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Integrated decision and control of human-engineered complex systems

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This paper presents a comprehensive decision and control strategy for human-engineered complex systems to achieve simultaneously the following objectives: (i) high-performance with quality assurance; (ii) reliability and structural durability with extended service life and (iii) operability over a wide range. Results from several systems-theoretic disciplines, such as probabilistic robust control (PRC), damage mitigating control (DMC), health and usage monitoring (HUM) and discrete event supervisory (DES) decision and control have been synergistically combined to achieve the above goal. The proposed decision and control system is hierarchically structured with two-tier architecture. The lower tier incorporates continuously-varying control that is designed using a combination of PRC and DMC, and the upper tier is designed to provide information and intelligence through DES decision and control that monitors the system response for detection and mitigation of anomalous behaviour, performance degradation and potential degradation of structural durability. To assure desired quality at permissible levels of risk as well as under different operating conditions, the PRC at the lower tier makes a trade off between robustness and performance, while damage mitigation in critical structures is achieved via DMC that also facilitates health and usage monitoring of the complex system. Based on the information derived from the observed time series data, the DES decision and control at the upper tier may decide to switch, in real time, to one control module from another in order to satisfy the specified performance and safety requirements. The switching actions are executed at the lower tier. The integrated system, including the proposed decision and control architecture, has been tested and validated on a rotorcraft simulation test bed.

Keywords: Probabilistic robust control; Damage mitigating control; Health and usage monitoring; Discrete event supervisory control

1. Introduction

Reliability, performance and enhanced operating range of large-scale human-engineered systems (e.g. multi-national business, space exploration and military command and control) are of paramount importance to successful completion of their missions. The operation of these missions can be viewed as an interconnected complex dynamical system. (The notion of a complex system is briefly presented in Appendix A.) The complexity in such systems emerges as a consequence of non-linear, non-stationary, multi-time-scale and uncertain

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dynamics of the mutually interacting subsystems. Under these circumstances, a variety of hidden anomalies and faults may inconspicuously spread through the system and alter its dynamic behaviour from strict order to chaotic; the consequence could be pervasive failures, resulting in mission disruption.

The main aim of the research work presented in this paper is to formulate a comprehensive control and health management strategy for human-engineered complex dynamical systems to achieve high performance and reliability over a wide range of operation. This goal could be achieved by a hierarchically structured decision and control system that synergistically combines the technologies from several systems-theoretic disciplines: (i) probabilistic robust control (PRC) (Horn *et al.* 2003, Tolani *et al.* 2004); (ii) damage mitigating control (DMC) (Horn *et al.*); (iii) discrete event supervisory (DES) decision and control (Cassandras and Lafortune 1999) and (iv) health and usage monitoring (HUM).

While the technologies of PRC and DMC form the backbone of the continuous-domain control system at the lower tier, the DES decision and control module at the upper level serves as an intelligent agent and provide pertinent information on plant operation and health status. The DMC deals with the usage monitoring or operational control part of health management, whereas, the task of health monitoring is taken care by the anomaly detection tools. In essence, an integrated strategy has been proposed for the comprehensive health management and control of complex dynamical systems. The proposed decision and control architecture has been validated on two independent simulation test beds of rotorcraft dynamics and aircraft propulsion. The current paper, owing to the page limit, provides a very concise overview and focuses on rotorcraft, as an example of complex systems operation and control. For details, the readers may refer to Tolani (2005).

This paper is based on detailed simulation experiments performed on rotorcraft simulation and control (RSC) test bed. The aim here is to develop, explain and validate the theory by using this test bed that exhibits salient features of complex systems listed in Appendix A. A mathematical description and simulation of rotorcraft's flight dynamics need to embody the complex aerodynamic, structural and other internal (e.g. propulsion and actuation) dynamic effects that together influence the response of the aircraft to pilot's controls (e.g. handling qualities) and external atmospheric disturbances (e.g. ride qualities) (Padfield 1999). This interaction is highly complex and the dynamic behaviour of the rotorcraft is often limited by local effects that rapidly grow in their influence to inhibit larger or faster motion (e.g. blade stall). A non-linear dynamic model of the UH-60A black hawk helicopter has been adopted for this study (Khalil 2002). The GENHEL simulation code is widely used by industry and the US government and is accepted in the rotorcraft community as a validated engineering model for evaluation and analysis of handling qualities analysis and flight control systems. The GENHEL 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 closely represents the dynamics 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 analysis, design and evaluation of the controllers presented in the present paper.

Future generation military rotorcraft need to satisfy more stringent handling qualities in order to perform better in ever-demanding missions. As a result, the control systems must be able to provide higher bandwidth, improved attitude quickness, less cross-coupling and better disturbance rejection than current operational rotorcraft. The limits on flight control performance for rotorcraft are generally more restrictive than those of fixed-wing aircraft. For example, 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 owing to this coupling, and has been observed on helicopters with high bandwidth control systems (Dryfoos 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.

