Proceeding of the 2004 American Control Conference
Boston, Massachusetts June 30 - July 2, 2004

HIERARCHICAL CONTROL OF FUTURE GENERATION ROTORCRAFT

Devendra K Tolani   Joseph F Horn   Asok Ray   Jialing Chen

The Pennsylvania State University
University Park, PA 16802

Keywords: Helicopter control; Probabilistic robust control; Symbolic Dynamics

Abstract

A two-tier architecture of hierarchical control is proposed for future generation rotorcraft that demand enhanced performance and reliability. The continuously-varying controller at the lower tier is designed using probabilistic robust control approaches. The discrete-event supervisory controller at the upper tier is built upon the concepts of time-frequency analysis, symbolic dynamics, and automata theory. Results of simulation experiments based on the GENHEL model of UH-60 Black Hawk helicopter are presented. Copyright © 2004 ACC

1. INTRODUCTION

Future military rotorcraft will need to meet more stringent handling qualities requirements in order to perform more demanding missions. As a result, future rotorcraft control systems should provide higher bandwidth, improved attitude quickness, less cross-coupling and better disturbance rejection than current operational aircraft. However, the limits on flight control performance for rotorcraft are generally more restrictive than those of fixed-wing aircraft. Both the out-of-plane (flapping) and in-plane (lagging) motions of the rotor blades result in a number of dynamic modes that can couple with the motion of the fuselage with only moderately high feedback gains. The air resonance phenomenon occurs when one of the lagging modes becomes very lightly damped or even unstable due to this coupling, and has been observed on helicopters with high bandwidth control systems (Dryfoos, et al., 1999). The core focus of the paper is to design a control architecture that achieves high performance over a wide range of operation with high reliability.

Robust control theory allows control designs based on a simple low-order plant model with well-defined uncertainty bounds that account for model simplifications, non-linearity, and variations in operating conditions. It is well known that the demands on system stability robustness and desired nominal performance could be contradictory to each other. The deterministic worst-case robust design could cause unduly conservativeness and thus degrade system nominal performance. Instead of stability guarantee under worst-case uncertainties, recent results in probabilistic robust control indicate that complexity of the controller can be greatly reduced and/or system performance can be significantly improved by allowing a small well-defined risk of instability; e.g., see (Lagoa, 1999). Furthermore, by specifying different levels of risk at different flight regimes, the control design could obtain the flexibility in trading off stability robustness and desired performance.

Military rotorcraft handling qualities specifications dictate different levels of flight control system performance when performing various mission tasks (ADS-33E, 1999). For example, if the aircraft is in cruise flight, the bandwidth and attitude quickness requirements are relatively low, and a low-risk / low-performance controller would be adequate. On the other hand, when performing aggressive combat tasks or precision maneuvers it may be desirable to achieve the maximum available performance. A high-risk controller might be used if there is a mechanism to recover, in the event that the controller initiates instability. A higher-level supervisory controller can govern the acceptable level of risk as well as the desired level of performance. Such a system would need to monitor the response of the vehicle to detect degradation in performance or stability, and also take into account external inputs such as the current mission task and environmental conditions. The high level supervision would be an appropriate application of discrete-event control.

In this paper an upper level supervisory control scheme is proposed for the lower level probabilistic robust control of rotorcraft (Horn, et al., 2003). The ultimate goal here is to augment the lower level probabilistic controller with a higher level supervisor (referred to as Supervisor in the sequel) in the discrete-event setting, to achieve high performance and reliable operation over a wide range of operation. The function of this supervisory control scheme is to autonomously determine the desired level of performance based on environmental and operational conditions. The system should have the capability to detect the onset of instability based on available sensor data and additional information on vehicle operation and maintenance.

The control architecture is formulated as a hierarchical control system. Discrete-event control is used for high-level supervision; probabilistic robust control is used as the low-level controller. The supervisory control chooses from a bank of robust control designs with different levels of risk and performance. This paper focuses on the techniques that can be used for event generation for higher-level supervisory controller.

