2002

NASA FACULTY FELLOWSHIP PROGRAM

MARSHALL SPACE FLIGHT CENTER
THE UNIVERSITY OF ALABAMA

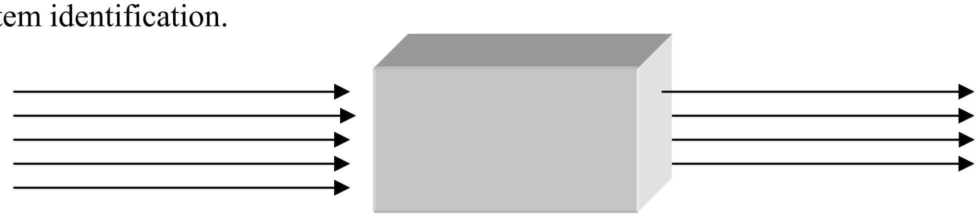
SYSTEM IDENTIFICATION OF X33 USING NEURAL NETWORK

Prepared By:	Shiv Aggarwal
Academic Rank:	Professor
Institution and Department:	Embry Riddle Aero. University Department of Physical Sciences
NASA/MSFC Directorate:	Space Transportation
MSFC Colleagues:	Drs. John Hanson & Chong Lee

Introduction

Modern flight control research has improved spacecraft survivability as its goal. To this end we need to have a failure detection system on board. In case the spacecraft is performing imperfectly, reconfiguration of control is needed. For that purpose we need to have parameter identification of spacecraft dynamics.

Parameter identification of a system is called system identification. We treat the system as a black box which receives some inputs that lead to some outputs. The question is: what kind of parameters for a particular black box can correlate the observed inputs and outputs? Can these parameters help us to predict the outputs for a new given set of inputs? This is the basic problem of system identification.



Input **Black Box** **Output**

The X33 was supposed to have the onboard capability of evaluating the current performance and if needed to take the corrective measures to adapt to desired performance [3]. The X33 is comprised of both rocket and aircraft vehicle design characteristics and requires, in general, analytical methods for evaluating its flight performance [9].

Its flight consists of four phases: ascent, transition, entry and TAEM (Terminal Area Energy Management) [4]. It spends about 200 seconds in ascent phase, reaching an altitude of about 180,000 feet and a speed of about 10 to 15 Mach. During the transition phase which lasts only about 30 seconds, its altitude may increase to about 190,000 feet but its speed is reduced to about 9 Mach. At the beginning of this phase, the Main Engine is Cut Off (MECO) and the control is reconfigured with the help of aerosurfaces (four elevons, two flaps and two rudders) and reaction control system (RCS). The entry phase brings down the altitude of X33 to about 90,000 feet and its speed to about Mach 3. It spends about 250 seconds in this phase. Main engine is still cut off and the vehicle is controlled by complex maneuvers of aerosurfaces. The last phase TAEM lasts for about 450 seconds and the altitude and speed, both are reduced to zero.

The present attempt, as a start, focuses only on the entry phase. Since the main engine remains cut off in this phase, there is no thrust acting on the system. This considerably simplifies the equations of motion. We introduce another simplification by assuming the system to be linear after some non-linearities are removed analytically from our consideration. Under these assumptions, the problem could be solved by Classical Statistics by employing the least sum of squares approach. Instead we chose to use the Neural Network method. This method has many advantages. It is modern, more efficient, can be adapted to work even when the assumptions are diluted. In fact, Neural Networks try to model the human brain and are capable of pattern recognition.

Variables of the Project

In this section we will mention all the variables used in this project.

Input Variables

α, β, = vehicle angle of attack, vehicle angle of side slip (both measured in radians)
p, q, r = body axis roll rate, pitch rate and yaw rate (in radians per second)
M, A = Mach Number (dimensionless) and Altitude (in kilometers)
δts, δ_{ta}, δ_{fa} , δ_{rud} = symmetric trail deflection, asymmetric trail deflection, asymmetric flap deflection, rudder deflection (all in radians)

Output Variables

αd, βd, pd, qd, rd = time rate of change(d for dot) of associated variables (first two in rad/s, the last three in rad/s^2)

Other Variables

γ, μ = flight path angle, bank angle (about the velocity vector) (both in radians)
g_0, g_Y, g_L = gravitational acceleration in earth z-axis, Components of g_0 along the wind Y, and Z axis (all in ft/s^2). Also $g_Y = g_0 \cos \gamma \sin \mu$ and $g_L = g_0 \cos \gamma \cos \mu$
I_{ii}, I_{ij} = Vehicle body axes (moment, product) of inertia (in slug.ft^2) $\Gamma = I_{xx}.I_{zz} - I_{xz}^2$
V, m = Vehicle velocity (ft/s), Vehicle mass (slug)
Y, L = lateral force along the wind Y-axis, aerodynamic lift along negative wind Z-axis (in lb)
Lb, Mb, Nb = rolling, pitching and yawning moments (in ft-lb)

