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Performance Reports Covering Previous Budget Periods for Grant No. DE-FG02-90ER14140

1 Performance Report

The grant in its previous budget period has already resulted in successful completion of the Ph.D. programs for two graduate students Dr. Y.T. Wu and Dr. Mrdjan Jankovic. A short abstract of each of their thesis is enclosed in Appendix I. The grant has also been used to support three other graduate students currently working with the P.I. Various papers submitted and/or accepted by referred journals and conferences have been enclosed in Appendix II. A list of invited presentations made by the P.I. and a list of forthcoming invited presentations have been included in Appendix II as well.

What follows now is a technical description of performance and achievements.

1. Motivated from problems in linear time varying system theory, the P.I. worked on the problem of coefficient assignment of a linear time varying system by a linear time varying compensator. The coefficient assignment problem is an obvious generalization of the pole assignment problem for linear time invariant systems, and can be applied to guarantee transient performance of the time varying dynamical system in the closed loop. Among the main results of this research effort, it has been shown that, provided the coefficients of the time varying plant and the coefficients of the closed loop system are given, the compensator coefficients which places the given coefficients of the closed loop system itself satisfy a nonlinear recursion. Various properties of this nonlinear recursion have been studied including the fact that in certain cases the phase portraits of these recursions could be chaotic. Such a recursive design of compensators for a linear time varying plant for the purpose of ascertaining a suitable transient behavior is new and has never been investigated before.

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2. Many problems in time varying systems are such that the time variation is as a result of internal parameters that are changing in time. Many often, these internal parameters satisfy an ordinary differential or a difference equation. Together, they constitute a nonlinear system which is in fact a time varying system with internal structure. An important class of such systems arise in computer vision where the goal is to estimate motion and shape parameters of a moving rigid body with the help of CCD cameras and control robot arms for suitable manipulation of objects in the environment. Thus if a moving textured surface produces time varying image on the image plane of a camera, the moving image can be characterized by a time varying dynamical system known as "optical flow". The optical flow equation in general contains internal parameters that describe the geometric position of the surface being observed. These internal parameters satisfy differential equations that describe how the surface being observed actually moves.

The P.I. is presently working on introducing a new technology, that of a **Visually Guided Control System**. It has been shown that such a system can be analyzed as a perspective system with internal parameters. In particular, the motion and shape estimation can be posed as a parameter identification problem. Robust manipulation of a rigid body can be posed as a perspective controllability problem. Among the technical results shown, the following is quite interesting and is also of independent interest:

Given a plant $\dot{x} = Ax$ $x(0) = x_0$, $y = Cx$ where A is a $n \times n$ matrix, C is a $m \times n$ matrix. Assume that $m > 1$ and let $z(t)$ be the observed output which is given by $z = [y]$ where $[y]$ stands for the homogeneous line which passes through the origin and y . The problem is to find necessary and sufficient conditions to observe $[x_0]$. It has been shown that, over the field of complex numbers, necessary and sufficient condition that $[x_0]$ is observable is given by

$$\text{rank} \begin{bmatrix} (\lambda_i I - A) & (\lambda_j I - A) \\ C \end{bmatrix} = n$$

for all λ_i, λ_j (not necessarily distinct) eigenvalues of A . Over the field of real numbers, the above condition is sufficient but not necessary.

The above result generalizes a well known PHB rank test for the observability of a linear dynamical system.

3. The P.I. has also worked on an observer design problem for a class of nonlinear systems. The problem of observer design for this class of nonlinear systems is shown to be equivalent to that of observer design for a family of time varying linear systems. An observer based on Kalman Filter has been considered and under a suitable generalization of the well known uniform complete observability condition, the estimation error of the observer is shown to be globally exponentially stable. Unfortunately however, this generalization of uniform complete observability condition is impossible to be verified and a new sufficient condition has been obtained. As a corollary of this result a sufficient condition for persistency of excitation in parameter identification has been derived. The results are illustrated via an example derived from the model of rotating rigid body.