This paper is organized as follows. In second section a brief introduction about the probabilistic robust control design scheme is presented. The third section describes a Fast Fourier Transform (FFT) based supervisory control. In the fourth section a novel symbolic dynamics and wavelet based scheme is presented for higher level supervision. The fifth section describes the rotorcraft simulation and control test-bed, on which various simulation experiments were conducted. Finally, the last section deals with conclusions and future work.

2. PROBABILISTIC ROBUST CONTROL

A probabilistic robust control design is proposed and the concept is validated on a non-linear simulation model (Howlett, 1989). The objective is to control the lateral-directional degrees of freedom on a UH-60A utility helicopter. A bank of μ-controllers is designed where the robust stability requirements are relaxed in order to achieve better performance. It is observed that some of the controllers are stable and operate effectively with the non-linear simulation even though the uncertainty bounds are reduced below the uncertainty levels observed for the non-linear plant model. Monte Carlo simulations show the expected trend in risk level and performance as the weights were varied.

Frequency domain identification techniques are used to identify the linear dynamics and to establish uncertainty bounds of the aircraft dynamics (Tischler, 1991). To estimate the uncertainty bounds associated with varying operating conditions, the frequency response characteristics for four additional flight conditions were calculated: 20 knots forward, rightward, rearward, and leftward flight. Uncertainty bounds are estimated based on the maximum difference between the nominal linear model and the five sets of frequency response data. The state variables are roll rate, yaw rate, and lateral flapping angle. The control inputs are lateral and pedal control in equivalent inches of stick position. The plant outputs are yaw and roll rate measured in deg/sec

The plant model has dynamic uncertainty with radius one. The risk-adjusted controllers are designed using uncertainties with reduced radii, r_i, in the interval [0,1]. The μ-synthesis method was used to design a set of controllers to maximize performance and robustly stabilize the closed loop for uncertainty radius $\|\Delta\| \le r_i$. The 25th order controllers were then reduced to 9th order using Hankel–norm model reduction technique. Since $r_i < 1$, these controllers do not robustly stabilize the plant. Therefore, the risk of instability associated with each controller was estimated using Monte Carlo simulation.

To address the problem of risk assessment in the presence of dynamic uncertainty recent results on probabilistic robustness were used. A set of random transfer functions was generated using the algorithm in (Lagoa, et al., 2001) to represent the uncertainty perturbations. The algorithm generates random discrete transfer functions that can be completed to a transfer function with infinity norm less or equal than one. Tustin transformations are then used to obtain continuous time random transfer functions.

Ten thousand samples were used to determine the risk. The estimated risk associated with each of the controllers is presented in Table 1. Each controller was also evaluated in terms of performance using the nominal plant model. The roll axis and yaw axis bandwidths were calculated according to handling qualities specifications (ADS-33E, 1999) and are shown in the table in units of rad/sec. A higher bandwidth corresponds to better performance. The results show the expected trend as risk is traded with performance.

When the controllers were implemented in the non-linear simulation model, it was found that the very high-risk controllers (C1 and C2) invariably resulted in instability (these controllers could then be eliminated). The controllers with medium-to-high risk tended to perform well but could result in instability as the operating condition varied or for significantly large disturbances. The low-risk controllers resulted in significantly degraded performance.