The existing theory of robust control allows 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 be unduly conservative and thus degrade the system's nominal performance. Recent results in probabilistic robust control indicate that instead of enforcing guaranteed stability under worst-case uncertainties, complexity of the controller can be greatly reduced and the system performance can be significantly improved by allowing a small well-defined risk of instability (Lagoa 1999). Furthermore, by specifying different levels of risk at different flight regimes, the control system design could have increased flexibility in trading off stability robustness and desired performance. Since, current and future military rotorcraft missions are very demanding in terms of pilot workload, improvements in handling qualities in terms of bandwidth and response quickness are necessary. Recent studies reveal that the damage rate in rotorcraft components can increase when using higher performance flight control systems (Ray *et al.* 1994, Rozak and Ray 1997). Thus, the pursuit of lower maintenance costs and better handling qualities may be contradictory. The incorporation of component damage in the flight control design and optimization process is warranted, but it must be balanced against the handling qualities requirements of the aircraft mission.

Recent research has focused on carefree manoeuvring (CFM) systems for rotorcraft (Horn and Sahani 2001, Horn *et al.* 2002). CFM systems use advanced flight controls and cueing systems to avoid envelope limits. CFM systems incorporate algorithms to detect approaching limits, and then assist in avoiding the limit either by directly restricting control inputs through the AFCS, or by issuing a tactile or other type of cue to the pilot. Since many envelope limits are associated with structural requirements on the aircraft (e.g. torque limits and load factor limits), CFM might significantly extend life of structural components without any appreciable loss of performance. There is also an added benefit of reducing workload since CFM relieves the pilot of monitoring envelope limits. However, CFM technology does not contribute towards life extension or damage mitigation while the aircraft is operating within the specified flight envelope.

In DMC (Ray *et al.* 1994), component damage is incorporated in the optimization of the flight control system in order to minimize damage rate. A related concept is life extending control (LEC) (Ray and Caplin 2000), in which the remaining service life is extended based on the current and past information as well as the projected future usage, and the controller is adjusted to reduce damage rate as damage accumulates on the system. Previous work has demonstrated the concept of DMC for a number of aerospace applications including rocket engines (Ray *et al.* 1994), fixed-wing aircraft structures (Ray and Caplin 2000) and helicopter rotor systems (Rozak and Ray 1997). Damage mitigating control may result in a trade-off between flight control performance (in terms of handling qualities) and structural durability. A damage mitigating control system might be used to revert the aircraft to a degraded mode of operation (i.e. reduced performance) if the onset of wide-spread damage is anticipated. Such a controller might also reduce the rate of damage with minimal impact on handling characteristics if there is sufficient redundancy in control inputs. DMC can thus significantly reduce the probability of catastrophic failures and allow the aircraft to react intelligently to circumvent failures encountered as damage accumulates.

The development of HUM systems provides new opportunities to reduce the operational costs of rotorcraft. In particular, the concept of condition-based maintenance (CBM) uses advanced data fusion algorithms to identify damaged components so that their replacement can be based on their actual condition rather than hours of usage (Garga *et al.* 2001). There is an opportunity to close the loop by integrating HUM systems with the flight control system. As the HUM system detects increasing damage levels, the control system is modified to reduce the damage rate, possibly by sacrificing a small amount of performance in terms of handling characteristics such that allowable tasks would be restricted. Likewise, the control system might be used to inject small disturbances in order to assist in the diagnosis of damage and anomalies as well as prognosis of potential failures.

Handling qualities specifications (Anon 2000) of military rotorcraft dictate different levels of flight control system performance when performing various mission tasks. 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 manoeuvres 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.

The current paper proposes an upper-level supervisory control scheme for the lower level PRC (Horn *et al.* 2003, Tolani *et al.* 2004) and DMC of rotorcraft (Bridges *et al.* 2003). Figure 1 shows the overall supervisory architecture of the RSC test bed and figure 2 fills in the details. The signal notation of figure 2 is presented in table 1. The ultimate aim of the present paper is to propose a comprehensive strategy for health management and control of future-generation rotorcraft. The core focus areas are high performance and reliability over a wide

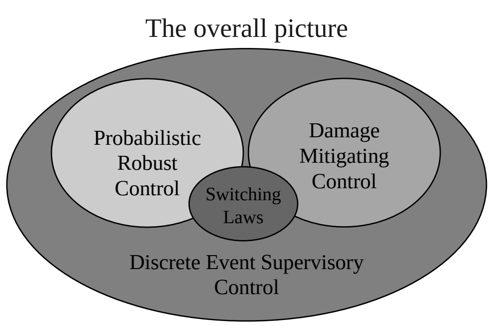

Figure 1. Overall architecture.