Among the many application of the observer design problem, we consider an approach to control elastic modes of the joints using only measurements of the variables on the rotor side. First, a simple and robust observer for an elastic joint robot is proposed to estimate link positions and velocities. The state estimates are then used in a fast inner loop to stabilize oscillations in the joints. The observer based controller obtained in this way is very simple and robust with respect to parameter uncertainties. Simulations have shown good performance of the observer in the presence of measurement noise and confirmed that the closed loop system performs well, despite the significant mismatch between parameters of the robot and the observer.

4. The P.I. has investigated the problem of visually-guided tracking of a moving object by a robot manipulator. Two different tracking schemes have been proposed that are either position based or image based. Each of the two schemes consists of two aspects viz. Estimation of the motion parameters of the moving object by vision based techniques and design of a tracking controller by nonlinear regulator theory. The overall performance has been demonstrated by simulation wherein the performance of the two proposed schemes has been compared.

To summarize the achievements so far, P.I. proposes to introduce visually

guided control systems as a part of a new technology in feedback control system analysis and design. The associated perspective system theory has been introduced and the corresponding perspective observability problem has been solved. Partial results in perspective identifiability problems have also been derived and many questions like the perspective realization problem remain open. In many instances a new class of observers are proposed that perform the parameter identification. Finally, visually guided tracking problem has been analyzed for the case of a robot manipulator.

In short, Perspective System Theory has been established as a new tool for the analysis and design of Vision Based Dynamical System. Further investigation of this challenging problem is proposed.

2 Appendix I

2.1 Summary of the thesis entitled "Estimating Three Dimensional Motion Parameters from Feature Based Image Sequence: A Perspective System Approach," by Yaw-Tyng Wu

A new approach is presented for the estimation of object motion parameters based on a sequence of perspective images. The problem considered is that of a rigid body undergoing an unknown movement which consists of a constant translational velocity and a constant rotational velocity with respect to a camera. The velocities are assumed to be the parameters to be estimated. The measurement data consists of a sequence of image coordinates of a geometric feature. In this dissertation, such a feature is considered to be a point, a straight line, or a planar second order polynomial curve.

By modeling the object dynamics and the observation as time functions, we obtain a dynamical system. For each of the above features, we show that the dynamical system so obtained forms a special class of nonlinear system, called perspective system. As a consequence, the problem of motion estimation reduces to a problem of identifying the parameters of a perspective system for which one could apply various existing techniques from system theory.

We derive necessary and sufficient conditions for identifiability of motion parameters. Based on a theory of perspective system introduced in this thesis

we obtain an observer for a rigid body undergoing pure rotation. Numerical solution to the motion estimation problem via line correspondence is given as an example to show the usefulness of our approach. Results show that the solution to the estimation problem can always be obtained accurately and are reasonably robust if identifiability conditions are satisfied.

An important aspect of our algorithm is that it requires us to consider the motion of a single point (for the point correspondence problem) or the motion of two straight lines (for the line correspondence problem) in order to identify the motion parameters. This fact may be considered with the existing results in the literatures where more feature correspondences are required.

2.2 Summary of the thesis entitled “Observer Design and Identification of Nonlinear Systems,” by Mrdjan Jankovic

The main topic of this dissertation is observer design for nonlinear systems. Inspired by results in the areas of linear time varying systems and parameter identification, we propose an observer based on the Kalman filter for a class of nonlinear systems. It is shown that the state estimates are convergent under an observability assumption which is a suitable generalization of the notions of uniform complete observability for linear systems and persistence of excitation in parameter identification.

The class of nonlinear systems for which an observer can be designed is extended by using a high-gain compensation for a portion of nonlinearities present in the system. One of the observers with high-gain compensation is based on a parameter identifier and the interesting feature of this observer is that it does not need the propagation of the Riccati equation which is necessary in all observers based on the Kalman filter. This has important practical consequences because the computational complexity associated with the real time propagation of the Riccati equation often prohibits the application of observers that contain it.

The uniform complete observability assumption that guarantees the convergence of the state estimates for the proposed observers is very difficult or even impossible to check in advance. Therefore, a checkable sufficient condition is developed which gives, as a corollary, a sufficient condition for the

persistence of excitation. The usefulness of these results is illustrated by a number of examples derived from the models of physical systems. Most of the examples have some practical significance.

Finally, based on the results of this work, two observers for robots with elastic joints are proposed. Because its assumed measured variables coincide with those typically measured in industrial robots and because of its simplicity and robust performance, one of these observers is a good candidate for application in controller design.

