DOUBLE-OPTIMAL, ANTI-SATURATION, INTEGRATED GUIDANCE AND CONTROL OF KINETIC KILL INTERCEPTORS

1 COVER SHEET (ON-LINE SHEET)

2 IDENTIFICATION & SIGNIFICANCE OF THE OPPORTUNITY

The theoretical basis for current guidance, navigation and control (GNC) algorithms implemented in interceptors, has evolved from linear control theory for the case of simple target maneuvers. These implementations have suffered from a lack of robustness when future-threat target maneuvers are encountered. Also, the spiraling and chaotic nature of ballistic targets in the atmosphere stress current GNC capabilities to derive and execute a maneuver with speed and accuracy to effect a direct hit.

To improve hit rate performance and enhance prototyping, this proposal presents a new GNC approach with solutions for the following major technology aspects;

- An offline Neural Network (NN) identification of a nonlinear kinetic kill interceptor model
- Optimal linearization of the identified nonlinear kinetic kill interceptor model
- Optimal design of a tracker/controller
- Acceleration anti-saturation provision

The proposed overall approach involves the solution of two optimization problems in order to design an integrated kinetic kill interceptor guidance and control system. The first optimization problem takes a general nonlinear kinetic kill interceptor model and develops optimal linear models at each operating point of interest, by minimizing the norm difference between the states in the nonlinear system and the set of desired linear systems. While the nonlinear model could be either continuous-time or discrete-time, in this case a discrete-time nonlinear model is identified using fast-sampled input/output kinetic kill interceptor data. Using neural networks, which are capable of approximating any nonlinear function with arbitrary precision [1], we are able to accurately capture the dynamics of the kinetic kill interceptor. The NN model is then optimally locally linearized, thus yielding optimal local linear models that have the exact dynamics of the original system, not only at the equilibrium points but also at any operating point of interest, with minimum modeling errors in the vicinity of those operating points. The importance of this step is that in a real system with only input/output data available, we are able to accurately capture the nonlinear dynamics of the system using NN offline only.

The second interceptor optimization problem then determines the optimal linear controller/tracker that minimizes an appropriate objective function. The advantage of this approach is that a single Jacobian linear model of the kinetic kill interceptor is not used, but rather a set of optimal linear models parameterized by kinetic kill interceptor operating point conditions are used. The significance is that the optimal linear models at every operating point of interest accurately capture the nonlinearities of the kinetic kill interceptor, without assuming steady state or small signal operations of the kinetic kill interceptor. This proposed approach has proved extremely successful in developing trackers for systems with chaotic inputs whose dynamics change quite severely in short periods [2, 3, 4]. An anti-digital redesign approach newly presented in [2] to estimate the parameters of a continuous-time controller from the parameters of a digital controller, without directly utilizing a continuous-time model of the kinetic kill interceptor, is also proposed. This is attractive as identification of continuous-time models is more difficult than identification of discrete-time models.

One major concern of kinetic kill interceptor guidance and control design is that of acceleration saturation. In this regard, it is well know that the lack of adequate acceleration capability could result in additional miss distance issues. Acceleration saturation generally result due to angle of attack constraints at high altitudes, kinetic kill interceptor structure limits at low altitudes in the case of endoatmospheric interceptors, and thrust-to-weight ratio limits in the case of exoatmospheric kinetic kill interceptors. As part of an integrated offering, this proposal also presents a digital redesign based anti-saturation scheme that is incorporated into the overall kinetic kill interceptor GNC scheme.

2.1 Identification of a nonlinear state space model using a neural network

For purposes of phase1, using fast-sampled input-output data from a known kinetic kill interceptor model of the form

$$\dot{x}(t) = f(x(t)) + g(x(t))u(t), \tag{2.1}$$

where $x(t)$ is the state vector, $u(t)$ the control input and

$f : \Re^n \rightarrow \Re^n,$
$g : \Re^n \rightarrow \Re^{nxm},$
$x(t) \in \Re^n,$
$u(t) \in \Re^m.$

we identify a neural network discrete-time model of the form [2]

$$\boldsymbol{x}(k+1) = \hat{\boldsymbol{F}}(\boldsymbol{x}(k), \boldsymbol{u}(k)), \tag{2.2}$$

where $\hat{\boldsymbol{F}} : \boldsymbol{R}^{n+m} \rightarrow \boldsymbol{R}^n$ is the neural network discrete-time model of the system, which calculates the state $\boldsymbol{x}(k+1)$ at the sampling time $k+1$ as a nonlinear function of the state $\boldsymbol{x}(k)$ and the input $\boldsymbol{u}(k)$ at the previous sampling time k. Note that in general, a neural network state-space model is nonlinear in both the state and the input. For the current work, it is assumed that the order n of the system is known, and that all states are available.