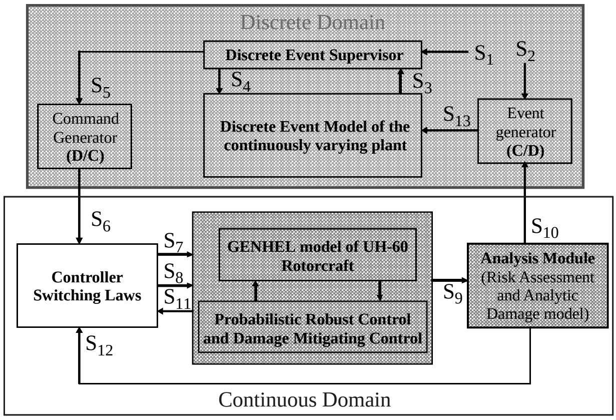

Figure 2. Detailed control architecture.

Table 1. Notation of signals.

Name	*Explanation*
S_1	External commands treated as uncontrollable events
S_2	Other information
S_3	Observable events
S_4	Disabling controllable events
S_5	Input to command generator from DES
S_6	Input to control switching module from command generator
S_7	Input to the plant from control switching module
S_8	Reference signals
S_9	Output of the plant/controller fed to the analysis module
S_{10}	Output of the analysis module fed to the event generator
S_{11}	Output of the plant/controller fed to the control switching module
S_{12}	Output of the analysis module fed to the control switching module
S_{13}	Output of the event generator fed to the DES plant model

range of operation. The lower-tier controller depicted in figure 3 is designed using the PRC and the DMC approach. In the PRC approach, by allowing different levels of risk under different flight conditions, the control system can achieve the desired trade off between stability robustness and nominal performance (Hespanha and Morse 1999). In the DMC approach, component damage is incorporated in the control law to minimize damage rate and extend the operational life of the system. The DES-based upper-tier supervisory controller monitors the system response for any anomalous behaviour that might lead to potential instability or loss of performance. The supervisor then switches between various lower level controllers. The core idea of the current paper is to design a framework where the upper level DES mimics human intelligence and chooses what is best for the system and the mission requirements.

The present paper is organized as follows. Section 2 presents the lower-tier design. Section 3 describes the hierarchical control strategy and the results. Section 4 describes the rotorcraft simulation and control test bed, on which various simulation experiments were conducted. Finally, the paper is concluded in Section 5 along with recommendations for future work. The notion of complex systems is briefly presented in Appendix A.

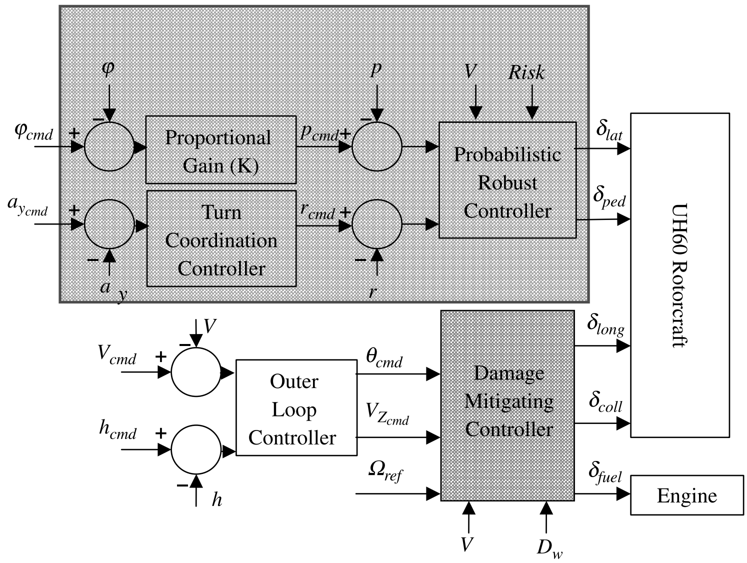

Figure 3. Lower level control architecture.

2. Lower-level control design

This section presents the details of lower-tier design and is composed of three subsections. Subsection 2.1 provides the details about the PRC. Section 2.2 explains the concept of DMC and control switching scheme is presented in Section 2.3.

2.1 Probabilistic robust control

A PRC 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 controllers is designed based on the theory of H_∞-based structural singular value (μ) synthesis, 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 simulation experiments 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 rotorcraft dynamics (Tischler and Cauffman 1992). To estimate the uncertainty bounds associated with varying operating conditions in the low-speed regime (around hover), the frequency response characteristics for four additional flight conditions were calculated: 20 knots forwards, rightwards, rearwards and leftwards 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 movements of stick position. The plant outputs are yaw rate and roll rate, measured in deg/s similar methods were used to estimate the uncertainty bounds for three other speed regimes to cover the entire flight envelope up to 140 knots forwards speed.

