers and a chapter in the World Scientific Series on Machine Perception and Artificial Intelligence.

Their papers “A New Representation for Quartic Curves and Complete Sets of Geometric Invariants” in the International Journal of Pattern Recognition and Artificial Intelligence, “Pose Estimation and Object Identification Using Complex Algebraic Representations” in the Pattern Analysis and Applications Journal, and “Complex Representations of Algebraic Curves” in the Proceedings of the IEEE International Conference on Image Processing developed a new and simplified model-based approach to identifying and aligning free-form objects that are described by their boundary curves. The additional procedures outlined in their earlier papers “The Determination of Implicit Polynomial Canonical Curves” in the IEEE Transactions on Pattern Analysis and Machine Intelligence, “Fitting Circle Polynomials to Planar Objects” in the Proceedings of the First Workshop on Computer Vision, Pattern Recognition and Image Processing, and “A Complete Set of Geometric Invariants for Algebraic Curves” in the Proceedings of the International Conference on Industrial and Applied Mathematics explained how certain fundamental and classical mathematical results can be used to process computer images with a high degree of repeatability and reliability. The procedures outlined in these papers have been used in a variety of computer vision applications to locate and identify both static and moving objects.

In August of 2001, Bill gave a Plenary talk at the SSSC Conference in Prague, Czech Republic, where he drew many analogies between his earlier work in dynamical systems and his more recent investigations of algebraic (implicit polynomial) curves. In particular, he noted that the concept of canonical forms and complete sets of invariants were important and fundamental in both fields. He displayed examples of equivalent transformations for both linear systems and algebraic curves. He likened phase plane plots in control systems to implicit algebraic curves, and noted that the unique (two ellipse and a circle) structural decomposition of quartic curves is not unlike the Jordan form structural decomposition of state-space systems. Indeed, one might say that Bill never really "left" control systems to work on object recognition using algebraic curves, but rather that He used his control systems background whenever possible to enhance his understanding of new areas of research, including precision metrology; i.e. the final chapter in Bill's technical research dealt with the application of implicit polynomial methods to precision metrology.

Together with another new graduate student, Hulya Yalcin, some earlier algorithms for fitting implicit polynomial equations to both 2-D and 3-D object boundary sets were shown to be quite useful in modeling and measuring free-form manufactured parts, such as automobile bodies, aircraft wings and ship propellers. In their paper "The Precise Measurement of Free-Form Surfaces," Transactions of the ASME, Vol. 124, May, 2002, they describe a new procedure for comparing manufactured parts to a model part using implicit polynomial equations. Their theoretical procedures were then experimentally verified using a state-of-the-art Chameleon coordinate measuring machine obtained from Brown & Sharpe. Their results employed a "3L" fitting algorithm developed by Professor David Cooper and his students at Brown University, which allowed a fast and accurate fitting of measured points to an implicit polynomial equation. Several parallel profiles were used to quantify the distance errors between manufactured propeller blades and a model (ideal) blade. The results presented illustrated how their new model based measurement procedure could be employed to quickly and accurately determine the distance errors between model shapes and "identical" manufactured shapes.

Bill officially retired from Brown University in 2001 but he continued his research investigations for the next 3 years. In 2005 he was asked to assist with the teaching of the Freshman engineering course at Brown, something he had done several times in his earlier career. He agreed to do so and has continued to teach this course for the past 4 years and has no plans to discontinue this Fall assignment. Bill currently spends his winters in central Florida, playing golf, tennis, softball and pickleball, but he often can be found reclining by the pool, enjoying the warm weather and the company of his companion, Carol, a retired math teacher who recently bought a villa at Stone Creek in Ocala, Florida. He enjoys returning to Rhode Island in the Spring to his golf course condominium and visits with family and friends.

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