Equations of Motion

ANSI/AIAA recommended practice of using wind-axis force balances has been adopted. The angular equations of motion are resolved in body (not wind) axes system. The five equations of motion can be written in the matrix form OP = LP + NP where the actual output OP, linear part LP and nonlinear part NP are all 5 x 1 column matrices. Five elements of OP are the output variables αd, βd, pd, qd and rd. Five elements of LP are $-L/(mV \cos \beta) + g_L/(V \cos \beta)$, $Y/(mV) + g_Y/V$, $(I_{zz}.Lb + I_{xz}.Nb)/\Gamma$, Mb/I_{yy}, and $(I_{xz}.Lb + I_{xx}.Nb)/\Gamma$. Five elements of NP are $q - \tan \beta.(p \cos \alpha + r \sin \alpha)$, $p \sin \alpha - r \cos \alpha$, $I_{xz}.(I_{xx} - I_{yy} + I_{zz}).p.q/\Gamma + (Izz.(I_{yy} - I_{zz}) - I_{xz}^2).q.r/\Gamma$, $(I_{zz} - I_{xx}).p.r/I_{yy} + I_{xz}.(r^2 - p^2)/I_{yy}$, and $(I_{xx}.(I_{xx} - I_{yy}) + I_{zz}^2).p.q/\Gamma - I_{xz}.(I_{xx} - I_{yy} + I_{zz}).q.r/\Gamma$.

Methodology

Matrix NP basically arises because of the inertial cross couplings. Data (250 observations) was obtained from 6DOF (six degrees of freedom) MAVERIC (Marshall Aerospace Vehicle Representation In C) simulation from lift off to TAEM. NP was computed for each observation and then was subtracted from the corresponding output observations. Modified output OPM was given by OPM = OP – NP. This reduced the equations of motion to the matrix form OPM = LP.

Another assumption was made. We assumed LP = W*IP where W was the 12 x 5 weight (system identification) matrix and the input IP was the 12 x 1 input column matrix. This assumption is equivalent to saying that elements of OPM are the linear combinations of the elements of IP. The elements of matrix W were identified by training the neural network through the supervised learning. Five artificial neurons were used in the network, one for each output. Widrow-Hoff Delta learning rule was employed.

Results

All the 60 parameters of the problem (60 elements of W matrix) were successfully identified. The results were satisfactory, but not perfect. The imperfections are due to the nonlinearity in W because of the nonlinear dependence on β. Another source of imperfection is the time series nature of data which results in the multicollinearity problems. But both these problems are surmountable, given more time to analyze the problem.

Future Scope of the Project

The first next logical step would be to take care of some of the known weaknesses of the model, like a better treatment of the nonlinearities. Neural Network approach is an excellent tool for the purpose. On the mathematics side one may like to incorporate radial or Volterra orthogonal polynomials. The problem of multicollinearity introduced by the time series nature of the data may be handled by giving some weight to the past observations. The second step would be system identification in the ascent and transition phase of the flight. A last step might be to combine everything we have learnt in an attempt to automate the system.

Resources

This project required the use of many software tools. The main software chosen for the project were MATLAB [2],[10],[11] and NEURAL NETWORK TOOLBOX. MATLAB is software dealing with the manipulation of matrices and NEURAL NETWORK TOOLBOX deals with the methodologies of neural networks. A number of books from Redstone Scientific Information Center (RSIC) provide wealth of information related to the project [1],[3],[6],[7],[8].

Conclusion

The problem of System Identification can be perhaps adequately handled by using the presently available resources provided by MATHLAB and NEURAL NETWORK TOOLBOX.

Acknowledgements

The author would like to thank the entire team of engineers and scientists in the vehicle flight mechanics group of the Marshall Space Flight Center's Space Transportation Directorate.

Warren Adams provided the most needed computer hardware support. Bradley Burchett, Mehmet Sozen, and Ashok Batra were generous with their time in clarifying some of the subtleties of Computer Software. My MSFC colleagues Drs. John Hanson and Chong Lee were kind and amiable. They provided guidance without any reservations, whenever I needed.

References

[1] Cooper (1998). *Introduction to Partial Differential Equations with MATLAB,* Birkhauser

[2] Etter (1993), *Engineering Problem Solving with MATLAB*, Prentice Hall

[3] Hagan, Demuth & Beale (1996), *Neural Network Design,* PWS Publishing Company

[4] Hall C.E., Gallaher M.W., and Hendrix N.D. (1998). X33 Attitude Control System Design for Ascent, Transition, and Entry Flight Regimes, AIAA-98-4411 American Institute of Aeronautics and Astonautics, pp 1-10

[5] Hanson J.M. (2002). A plan for Advanced Guidance and Control Technology for 2nd generation Reusable Launch Vehicles AIAA Guidance, Navigation & Control Conference Proceedings pp 1-10

[6] Ogata (1994), *Designing Linear Control Systems with MATLAB,*Prentice Hall

[7] Ogata (1994), *Solving Control Engineering Problems with MATLAB*, Prentice Hall

[8] Tsoukalas & Uhrig (1997), *Fuzzy and Neural Approaches in Engineering*, John Wiley & Sons, Inc

[9] Ward D.G., Monaco J.F., and Bodson, M. (1998). Development and Flight Testing of a Parameter Identification Algorithm for Reconfigurable Control, Journal of Guidance, Control and Dynamics Vol. 21, No. 6, pp 948-956

[10] William Palm III (2001), *Introduction to MATLAB 6 for Engineers*, McGraw Hill

[11] Wilson & Turcotte (1997), *Advanced Mathematics and Mechanics Applications using MATLAB,* CRC Press