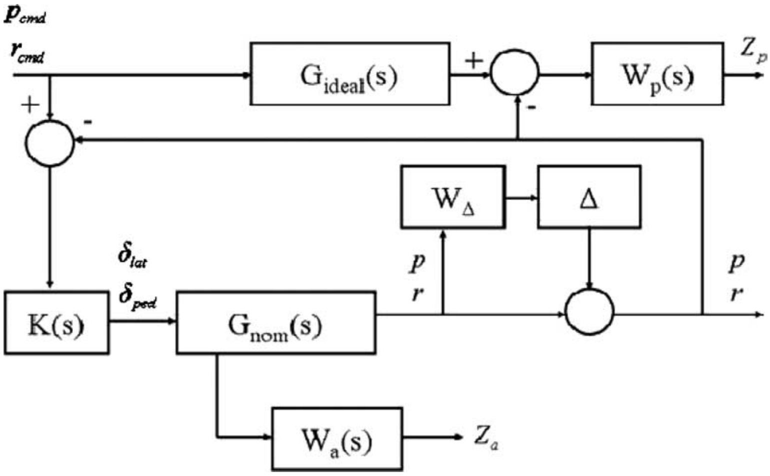

Figure 4. Augmented plant model for PRC synthesis.

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]. Figure 4 shows the augmented plant model used for PRC synthesis. The μ-synthesis method was used to design a set of controllers to maximize performance and robustly stabilize the closed loop for uncertainty radius $\|\Delta\| \leq r_i$. 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.

Analytical techniques of probabilistic robust control (Lagoa *et al.* 2001) have been used to address the problem of risk assessment in the presence of dynamic uncertainty. A set of random transfer functions was generated 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 2. 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 (Anon 2000) and are shown in the table in units of rad/s. A higher bandwidth corresponds to better performance. The results show the expected trend as risk is traded with performance.

Table 2. Risk and performance of controllers in low-speed regime.

Number	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

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. On the other hand, the low-risk controllers resulted in significantly degraded performance.

2.2 Damage mitigating control

One of the objectives of this paper is to investigate the feasibility and potential benefits of implementing a damage mitigating control system on an operational rotorcraft (Bridges *et al.* 2005). Figure 5 depicts the damage mitigating control module. At the most basic level, the DMC system uses a dynamic gain-scheduled controller. This controller includes parameters to vary the controller with flight condition, as in traditional gain scheduling; however, the controller also includes a parameter (subsequently referred to as the damage weight) that adjusts the level of damage mitigation in the controller. At a higher level of control, the DMC system may be integrated with a HUM system in order to monitor damage in real time. As damage begins to accumulate, the level of damage mitigation can be increased, possibly to a level such that handling qualities are diminished, and the aircraft may need to operate in a degraded mode with a restricted flight envelope.

To demonstrate the concept of damage-mitigating control, controllers for a military helicopter have been developed over the entire speed envelope (hover to 150 knots). These controllers are designed to regulate the heave, pitch and rotor speed degrees of freedom by providing collective and longitudinal cyclic inputs to the mechanical mixer and an rev/min governor input to the engine throttle. A multi-input, multi-output (MIMO) design approach is used for integrated flight and propulsion control.

There are a number of objectives in the controller design. First, the controller should track vertical speed and pitch angle commands while regulating main rotor speed. This command tracking is designed to meet level 1 handling qualities, as specified in the ADS-33E standard

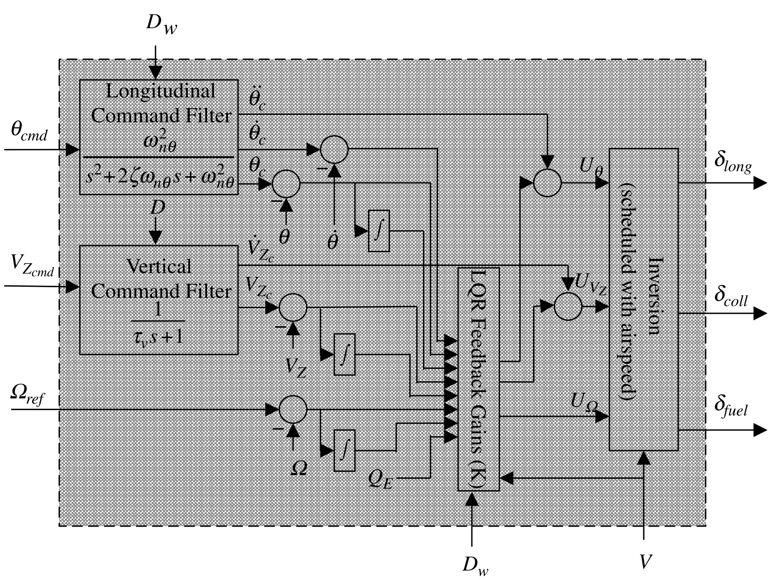

Figure 5. Damage mitigating control module.

(Anon 2000). Second, the controller should also be designed to operate effectively over a range of flight speeds (hover to 150 knots). Lastly, the controller is designed to reduce torque loads to the main transmission based on the damage weight, which acts to reduce the damage to the transmission. In order to achieve these objectives, a gain-scheduled controller is developed using an explicit model-following control scheme.