2.2 Optimal Linearization of nonlinear systems

The approach of using local models parameterized by operating point conditions is an effective way of dealing with nonlinear modeling and control problems. This is particularly attractive as the complete set of well established linear analysis and design techniques can be directly applied with this approach. Unlike Jacobian linearization which typically yields affine models except at system equilibrium points, the proposed optimal linearization scheme yields true linear models that are also optimal at every operating point of interest.

Consider a family of nonlinear system models given by

$$\dot{x}(t) = f(x(t)) + g(x(t))u(t), \tag{2.3}$$

where $x(t)$ is the state vector, $u(t)$ the control input and

$f : \Re^n \to \Re^n$,
$g : \Re^n \to \Re^{nxm}$,
$x(t) \in \Re^n$,
$u(t) \in \Re^m$.

We can develop a local linear model (A_j, B_j) at some operating point of interest $(x_j,\ u_j)$, which is not necessarily an equilibrium point of the system. Let the linearized model be given by

$$\dot{x}(t) = A_j x(t) + B_j u(t), \tag{2.4}$$

with A_j and B_j constant matrices of appropriate dimensions. As indicated in [5], these constant matrices are given by

$$a_i = \nabla f_i(x_j) + \frac{f_i(x_j) - x_j^T \nabla f_i(x_j)}{\left\| x_j \right\|_2^2} x_j, \quad x_j \neq 0, \tag{2.5}$$

$$B_j = g(x_j), \tag{2.6}$$

where a_i^T is the i^{th} row of matrix A_j. To illustrate this procedure for an uncoupled nonlinear system, consider the chaotic attractor [4]

$$\begin{aligned} \dot{x}_1(t) &= a(x_2(t) - x_1(t)), \\ \dot{x}_2(t) &= (c-a)x_1(t) - x_1(t)x_3(t) + cx_2(t), \\ \dot{x}_2(t) &= x_1(t)x_2(t) - bx_3(t), \end{aligned} \tag{2.7}$$

where $a = 35$, $b = 3$ and $c = 28$. Using the above procedure [4], we have

$$A_j = \begin{bmatrix} -35 & 35 & 0 \\ -7 - x_{3j} + \dfrac{x_{1j}^2 x_{3j}}{\|x_j\|_2^2} & 28 + \dfrac{x_{1j} x_{2j} x_{3j}}{\|x_j\|_2^2} & -x_{1j} + \dfrac{x_{1j} x_{3j}^2}{\|x_j\|_2^2} \\ x_{2j} - \dfrac{x_{1j}^2 x_{2j}}{\|x_j\|_2^2} & x_{1j} - \dfrac{x_{1j} x_{2j}^2}{\|x_j\|_2^2} & -3 - \dfrac{x_{1j} x_{2j} x_{3j}}{\|x_j\|_2^2} \end{bmatrix}, \text{ for } \|x_j\|_2^2 \neq 0, \tag{2.8}$$

$$A_j = \begin{bmatrix} -35 & 35 & 0 \\ -7 - x_{3j} & 28 & -x_{1j} \\ x_{2j} & x_{1j} & -3 \end{bmatrix}, \text{ for } \|x_j\|_2^2 = 0.$$

$$B_j = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}. \tag{2.9}$$

As shown in [3], the above procedure could also be extended to a more general class of continuous-time or discrete-time nonlinear system. This proposal extends the procedure to a nn-degree-of-freedom nonlinear kinetic kill interceptor model.

2.3 Design of an optimal linear tracker/controller

As described before, an optimal local linear model is obtained at each operating point, by optimally linearizing the neural network model. Then, a local linear digital controller is designed based on this optimal linear model, according to a three-step procedure. First, optimal control techniques are utilized to design a fast-rate digital controller. Then, the anti-digital redesign methodology is used to estimate a local continuous-time controller, equivalent to the fast-rate digital controller in the state-matching sense. Finally, digital redesign is used to design and implement a slow-rate digital controller. Implementation of a continuous-time controller by means of a digital controller with a relatively low sampling rate offers several advantages, including flexibility to change controller parameters, reduced control gains and providing enough computation time to design and implement rather complex control strategies.

