NASA-CR-197661

FINAL
IN-08-CR
OCIT
43631
P-3

Final Report on NAG1-1088
Submitted by L. Valavani

'Design of High Performance Multivariable Control Systems for Supermaneuverable Aircraft at High Angle of Attack'

This grant was undertaken as a followon to prior experience in controlling the HARV for high performance, using H2 and H_∞ controllers, appropriately designed for fault tolerance as well, given the considerable redundancy offered by the vehicle's control surfaces. One of the main features of this class of aircraft was the thrust vectoring capability, which dramatically enhances maneuverability/controllability at high 's. This study, performed independently of a NASA/LaR.C. grant, culminated in P. Voulgaris's M.S. thesis; a paper was also published in the AIAA Journal of Guidance, Dynamics and Control.

The main motivation for the work under the present grant was to use nonlinear feedback linearization methods to further enhance performance capabilities of the aircraft, and robustify its response throughout its operating envelope. The idea was to use these methods in lieu of standard Taylor series linearization, in order to obtain a well behaved linearized plant, in its entire operational regime. Thus, feedback linearization was going to constitute an 'inner loop', which would then define a 'design plant model' to be compensated for robustness and guaranteed performance in an 'outer loop' application of modern linear control methods. The motivation for this was twofold; first, earlier work(I. Craig's M.S. thesis) had shown that, by appropriately conditioning the plant through conventional, simple feedback in an 'inner loop', the resulting overall compensated plant design enjoyed considerable enhancement of performance robustness in the presence of parametric uncertainty. Second ,the nonlinear techniques did not have any proven robustness properties in the presence of unstructured uncertainty; a definition of robustness (and performance) is very difficult to achieve outside the frequency domain; todate,none is available for the purposes of control system design. Thus, by proper design of the outer loop,such properties could still be 'injected 'in the overall system.

Five M.S. and one Ph.D. theses were totally or partially supported by the grant.These are listed in chronological order below:

1. Inoue, Akihiko, "Design Methods for Robustly Performing Systems Under Parametric Uncertainty," M.S. thesis,Dept. of Mech. Engg.,M.I.T., May 1990.
2. Yip, Patrick, "Nonlinear High Performance Control for Supermaneuverable Aircraft at High Angles of Attack," M.S. thesis, Dept. of Aeronautics and Astronautics,M.I.T., February 1991.
3. Resnick,Carl,"Performance Comparison of Existing Control Methods Under Structured Uncertainty," M.S.thesis,Dept.of Aeronautics and Astronautics,M.I.T.,March 1991.
4. Stoerdal, John,"Issues in Feedback Linearization with Uncertainty," M.S. thesis, Dept. of Aeronautics and Astronautics, M.I.T., June 1992.
5. Vos, David, "Experimental Control of the Monocycle: A Benchmark Example for Interfacing of Control Technologies," Ph.D. thesis, Dept. of Aeronautics and Astronautics,M.I.T., June 1992.
6. Akutowicz, Alfons, "Issues in Nonlinear Control and Estimation," M.S. thesis, Depts. of Aeronautics and Astronautics, and Electrical Engineering, M.I.T.,June 1993.

Theses #2 and #6 were totally supported by the grant and were directly related to the HARV. In his thesis, Patrick Yip used feedback linearization to control the HARV at various angles of attack, up to about 40deg..At higher angles, because of a model 'switch' at just over 40deg, the performance was not guaranteed; for some extreme cases, stability was also lost. This is probably attributable to the fact that, at those angles, the aerodynamic coefficient fits were not good. Two kinds of approximations were used for those coefficients: first, linearized values were used around nominal control settings; next, second order polynomial fits were obtained for each coefficient, for dependence on one parameter only, that which was considered dominant-from various simulation tests- for the particular coefficient at hand.Scheduling around this linearization was incorporated in the overall scheme to accomodate a large portion of the operating envelope. In a comparative study of various outer loop controllers, it was found that a simple pole placement compensator was superior, in both performance and robustness, to H2 and H_∞ optimal linear designs; this could be explained on the basis of outer loop controller compatibility to the inner loop controller induced structure; simply put, since the inner loop feedback linearization scheme ,ideally, creates a bank of integrators out of the nonlinear system dynamics,by appropriate transformations and feedback, a controller which does not negate such a structure has the best chance in the outer loop. Clearly, then , the truly multivariable schemes are at a disadvantage over pole placement, which ,in a decoupled system, works on a loop by loop basis.