2.3 Switching

Another topic that must be addressed is the issue of switching between controllers. As discussed in previous sections, the controller architecture results in a bank of controllers with different risk and performance levels (table 2). Furthermore, several such banks of controllers are designed for different airspeeds. The system will switch between controllers as the aircraft transitions to different airspeeds or when the upper-tier supervisor determines that it should switch to a higher or lower risk controller. The issue of instability owing to switching between the controllers has to be addressed. A switching law is proposed, which guarantees stability of the closed-loop system while the controllers are being switched.

It has been shown (Liberzon 2003) that when all subsystems are Hurwitz stable, then the entire system is exponentially stable for any switching signal if the time between two consecutive switching operations, called the “dwell time”, is sufficiently large. The concept of dwell time can be further extended to “average dwell time” (Hespanha and Morse 1999, Liberzon 2003), which means the average time interval between two consecutive switching operations is not less than a specified constant. It was shown that if the average dwell time is sufficiently large, then the switched system is exponentially stable. The dwell-time concept is a reasonable approach for real-time implementation since it is counter-intuitive and counter-productive to switch controllers too frequently.

For this system, an average dwell time is selected that is sufficiently large to guarantee the stability when switching between any of the controllers. A dwell time of 2 s was found to be sufficient for this application. When the decision is made to switch controllers, the current controller and the new controller are run simultaneously. The control signal is gradually switched between the two controllers over the 2 s dwell time. A “blend parameter” is ramped in over the 2 s interval and used to generate a weighted average of the two control signals. This approach was found to be sufficient to demonstrate the concepts in this paper, and a more rigorous approach to switching is left for future work.

3. Hierarchical control

Hierarchically structured information and control systems occur for at least two related reasons: First, the great complexity of many natural and man-made systems limits the ability of humans and machines to describe and comprehend them. Second, the inherent limitations on the information processing capacity of feedback regulators results in the regulators (and possibly the controlled systems) being organized in special (in particular hierarchical) configurations.

The notion of discrete event system (Cassandreas and Lafortune 1999) fits in very well with the idea of Hierarchical architecture. Intuitively, lower-level control (i.e. the domain of continuous control) implies the traditional frequency or time domain based control strategies, which are designed to follow certain specifications (e.g. regulator problem). In essence, lower-level control is usually precise but not intelligent. On the other hand, the proposed upper-level supervision tries to mimic human intelligence by its heuristic design.

3.1 Hierarchical probabilistic robust control

A common form of instabilities that occur in uncertain dynamical systems is of unstable focus type (Khalil 2002) that results in diverging oscillations that can be detected using frequency-domain 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 is non-oscillatory and slowly divergent, 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 6 represents the response of the rotorcraft 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 6 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 upper-level supervisor switches to a more conservative controller.

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

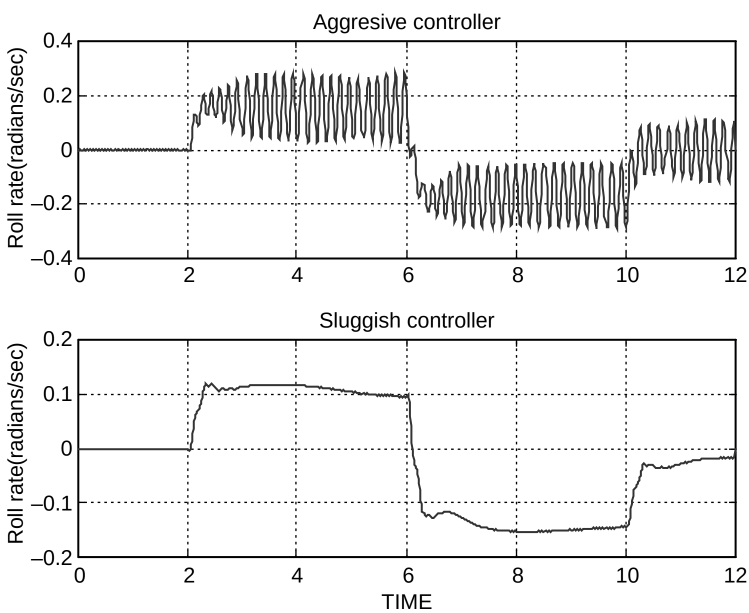

Figure 6. High-risk/low-risk controller response.

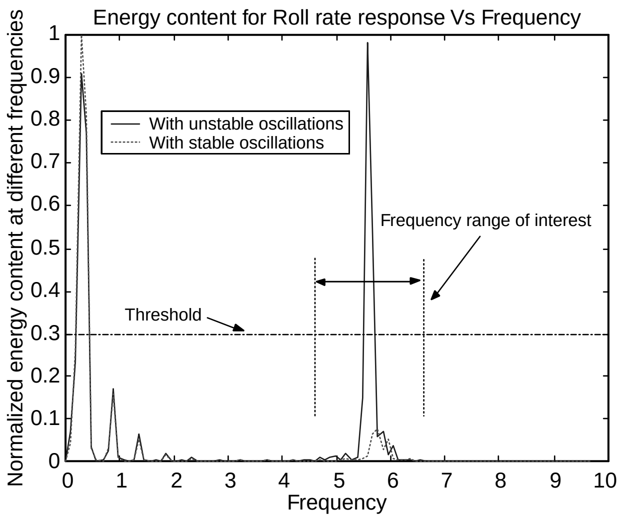

Figure 7. Energy content of the roll rate response.