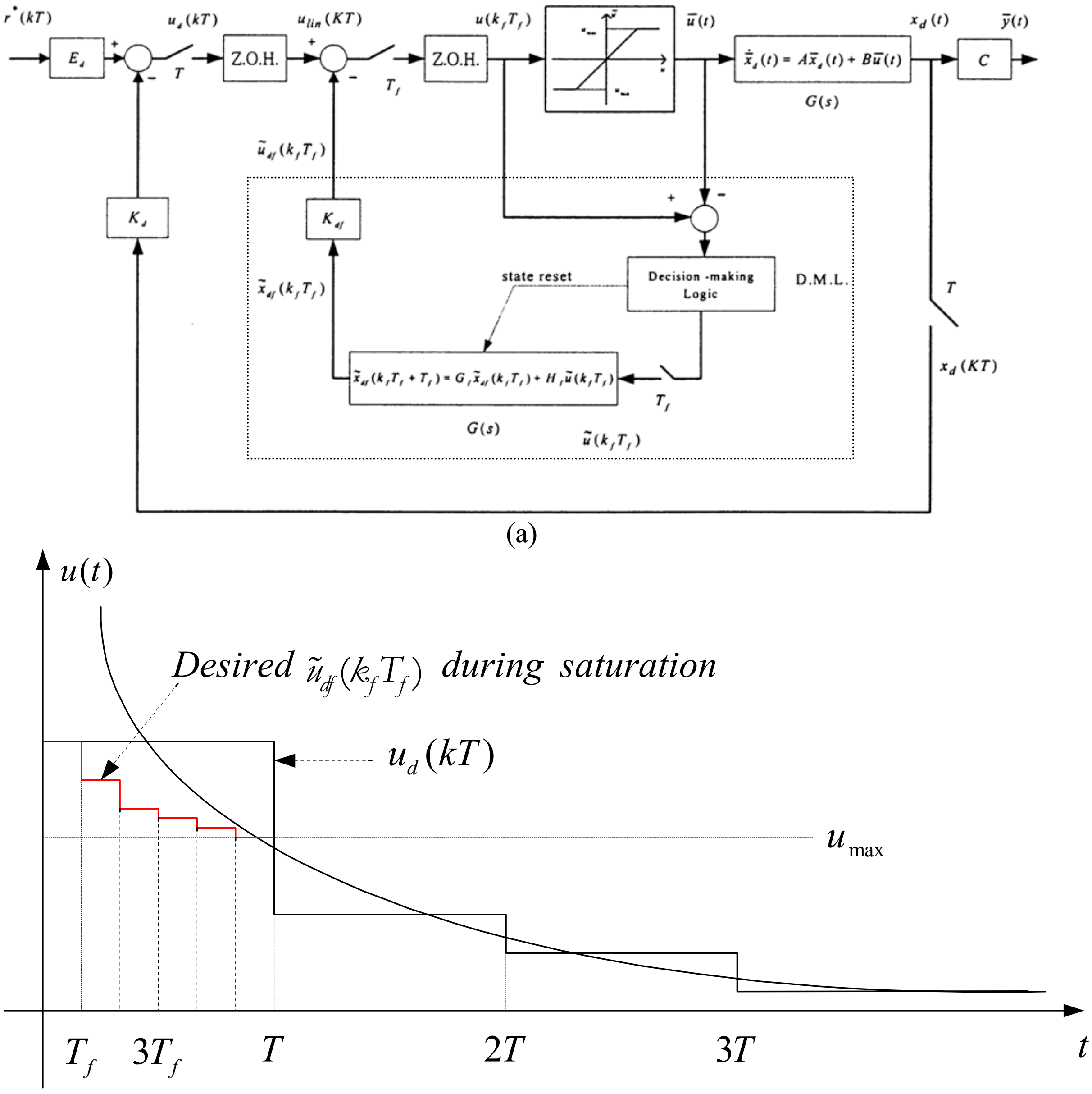
2.4 Digital redesign and input saturated systems

Digital redesign offers an important benefit that derives from an inherent characteristic of digital systems that can be used to advantage in the design of digital anti-saturation schemes. Digital redesign comprises the conversion of a continuous-time controller to an equivalent low-sampling rate digital controller, based on an appropriate approximation of the continuous input to the system by a piecewise-constant signal. The digitally redesigned piecewise-constant controller developed by us is able to make the state of the digitally redesigned hybrid system closely match the state of the analogously controlled system, therefore yielding much smaller control gains than the corresponding continuous-time gains.