Alfons Akutowicz, in his thesis, tried to obtain a 'true to the word' feedback linearization for the HARV, and for this purpose used truly nonlinear analytical expressions for the various aerodynamic coefficients,obtained by higher order polynomial fits on two dominant parameters. However, due to the fact that a diffeomorphism was very difficult to obtain for exact(input-state) linearization, the internal plant zero dynamics severely compromised the overall controller capability. This is consistent with theory that, as long as system deviations remain bounded within a region where the (noninimum phase) zeroes response remains small, the feedback linearized system remains stable; otherwise, this property may be lost. Alfons then went on to further examine issues in feedback linearization robustnes to inexactly satisfied involutivity conditions, internal zeroes dynamics and the conditions under which input-output linearization could either be forced to evolve in a manifold where the zeroes dynamics are minimalized, by appropriate input modification,or are simply ineffective due to certain continuity and degeneracy properties of the original plant structure and its Lie algebra. He proved a number of theorems along these lines,discussed in detail in his thesis. This aspect of his work is a precursor to subsequent work by various authors,e.g. Talwar, Namachchivaya and Voulgaris, on conditions for 'Approximate Feedback Linearization '. Lastly, some studies were conducted in nonlinear estimation and smoothing; it was found that, although feedback linearized filtering algorithms perform similarly to the standard nonlinear filters, they have a clear advantage in outperforming the latter in smoothing problems, at a considerably reduced computational burden.

J.Stoerdal's thesis further explored feedback linearization robustness issues to parametric uncertainty, by comparing the performance of feedback linearized systems to more classical approaches, using modern control techniques on Taylor series linearized plants. The class of systems studied were representative second and third order nonlinear systems, with a number of nonlinear effects, such as Coulomb friction,piecewise linear functions,Duffing's and Mathieu's equations. Robustness to unstructured uncertainty was simultaneously explored. Invariably, feedback linearized systems outperformed other compensation schemes on both counts together;the response to noise was comparable. Although this thesis directly addressed research issues consistent with the grant objectives, it was fully supported by a Norwegian education grant.

The theses by A. Inoue and C. Resnick focused primarily on various alternatives for designing 'inner-outer loop' combinations to enhance system robustness properties to parametric and unstructured uncertainty.These were also supported by other means, except for the supervisor's time .

Finally, in his Ph.D. thesis, D.Vos designed a feedback linearizing controller based on state estimates obtained from an observer.The essence of the design is ,in fact, this single design point observer, which runs in transformed coordinates and is driven directly by the system space sensor signals to yield the state estimates for use in the control law.This controller,designed at only one operating parameter value,showed remarkable robustness when applied to a unicycle, in operation over the entire envelope for arbitrary parameter variation.This scheme offers considerable improvement over an earlier observer based feedback linearization scheme, proposed by J. Cro Granito in his Ph.D. thesis, both in terms of ease of implementation as well as in performance; the latter required the implementation of a nondivergent observer in the form of an Extended Kalman Filter.

In conlusion, the lessons learned in the context of the research conducted for this grant are quite valuable, both from a theoretical as well as a practical viewpoint. First, the method of feedback linearization was successfully applied to control the HARV over large portions of its operating envelope, at least in the nonlinear simulation supplied to M.I.T. by NASA/Langley R.C.. Even though it was not possible, within the present grant, to robustly achieve this control for parametric uncertainty and other inaccuracies in the model throughout, valuable insights were gained as to some inherent robustness properties that feedback linearization can have, if appropriately modified. This topic, which is of great importance to design, was somewhat explored in the present grant ,with very encouraging results, and has been further taken up subsequently by researchers in the field. In adddition, the corollary issue of system performance and stability when two controllers of very different time constants (one very fast and the other slow) are present in the compensation scheme, provided well documented motivation for subsequent work, and was partially addressed by P. Voulgaris in his Ph.D. thesis.