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 7.

The bottom plate of figure 8 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 s as shown in the top plate of figure 8. The 2.2 s dwell time in which the controller 7 is blended in, is chosen using the formulation proposed by Zhai *et al.* (2000). The bottom plate of figure 8 shows that this approach clearly stems the incipient instability.

3.2 Hierarchical control for damage mitigation

The discrete event supervisor in the hierarchical control system is built upon a deterministic finite-state automaton (DFSA) model of the plant. Tables 3 and 4 respectively list the events and states of the automaton.

Figures 9 and 10 represent the implementation of hierarchical control scheme for the damage mitigating control of rotorcraft. As explained before, DMC incorporates component damage into the synthesis of the controllers. The controllers are categorized by a variable parameter called damage weight (D_w). Normalized D_w varies between 0 and 10. The value 10 implies maximum emphasis is being given to damage mitigation and thus the response for this category of controllers is relatively sluggish. On the other extreme, the controllers with $D_w = 0$, are a class of extremely agile controllers where the main emphasis is performance and these may cause an increase in damage rate. This section presents an elaborate scenario where these controllers are tested.

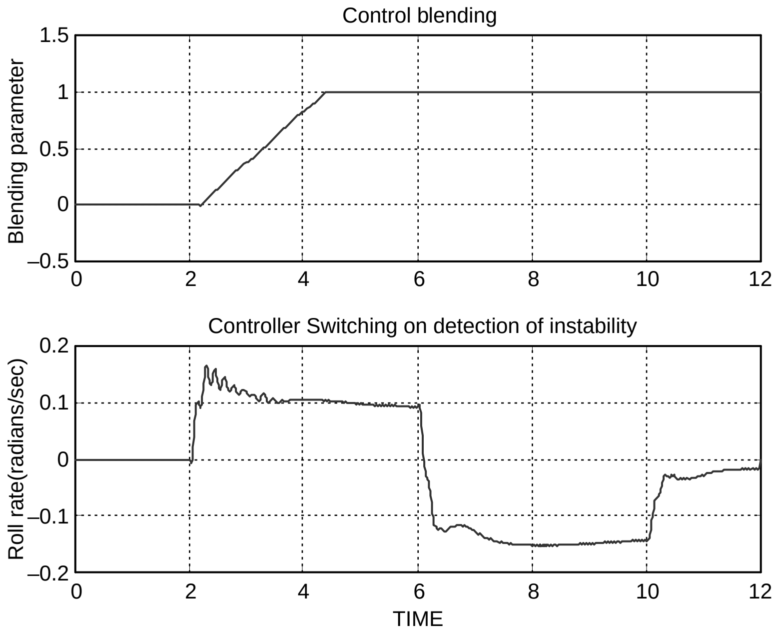

Figure 8. System recovery from instability.

Table 3. Notation of events.

Name	*Explanation*
a	Start mission
b	Increase speed over 40 knots
c	Decrease speed below 40 knots
d	Increase speed over 80 knots
e	Decrease speed below 80 knots
f	Increase altitude over 100 ft
g	Decrease altitude below 100 ft
h	Increase altitude over 500 ft
i	Decrease altitude below 500 ft
j	Detection of high damage
k	Detection of low risk of enemy fire
l	Detection of high risk of enemy fire
m	Go to original state before enemy fire was detected

Table 4. Notation of states.

Name	*Explanation*
1	On ground
2	Low altitude, low speed
3	Low altitude, mid speed
4	Low altitude, high speed
5	Mid altitude, low speed
6	Mid altitude, mid speed
7	Mid altitude, high speed
8	High altitude, low speed
9	High altitude, mid speed
10	High altitude, high speed
11	Unfriendly territory with low risk of enemy fire
12	Unfriendly territory with high risk of enemy fire
–	Corresponding high-damage states

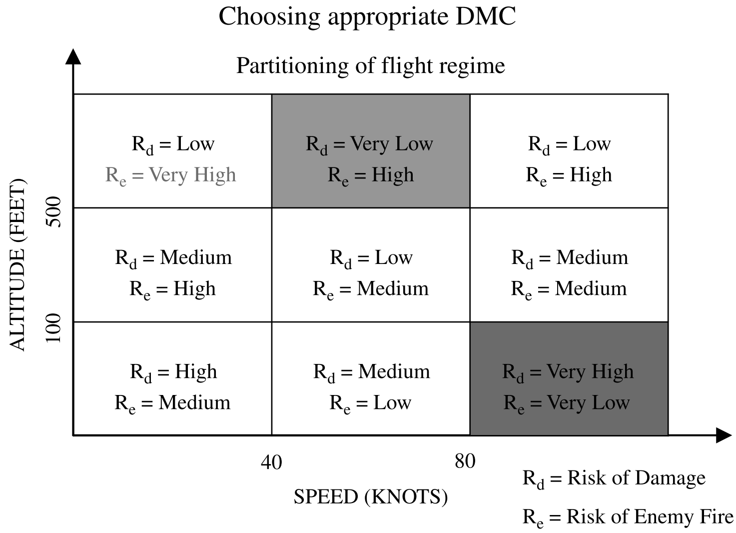

Figure 9. Choosing appropriate DMC.