3 Appendix II

3.1 List of PhD Students Supported by the Grant

- **Y.T. Wu** Some New Problems in Perspective System Theory, Washington University, Saint Louis, December 1991.
- **M. Jankovic** Observer Design and Identification of Nonlinear Systems, Washington University, Saint Louis, December 1992.
- **M. Lei** Some New Problems in Visual Control Theory
- **Zhenyu Yu** Application of Visual Control to Robot Manipulation.
- **Jing Zhou** On Some Computational Problems in Visual Control

3.2 Papers Submitted to/Accepted by Refereed Journals

- Bijoy K. Ghosh and P. R. Bouthellier, Simultaneous Coefficient Assignment of Discrete Time MultiInput MultiOutput Linear Time Varying Systems: A New Approach for Compensator Design, Accepted for publication in SIAM J. Control and Optimization.
- M. Jankovic, A New Observer for a Class of Nonlinear Systems, Accepted for publication in Journal of Mathematical Systems Estimation and Control.
- Bijoy K. Ghosh, Mrdjan Jankovic and Y.T. Wu, Perspective Problems in System Theory and its Application to Machine Vision, Accepted

for publication in Journal of Mathematical Systems Estimation and Control.

- W. Dayawansa, B. Ghosh, C. Martin, X. Wang, A Necessary and Sufficient Condition for the Perspective Observability Problem, Accepted for publication in Systems and Control Letters.
- Ted Loucks, B. K. Ghosh, A Perspective Theory for Motion and Shape Estimation in Machine Vision, Submitted for publication in Journal of Mathematical Systems Estimation and Control.
- M. Jankovic, Observer Based Control for Elastic Joint Robots, Submitted to IEEE Transactions on Robotics and Automation.

3.3 Papers presented at Conferences

- Bijoy K. Ghosh and Y.T. Wu, Observability of Perspective Systems: A New Approach to Computer Vision, Proceedings of the Second Bozeman Conference, Bozeman, Montana, August 1- 7, 1990. Computation and Control II, Birkhauser, Boston, 1991, pp. 125-134.
- Bijoy K. Ghosh and Y. T. Wu, Observability and Identifiability Problems in Perspective Systems: A New Approach to Computer Vision, SPIE Vol. 1607 Intelligent Robots and Computer Vision X: Algorithms and Techniques (1991), pp. 589-600.
- M. Jankovic, Exponentially Stable Observer for Elastic Joint Robots, To be presented at the 31st IEEE conference on Decision and Control at Tucson, Arizona, 1992.
- Ming Lei and Bijoy K. Ghosh, New Geometric Methods in Computing the Motion Parameters of a Rigid Body using Line Correspondences, Proceedings of the American Control Conference, 1992, pp. 1500-1504.
- Ming Lei and Bijoy K. Ghosh, A New Nonlinear Feedback Controller for Visually-Guided Robotic Motion Tracking, Submitted to the European Control Conference, ECC'93.

- Ted Loucks, B. K. Ghosh and John Lund, An Optical Flow Based Approach for Motion and Shape Parameter Estimation in Computer Vision, To be presented at the 31st IEEE conference on Decision and Control at Tucson, Arizona, 1992.
- Bijoy K. Ghosh, M.Jankovic and Y. T. Wu, Some problems in Perspective System Theory and its Application to Machine Vision, Proceedings of the 1992 IEEE/RSJ International Conference on Intelligent Robots and Systems, Raleigh, NC, July 7-10, 1992, pp. 139-146.
- Bijoy K. Ghosh, M.Jankovic and Y. T. Wu, Some New Results in Perspective System Theory and its Application to Computer Vision, Proceedings of the Ninth Symposium on Energy Engineering Sciences - Fluid and Dynamical Systems, May 13- 15, 1991, at the Argonne National Laboratory, Argonne, Illinois, Report No. CONF-9105116, pp. 85-92.
- B. K. Ghosh and M. Lei, Visually guided robotic motion tracking, Proceedings of the Thirtieth Annual Allerton Conference on Communication, Control and Computing, September 30-Oct 2, 1992.