Table 1: Risk and Performance of Controllers

Controller	r_i	P_{weight}	Risk Factor	Roll BW	Yaw BW
C1	0.001	2.52	0.4552	8.8	4.5
C2	0.010	2.00	0.4178	8.8	4.5
C3	0.020	1.50	0.3949	8.8	4.5
C4	0.040	1.00	0.2889	8.0	4.3
C5	0.070	0.80	0.1876	7.5	4.1
C6	0.100	0.70	0.1555	7.0	4.0
C7	0.200	0.50	0.1353	6.2	3.6
C8	0.600	0.32	0.1176	5.1	3.0
C9	0.700	0.30	0.0841	3.1	2.6

3. FFT-BASED SUPERVISION

A common form of instabilities that occur in uncertain dynamical systems is of unstable focus type that results in diverging oscillations that can be detected using frequency based methods. For rotorcraft applications, this form of instability results from the lag progressing mode of the rotor. This can be detected at an early stage by a supervisory controller since the oscillations tend to have an a priori known narrow frequency range. In some cases, the instability could be non-oscillatory slowly divergent mode, which could be eliminated by including attitude and velocity feedback loops or by small modifications in the control system design.

The top plate of Figure 1 represents the response of the aircraft using a relatively high-risk controller C3. For moderately large inputs, this controller may cause slowly diverging oscillatory instability and cannot be used without higher level supervision. The bottom plate of Figure **1** shows the response of a relatively sluggish controller C7.

The proposed frequency-based method uses a moving-window approach that relies on time series data from available sensors. In rotorcraft, the roll rate response is one of the critical variables, which captures the onset of instability.

Let us consider the following scenario: Initially aggressive controller is used for better performance and handling qualities. On initiation of instability, it is required that Supervisor switches to a more conservative controller.

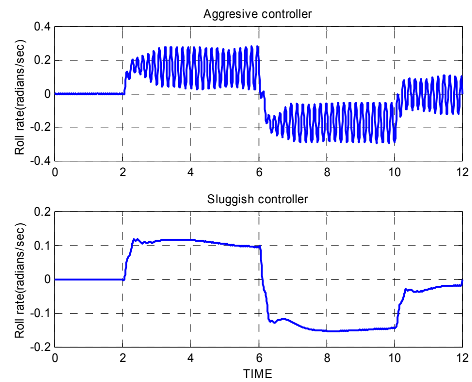

Figure **1**: High risk/low risk controller response

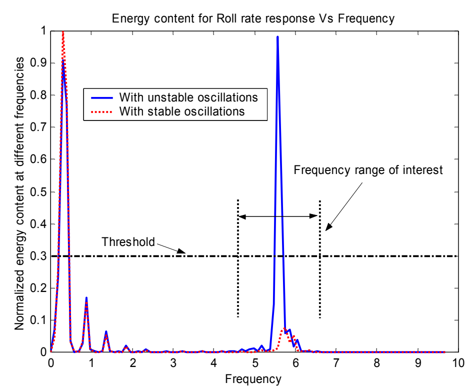

Figure **2**. Energy content of the roll rate response

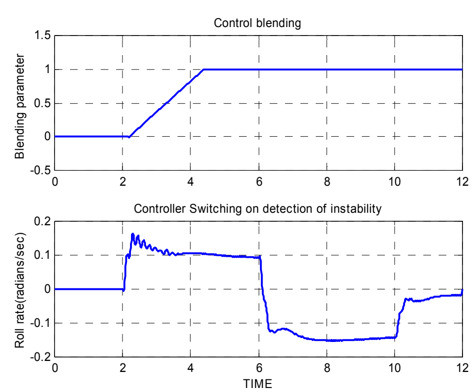

Figure **3**. System recovery from instability

A moving window approach is used to solve this problem, where a block of 1024 points in the time series data of roll rate are considered at any instant. Fast Fourier analysis of this data set is performed using validated Codes (Press, et al., 1992). As the system approaches instability, the energy content of the oscillatory modes increases. This energy across the frequency range is normalized so that the maximum energy is unity. Threshold techniques are then employed to determine whether the system is approaching instability. If so, Supervisor issues a command to switch to a relatively more conservative controller from the bank of pre-designed controllers. This process is repeated until the energy content of the high frequency terms is less than the threshold value. Two typical cases are shown in Figure **2**.