In some cases, the digital redesign gains are such that the control signal is below the input saturation limit. In these situations, the control signal can be directly implemented on the system without using anti-saturation compensation. However, if this is not the case, an anti-saturation compensator is required to reduce the input signal to the plant below the saturation limit, without significantly degrading the system's performance. Figure 1(a) shows the complete structure of a digitally redesigned sampled-data system with a minor-loop anti-saturation compensator. The anti-saturation compensator is shown inside the dotted rectangle in Figure 1(a).

The reduction of the control signal below its saturation limit is illustrated in Figure 1(b), which shows a typical continuous-time control law $u(t)$ and its piece-wise constant sampled version $u_d(kT)$, over several sampling intervals. It can be seen that, in any sampling interval, the amplitude of the piece-wise constant discrete-time control law $u_d(kT)$ is always less than or equal to the saturation limit ($u_{\max}$) of the continuous-time control law $u(t)$.

Based on this observation, combined with the optimal linear models proposed in the previous section, a conditioning scheme comprising of a slow-rate and fast-rate digital controller/tracker combination [3] is proposed to address the acceleration saturation problem in kinetic kill interceptors.



(a)

(b)

Fig. 1. (a) Digitally redesigned sampled-data system with a minor-loop anti-saturation compensator, (b) The control laws of an anti-saturation system

3 PHASE 1 - TECHNICAL OBJECTIVE

The specific questions to be addressed in phase 1 can be summarized in the following;

- Staring with a known nn-degree-of-freedom model of the form in (2.3), can we generate input-output data and use it to identify a discrete nonlinear model of the form (2.2)?
- Given a nonlinear nn-degree-of-freedom discrete-time kinetic kill interceptor model of the form in (2.2), how can the proposed optimal linearization technique be successfully applied to develop optimal linear models at general operating points of interest?
- Given the above optimal linear models, how can effective integrated controllers/trackers based on optimal designs be developed to track a chaotic type input or target?
- How can one adapt the proposed anti-saturation scheme to prevent or correct acceleration saturation in a nn-degree-of-freedom system?

4 PHASE 1 – WORK PLAN

Phase 1 will be executed in the following major tasks;

a) Acquire a representative nn-degree-of-freedom kinetic kill interceptor model with all appropriate parameters.

b) Develop the nonlinear discrete-time model in (2.2).

c) For the above nonlinear discrete-time, nn-degree-of-freedom system model, develop analytic expressions for the corresponding A_j and B_j matrices in (2.4), in terms of the general operating point (x_j, u_j), for the corresponding discrete-time case.

d) Confirm the fidelity of the developed optimal linear models.

e) Develop the optimal tracker parameters

f) Digitally redesign the above trackers for both the inner loop and outer loop anti-saturation scheme

g) Run simulations to compare hit rate performance with that of other methods

h) Develop phase 2 commercialization plan

i) Submit report of findings that also addresses rapid prototyping issues

5 RELATED WORK

The principal investigator has done work as part of his PhD dissertation [3], in the underlying techniques that form the basis of the proposal. The primary consultant, Dr. Leang Shieh has also done research in these areas as well as work on developing trackers for chaotic systems and the space station [4, 6-15]. The software engineer is also currently doing work in some of the underlying techniques [2].

6 RELATIONSHIP WITH FUTURE RESEARCH OR RESEARCH AND DEVELOPMENT

Current IGC schemes involve linearization of the nonlinear kinetic kill interceptor model through perturbation methods that involve numerous parameters, without a consistent method for determining those parameters. Other approaches involve the solution of state dependent Riccati equations (SDRE), which are extremely time consuming, particularly for online applications. Success of the proposed approach will provide a simpler alternative in which the only tuning parameters would be the selection of the $(Q \text{ and } R)$ matrices used in optimal control design. This approach also allows the full nonlinear behavior of the systems to be captured via offline NN, which are universal approximators capable of capturing nonlinearities to any desired degree of accuracy. In addition, since an optimal linearization scheme is used, the accuracy of the nonlinear behavior captured by the NN is not lost. In fact, this technique has proved very successful in dealing with chaotic systems, which are known for their very complex nonlinear behavior. The phase 1 effort will provide the basis for extensive simulation, testing and embedding of the design in a DSP chip during phase 2.