3.2.1 Scenario. The rotorcraft is flying over a terrain that is divided into two territories: enemy and friendly territory. The basic difference is that when flying in enemy territory there is chance that the rotorcraft may be shot down. (This risk has also been sub-categorized as high and low risk of enemy fire.) When flying in enemy territory, the rotorcraft has to fly close to the ground and at a high speed (nap of the earth flight) to avoid being shot. Damage mitigation is not an option here, therefore, the most aggressive controllers (low D_w) are employed in this case for better performance.

For rotorcrafts, it has been found that power vs airspeed curve is bucket shaped, i.e. for hover and high-speed regime, the rotorcrafts typically need more power compared to intermediate speed (shown by the green region in figure 9). Therefore, when the rotorcraft is flying in friendly territory and there is no risk (associated with enemy fire), in order to minimize damage, the rotorcraft flies at an intermediate speed and high altitude. Flying at high altitude is preferred (for damage mitigation) because the torque requirements do not

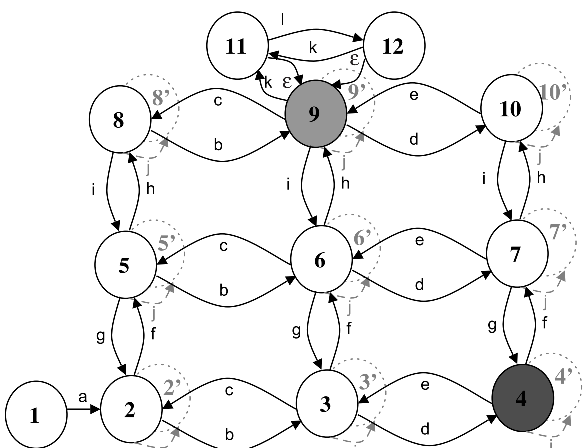

Figure 10. DES representation.

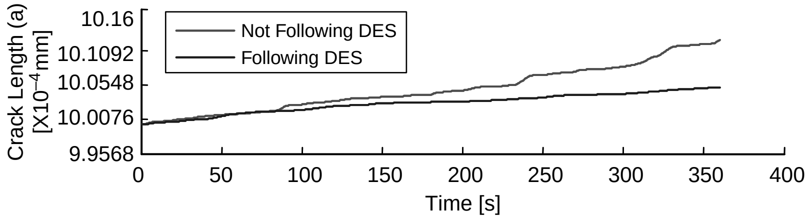

Figure 11. Comparison of damage in the two cases.

fluctuate with terrain (vs the case of a low flying rotorcraft that has to repeatedly climb up and down to follow a particular terrain).

There are two distinct health conditions defined for the rotorcraft based on the current state of the representative damage (crack length in the main bevel pinion of the helicopter transmission). These are represented by the dashed mirror states in the DES representation of the scenario in figure 10. The idea is, when the current damage is low, the rotorcraft can afford to use low damage weight controllers for more aggressive manoeuvring. For the other case, when the current damage state of rotorcraft is high, damage mitigation should be given more importance (by choosing high damage weight controllers) to avoid catastrophic failures.

Two sets of results are presented in this section. Figure 11 depicts the result for a piloted simulation scenario. The pilot follows the suggestion of the upper level DES control. Initially, pilot flies at a high altitude and when the rotorcraft enters the enemy territory it follows the terrain very closely, (nap of the earth flight) as suggested by the supervisor and finally regains the high altitude when it leaves the enemy territory. For this simulation, run the damage mitigation controller was turned on i.e. the damage weight D_w, which varies between 0 and10 is chosen based on the flight requirements: High damage weight controllers are used in friendly territory (higher damage mitigation and a relatively sluggish response) and low damage weight controllers are used in enemy territory (lower damage mitigation and a relatively fast response).