The bottom plate of Figure **3** starts with the high risk controller C3. As the normalized energy crosses the threshold within the specified frequency range, Supervisor issues a command to switch to a lower risk controller. The lower risk controller C7 is phased in at the onset of the Supervisor's command and becomes fully effective between 2.2 and 4.4 seconds as shown in the top plate of Figure **3**. The 2.2 second dwell time in which the controller 7 is blended in, is chosen using the formulation in (Zhai, et al., 2000). The bottom plate of Figure **3** shows that this approach clearly stems the incipient instability.

4. SYMBOLIC DYNAMICS AND WAVELET-BASED SUPERVISION

This section introduces the underlying concepts of symbolic dynamics and wavelet-based supervision for decision and control of future generation rotorcraft.

Time series data of roll rate, which is used for early detection of incipient instabilities, can be converted to a symbol sequence by partitioning the space Ω (over which the data evolves) into finitely many discrete blocks (Abarbanel, 1996; Badii and Politi, 1997), A. Let $\Phi \equiv \{\varphi_1, \varphi_2, \cdots, \varphi_n\}$ be a partition of Ω (i.e., $\bigcup_{j=1}^{n} \varphi_j = \Omega$ and $\varphi_j \cap \varphi_k = \varnothing \;\; \forall j \neq k$) into n blocks. Then, each block $\varphi_j \in \Phi$ is labeled as the symbol $\sigma_j \in \Sigma$, where the symbol set Σ is called the *alphabet* consisting of n different symbols. (Note that a block $\varphi_j \in \Phi$ is not necessarily a connected subset of the space Ω.) In this way, a data sequence, obtained from a trajectory of the dynamical system, is converted to a symbol sequence $\{\sigma_i, \sigma_j, \sigma_k, \cdots\}$ that characterizes the system dynamics represented by the data sequence.

Finding the dimensionality of the phase space of system dynamics can be difficult especially if the time series data are noise-corrupted (Abarbanel, 1996). Since the phase space dimension is often very large, finding an appropriate partition in which the symbols are to be generated can be difficult, if not impossible. To circumvent these difficulties, we propose to utilize the wavelet transform. After the wavelet transform is applied to the data, we partition the wavelet coefficients space that is a function of scale and time. After the partitioning is finalized, the sequence of symbols is generated from the scale series data at each time epoch. Then, a probabilistic finite state automaton is constructed from the symbol sequence at each time epoch. The anomaly measure at a given epoch is obtained as the norm of the difference between the state probability vector of the finite state machine at that epoch and the state probability vector of the finite state machine at nominal condition. Thus, the above vector measure quantifies possible growth of anomaly from the nominal condition as the system progresses in the slow time scale. The whole approach can be captured by Figure **4** as shown below.

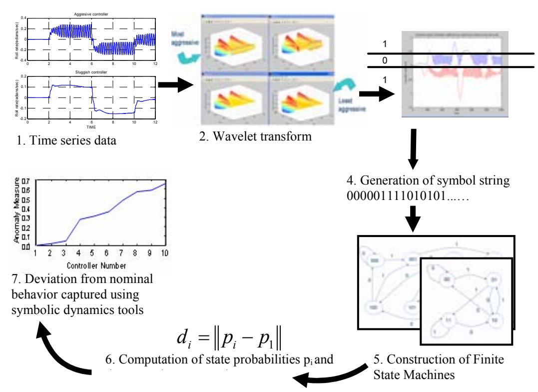

Figure **4**. Schematic for higher level supervision

Finite state machines, generated from the symbol sequences of a dynamical system identify its behavioral pattern. As the system trajectory evolves, different states are visited with different frequencies. The number of times a state is visited as well as the number of times a particular symbol $\sigma_i \in \Sigma$ is received, while sliding the window from a state leading to another state, is counted. In this way, the state probability vector $\boldsymbol{p}$ is calculated from the time series data associated with different controllers.