7 COMMERCIALIZATION STRATEGY

The potential market for the proposed approach could be sizeable, with anticipated interest from the major defense/aerospace companies. A more detailed commercialization plan will be developed as part of the phase 1 effort.

8 KEY PERSONNEL

Name:	**Dr. Alex C. Dunn**
Years of Experience	25
Position:	Owner, AfriTek, Inc.
Education:	Ph.D., University of Houston, Houston, TX Electrical and Computer Engineering, 2003 MSEE, University of Aston, Birmingham, UK Control Engineering and Digital Electronics, 1983 BSEE, University of Sierra Leone, Freetown, Sierra Leone Control Engineering, 1976
SBIR Assignment:	Principal Investigator and Program Manager. Dr. Dunn will lead and manage the SBIR Phase 1 effort. He is responsible for all formal project communications and reporting. Dr. Dunn will devote a minimum of forty hours a week to the effort.
Experience:	Prior to founding AfriTek, Inc., Dr. Dunn was a visiting professor at Tennessee Technological University from 7/2003 to 7/2004, where he conducted intelligent control systems research and taught graduate control engineering courses. His current research interests are in intelligent control systems and the application of advanced control techniques in the defense and aerospace industries. Dr. Dunn is a certified project manager and has successfully executed over $15 million in control system projects in industry. He has authored over ten formal functional/feasibility and detailed design reports for deployment projects in industry. Dr. Dunn has held senior position with Shell Oil, Honeywell, Setpoint, Inc. / Aspen tech, W. K. Kellogg and Ciba-Geigy.

Name: **Dr. Leang San-Shieh**
Years of Experience 34
Position: Professor, University of Houston.
Education: Ph.D., University of Houston, Houston, TX
Electrical and Computer Engineering, 1970
MSEE, University of Houston, Houston, TX
Electrical and Computer Engineering, 1968
BSEE, National Taiwan University
Control Engineering, 1958

SBIR Assignment: Research Expert. Dr. Shieh will provide research guidance and consulting to the SBIR Phase 1 effort. He will participate in design issues and review all technical documentation including the final report. Dr. Shieh will devote about ten hours a week to the phase 1 effort.

Experience: Dr. Shieh has been a professor in the department of electrical and computer engineering at the University of Houston since 1970 and is currently the director of the systems and computer engineering program. He is the recipient of more than ten college outstanding teacher awards, the 1973 and 1997 college teaching excellence awards, the 1998 college senior faculty research excellence award, and the 2003-2004 Fluor Daniel Faculty Excellence Award, the highest award given in the College, from the University of Houston's Cullen College of Engineering. Dr. Shieh also received the 1976 university teaching excellence award and the 2002 El Passo faculty achievement award from the University of Houston. He has published more than two hundred and fifty articles in various scientific journals. Dr. Shieh's research and teaching interests are in digital control, optimal control, self-tuning control and hybrid control of uncertain systems.

Name: **Mr. Jose Canelon (Venezuelan national)**
Years of Experience 10
Position: Research Assistant, University of Houston.
Education: Ph.D. Candidate, University of Houston, Houston, TX.
MSEE, Universidad del Zulia, Venezuela, 1997
Applied Computer Engineering
BSEE, Universidad del Zulia, Venezuela, 1994.
Electrical and Computer Engineering,

SBIR Assignment: Software Engineer/Research Assistant. Mr. Canelon will conduct activities as directed by the PI. He will conduct detailed computations, develop Matlab/Simulink code and run simulations as necessary. Mr. Canelon will devote about twenty hours a week to the phase 1 effort.

Experience: Mr. Canelon is an associate professor at the Universidad del Zulia, Venezuela. He is currently pursuing a Ph.D. degree at the University of Houston as a student of Dr. Shieh. As a Ph.D. candidate, he has been conducting research in an approach involving neural networks for the control of nonlinear unknown dynamic systems. Related to such research work, four papers have been accepted for journal publications, two for conference presentations and two others have been submitted for journal publication. In addition, Mr. Canelon has published other journal and conference papers in control and petroleum engineering.

9 FACILITIES/EQUIPMENT

All the work involved in the phase 1 effort will be done on desktop and personal computers at AfriTek offices and at the University of Houston.

10 CONSULTANTS

Dr. Karlos M. Grigoriadis, director of the interdisciplinary program in aerospace engineering at the University of Houston will be engaged as a consultant as needed.

11 PRIOR, CURRENT OR PENDING SUPPORT

AfriTek, Inc. has no current or pending support for this or a similar proposal.