3.4 Invited Presentations

- "Some New Results in Computer Vision," Invited Presentation at the second conference on Computation and Control, Montana State University, Bozeman, Montana, August 1-7, 1990.
- "Convergence Analysis of Linear Dynamical Systems by High Gain and High Dynamic Compensator," 2nd SIAM Conference on Linear Algebra in Signals, Systems and Control, San Francisco, California, Nov. 5-8, 1990.
- "Estimation of Motion and Shape Parameters of a Rigid Body from its Orthogonal and Perspective Projections," 2nd SIAM Conference on Linear Algebra in Signals, Systems and Control, San Francisco, California, Nov. 5-8, 1990.

- “Global Stabilization of Discrete Time Nonlinear Systems,” 2nd SIAM Conference on Linear Algebra in Signals, Systems and Control, San Francisco, California, Nov. 5-8, 1990.
- “Simultaneous design problems in linear system theory,”
“Perspective System Theory: A new perspective in machine vision,”

Presented the above series of two lectures at the Center for applied mathematics, University of Notre Dame, Notre Dame, Indiana 46556 on April 16th and April 18th, 1991.

- “Observability problems in perspective system theory and its application to computer vision,” Presented at the 2nd NIU Conference on Linear Algebra, Numerical Linear Algebra, and Applications, Northern Illinois University, DeKalb, Illinois, May 5, 1991.
- “Some New Results in Observer Design and its Application to Perspective Systems,” Presented at the 9th Symposium on Energy Engineering Sciences, Argonne National Laboratory, Argonne, IL, May 13, 1991.
- “A survey of simultaneous stabilization problems for linear time invariant systems and linear time varying systems,” Presented at the Department of Control Engineering, Tokyo Institute of Technology, Japan, June 12, 1991, and at the Department of Information Sciences, Tokyo Denki University, Hatoyama-Machi, Hikigun, Saitama, Japan 350-03, 24th June, 1991.
- “Some new perspective on machine vision,” Presented at the the Department of Mathematical Engineering and Information Physics, University of Tokyo, Bunkyo-ku, Tokyo 113, Japan, June 10, 1991, and at the Department of Mechanical Engineering, Nagoya University, Japan on 14th June, 1991 and at the Department of Information Sciences, Tokyo Denki University, Hatoyama-Machi, Hikigun, Saitama, Japan 350-03, 25th June, 1991.
- “Problems in perspective system theory and its application to correspondence problems in machine vision,” Presented at the Beckmann Institute, University of Illinois at Urbana, Champaign. Dec. 18, 1991

and at the General Robotics and Active Sensory Perception Laboratory (GRASP), University of Pennsylvania, 3401 Walnut Street, Philadelphia, PA 19104 on Feb. 19, 1992.

- “Perspective problems and its application to Computer Vision and System Theory,” “Algebraic Geometric methods in the study of line based correspondence problems in computer vision” and “A new nonlinear feedback controller for visually guided robotic motion tracking.” Presented at the Department of Mechanical Engineering for Computer-Controlled Machinery, Faculty of Engineering, Osaka University, 2-1 Yamadaoka, Suita, Osaka 565, Japan, on 25th July, 27th July and 1st August, 1992.
- “Some New Results in Computer Vision,” Invited Presentation at the third conference on Computation and Control, Montana State University, Bozeman, Montana, August, 1992.
- “Dynamical Systems approach to Computer Vision,” SIAM Conference on Applications of Dynamical Systems, Salt Lake City, Utah, October 15-19, 1992.

3.5 Forthcoming Invited Presentations

- Special Session on Time Varying Systems at The 1993 American Control Conference, Westin St. Francis, San Francisco, CA, June 2-4, 1993 (Organizer: Dr. Brad Lehman)
- Special Session on Image Based Control of Dynamical Systems at The 1993 American Control Conference, Westin St. Francis, San Francisco, CA, June 2-4, 1993 (Organizer: Dr. Banavar Sridhar)
- Invited to a special session on Time Varying Linear Systems Analysis and Control at IFAC 12th World Congress Sydney, Australia, July 19-23, 1993 (Organizer: Bittanti Sergio).
- Organized a special session on Image Based Control of Dynamical Systems together with Dr. H. Kimura and Dr. Pradeep Khosla at IFAC 12th World Congress Sydney, Australia, July 19-23, 1993

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