Having obtained the state probability vectors, the next step is to calculate the anomaly measure that signifies the change in stationary behavior of the dynamical system under different controllers. The state probability vector under the most aggressive controller C1 serves as a benchmark. The *deviation measure* d_i of a controller C_i is obtained as the norm of the difference between the state probability vector associated with that controller and the state probability vector for the benchmark condition. Obviously, the deviation measure at the benchmark condition is zero.

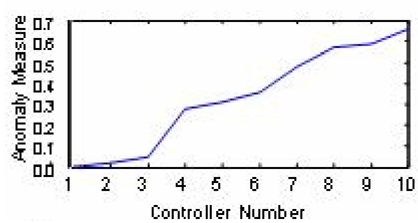

Figure **5**: Deviation measure of different controllers relative to the benchmark controller

Once the symbolic string has been generated by the methods described in the previous section, a finite state machine is created for each controller and the underlying state probability vectors are computed. Thus, in the context of the rotorcraft problem, there are ten such probability vectors corresponding to the ten different time series data sets of closed loop response.

The deviation measures, derived from time series data of rotorcraft simulation experiments, are shown in Figure **5**, where controller numbers are order according to decreasing risk (or increasing robustness). As the controllers become more and more robust, the closed loop response and the benchmark response become farther apart with respect to the deviation measure. This work can be further extended to design higher level supervisors which can be implemented in real time to detect onset of instability. Timely availability of this information is critical for decision and control for safe and reliable operation.

5. ROTORCRAFT SIMULATION AND CONTROL TESTBED (RSC)

A Rotorcraft Simulation and Control (RSC) test-bed was developed for real time simulation and testing of future generation control systems. The test-bed comprises of three computers. The first computer acts as the "plant", it uses a non-linear simulation model (GENHEL) of the UH-60A Black Hawk helicopter. The GENHEL rotorcraft simulation code is widely used by industry and the U.S. government and is accepted as a validated engineering model for handling qualities analysis and flight control design. The code models non-linear aerodynamic effects, and includes fuselage rigid body dynamics, rotor blade flapping and lagging dynamics, rotor inflow dynamics, engine/fuel control dynamics, actuators, and a model of the existing UH-60A automatic flight controls systems (AFCS). The code has been modified to allow for the disengagement of existing AFCS channels and for the integration of the controllers presented in this paper. Different Control System strategies such as upper level discrete event supervisory control; lower level probabilistic robust control and damage mitigating LPV control are implemented in the second computer. The third computer runs FlightGear which is an open-source, multi-platform, flight simulator. These three computers are connected by Ethernet and utilize Windows Sockets to communicate data with each other. The RSC test-bed is built under Microsoft Visual C++ environment and runs on Windows XP. Figure **6** shows the architecture of RSC test-bed. This test bed is designed to be flexible for testing other control strategies like those based on superstability theory that are currently being developed.

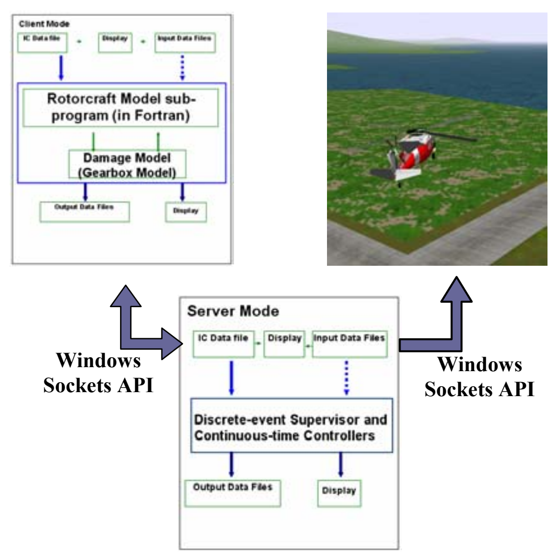

Figure **6**: RSC test-bed architecture

To successfully implement the switching strategy for a largely uncertain system whose model is unknown but belongs to one of many families of nominal (and known) models, one needs to design controllers for each family of possible models and a rule that orchestrates the switching between these controllers. The main challenge, when designing switching systems is to find the conditions leading to "safe" switching; i.e., rules that avoid undesirable behaviors like large oscillations or instability.