12 COST PROPOSAL (ON-LINE SHEET)

13 REFERENCES

[1] K. Hornik, M. Stinchcombe. and H. White, “Multilayer feedforward networks are universal approximators,” *Neural Networks*, vol. 2, pp. 359-366, 1989.

[2] J. I. Canelon, L. S. Shieh, S. M. Guo and H. A. Malki, “Neural network-based digital redesign approach for control of unknown continuous-time chaotic systems,” Accepted for publication in the *International Journal of Bifurcation and Chaos.*

[3] A. C. Dunn, “Input time-delay and input constrained systems: A digital redesign approach controller synthesis,” *Ph.D Dissertation,* University of Houston, May 2003.

[4] S. M. Guo, L. S. Shieh, G. Chen, C. F. Lin, “Effective chaotic orbit tracker: a prediction-based digital redesign approach,” *IEEE Transactions on Circuits and Systems – I, Fundamental Theory and Applications*, vol. 47, no. 11, pp. 1557-1570, 2000.

[5] M. C. M. Teixeira, S. H. Zak, “Stabilizing controller design for uncertain nonlinear systems using fuzzy models,” *IEEE Transactions on Fuzzy Systems*, vol. 7, no. 2, pp. 133-142, 1999.

[6] M. C. Wu, J. S. Tsai, A. C. Dunn, L. S. Shieh, “Weighted switching lifted digital redesign with state saturation for cascaded analog systems,” *IMA Journal of Mathematical Control & Information*, vol. 20, pp. 65-87, 2003.

[7] J. S. Tsai, J. Y. Lin, A. C. Dunn, L. S. Shieh, “Weighted-switching, digital redesigned, observer-based tracker for cascaded analog systems with saturating actuators and state constraints,” Submitted for publication to *IMA Journal of Mathematical Control & Information*, March 2003.

[8] J. S. Tsai, Y. C. Peng, A. C. Dunn, L. S. Shieh, “State-space, self-tuning control for singular nonlinear stochastic hybrid systems containing saturating actuators,” Submitted for publication to *IEEE Trans. Circuits and Systems*, September 2003.

[9] M. C. Wu, J. S. Tsai, A. C. Dunn, L. S. Shieh, “Output-reference tracking digital redesign with state saturation for cascaded analog systems,” Submitted for publication to *The Journal of the Franklin Institute*, May 2003

[10] J. W. Sunkel, L. S. Shieh, Y. L. Zhang, “Digital redesign of an optimal momentum management controller for the space station,” *Journal of Guidance, Control and Dynamics,* vol. 14, no. 4, pp. 712-723, 1991.

[11] X. M. Zhao, L. S. Shieh, J. W. Sunkel, Z. Z. Yuan, ‘Self-tuning control of attitude and momentum management for the space station*,” Journal of Guidance, Control and Dynamics,* vol. 15, no. 1 pp. 17-27, 1992.

[12] L. S. Shieh, W. M. Wang, J. W. Sunkel, "Digital redesign of cascaded analogue controllers for sampled-data interval systems," *IEEE Proceedings-Control Theory and Applications,* vol. 143, no. 6, pp 489-498, 1996.

[13] L. S. Shieh, G. Chen, J. S. H. Tsai, "Hybrid suboptimal control of multi-rate multi-loop sampled-data systems," *International Journal of Systems and Science*, vol. 23, pp. 839-854, 1992.

[14] L. S. Shieh, H. M. Dib, B. C. McInnis, "Linear quadratic regulators with eigenvalue placement in a vertical strip," *IEEE Trans. Automatic Control*, vol. AC-31, no. 3, pp. 241-243, 1986.

[15] L. S. Shieh, H. M. Dib, S. Ganesan, "Continuous-time quadratic regulators and pseudo-continuous-time quadratic regulators with pole placement in a specific region." *IEE Proc*., *Control Theory and Applications* , vol. 134, no. 5, pp. 338-346, 1987.

[16] R. Hanus, M. Kinnaert, J. L. Henrotte, "Conditioning technique, a general anti-windup and bump-less transfer method," *Automatica*, vol. 23, pp. 729-739, 1987.

[17] M. Xin, S. N. Balakrishnan, E. J. Ohlmeyer, "Integrated Guidance and Control of Missiles with $\theta - D$ Method," IFAC Conference on Aerospace, St. Petersburg, Russia.

[18] P. Zarcharan, "Tactical and Strategic Missile Guidance," AIAA, Reston, Virginia 2002.