6. CONCLUSIONS AND FUTURE WORK

This paper presents two different approaches to solve the problem of supervisory control. The first approach is a straight-forward application of fast Fourier transform (FFT) based methods to detect the onset of instability and has been successfully implemented for real-time simulation of rotorcraft. The second approach is an effective scheme based on symbolic dynamics and wavelet theory, which captures the deviation between different closed loop system responses subject to identical persistent input excitation. The results appear to be very powerful since a metric can now be assigned for the deviation from the nominal behavior.

Future work will involve finding out a methodology to formulate decision policies for switching to appropriate control module(s). Once the deviation from the nominal behavior is detected, the task will be to restore the system to the original state so that the desired closed loop behavior is maintained.

ACKNOWLEDGMENT

This work has been supported in part by the Army Research Office under Grant No. DAAD19-01-1-0646.

REFERENCES

Abarbanel H.D.I., (1996) *The Analysis of Observed Chaotic Data,* 1996, Springer-Verlag, New York.

Aeronautical Design Standard-33E-PRF (1999). Handling Qualities Requirements for Military Rotorcraft, *U.S. Army Aviation Systems Command, St. Louis, MO, December 1999*.

Atmanspracher, H. A.,and H. Scheingraber (1991). Reconstructing language hierarchies, *Information Dynamics*, eds., New York, p.45, Plenum, 1991.

Badii, R. and Politi, A. (1997). *Complexity, Hierarchical Structures and Scaling in Physics,* Cambridge University Press, Cambridge, U.K.

Crutchfield, J.P.,(1994). The Calculi of Emergence: Computation, Dynamics and Induction," *Physica D,* 75, pp. 11-54, 1994.

Dryfoos, J.B., B.D. Kothmann, and J. Mayo (1999). An Approach to Reducing Rotor-Body Coupled Roll Oscillations on the RAH-66 Comanche Using Modified Roll Rate Feedback. *55th Annual Forum of the American Helicopter Society, Montreal, Canada, June 1999*.

Horn, J, D.K.Tolani , C.M.Lagoa , Q.Wang , A.Ray (2003)Reliable Operation of Rotorcraft using probabilistic Robust Control. *Preprints 5th IFAC Symposium on Fault Detection, Supervision and Safety of Technical Processes* Washington , D.C. June-2003.

Howlett, J.(1989). *UH-60A BLACK HAWK Engineering Simulation Program: Volume I – Mathematical Model.* NASA CR-177542, USAAVSCOM TR 89-A-001, September 1989.

Kaiser, G.(1994). *A friendly guide to Wavelets*. Birkhäuser

Lagoa, C. M. (1999) . A Convex Parameterization of Risk-Adjusted Stabilizing Controllers. *Proceedings of the 38th IEEE Conference on Decision and Control, Phoenix, AZ, December 1999.*

Lagoa, C.M., M. Sznaier and B.R. Barmish (2001). An Algorithm for generating transfer functions uniformly distributed over H-infinity balls. *Proceedings of the 40th IEEE CDC, Orlando, Florida, December 2001*.

Press, W. H., S. A. Teukolsky, W. T. Vetterling, and B. P. Flannery (1992) *Numerical Recipes in C: The Art of Scientific Computing Second Edition.* Cambridge University Press.

Tischler, M.B. (1991). System identification requirements for high-bandwidth rotorcraft flight control system design. *American Control Conference, Boston, MA, June, 1991.*

Zhai, G., B. Hu, K. Yasuda, and A.N. Michel (2000). Stability analysis of switched systems with stable and unstable subsystems: an average dwell time approach *American Control Conference, 2000. Proceedings of the 2000 , Volume: 1 Issue: 6, 28-30 June 2000 Page(s): 200 -204 vol.1*