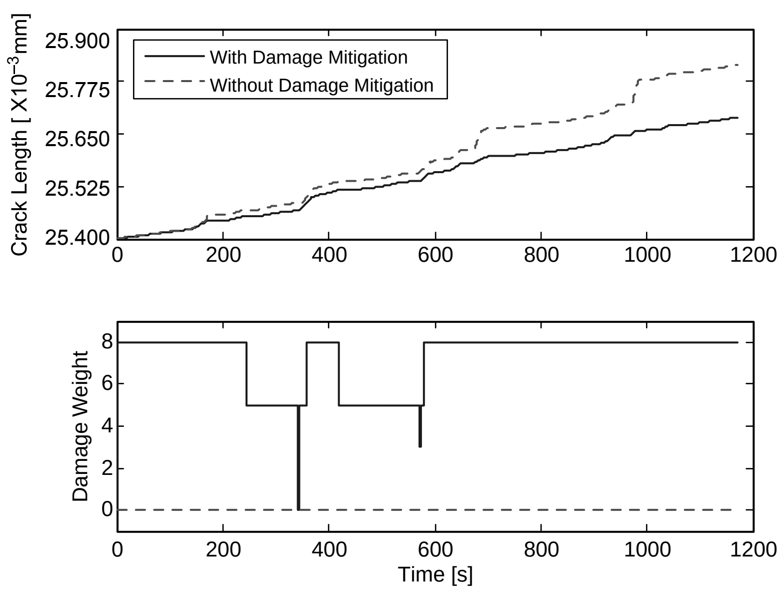

Figure 12. Crack length and damage weights.

For the next case, pilot chooses not to follow the DES recommendations (e.g. pilot chooses to fly close to earth even when the DES recommends flying at a higher altitude). For this simulation, run the damage mitigation controller was turned off, i.e. the damage weight D_w is fixed at 0. It can be clearly seen in figure 11 that when pilot chooses to follow the DES recommendations, the damage to the rotorcraft (in terms of crack growth) is significantly lower.

Figure 12 showcase the rotorcraft completely working under the control of hierarchical control scheme without any inputs from the pilot. Figure 12 shows the case where DES takes an active part in the simulation (unlike the previous case where it worked in an advisory capacity to the pilot). The first plate of figure 12 represents the damage increase (in terms of crack growth) for the two simulation runs. The improvement in terms of damage mitigation is very apparent from the figure. The bottom plate of figure 12 depicts the change of damage weight D_w over the simulation time.

4. Rotorcraft simulation and control (RSC) test bed

A 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 US 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 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 linear parameter varying (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.

5. Summary and conclusions

The crux of this paper is the development of a comprehensive control and health management strategy for human-engineered complex dynamical systems for achieving high performance and reliability over a wide range of operation. This goal is achieved by employing the results from diverse research areas such as PRC, DMC, DES control and HUM. Whereas, PRC and DMC form the basis of the lower-level continuous-domain control, upper-level supervision is based on DES control theory. As a specific example, the current paper proposes an innovative approach for reliable control system design of high performance rotorcraft to enhance handling qualities. The proposed decision and control system has a two-tier hierarchical architecture that consists of DES control at upper level and PRC and DMC at the lower level. The central idea of PRC is to allow for a small risk instability (under upper-level supervision) to design high-performance controllers, whereas, the DMC reduces the actual damage to a component in the control design scheme without any significant loss of performance.

The first suite of lower-tier controllers was designed using PRC approach. By allowing different levels of risk under different flight conditions, the control system achieves the desired trade-off between stability robustness and nominal performance. In the proposed scheme, a small well-defined risk of instability is acceptable because there is an upper-level monitoring and control system that serves as a watch dog to detect the onset of instability. Potential instabilities are predicted sufficiently in advance and hence can be quenched by switching to a more conservative controller. Similarly, an unduly conservative controller may be switched to a more aggressive controller for better performance, if there is no imminent risk of instability resulting from this action. These decisions are made by the DES controller based on the information received from the lower level. Therefore, for most of the operating regime, aggressive controllers can be used to achieve high performance. In this paper, this idea has been demonstrated for a rotorcraft but it can be easily extended to other non-linear complex dynamical systems where high-performance control action is required and a single control module may not be suitable for the entire operating range.

The second suite of lower-tier controller was designed using a damage mitigating control approach. At the most basic level, the DMC system uses a dynamic gain-scheduled controller. Similar to the traditional gain scheduling, this controller includes parameters that vary with flight condition. However, the controller also includes a parameter (damage weight) that adjusts the level of damage mitigation in the controller. The DMC system is integrated with a DES at the upper level of control. As damage accumulates, the effort of damage mitigation can be increased, possibly to a level such that handling qualities have to be compromised. In that case, the rotorcraft may have to be operated in a degraded mode, possibly within a restricted flight envelope.

The work reported in this paper, has the potential to be extended both in scope and size. A few key areas of interest are listed below.

(1) Command, control, communications, computers, intelligence, surveillance and reconnaissance (C4ISR)

The rotorcraft simulation and control (RSC) test bed currently simulates the operation of an rotorcraft unmanned ariel vehicle (RUAV). Integrating this test bed with networked robotics laboratory will enable the future researchers to explore the complex scenarios involving C4ISR. The coordinated/cooperative control of autonomous vehicle formation has emerged as a topic of significant interest. Application examples are: cooperative decision making and control of unmanned aerial vehicles (UAVs); formation flying for clusters of micro-satellites and coordination of mobile robots used for search and rescue missions. Of particular interest is the cooperative control of autonomous, UAV teams for missions that include:

i) cooperative search, acquisition, tracking and rescue;
ii) persistent intelligence, surveillance and reconnaissance
iii) task decomposition among heterogeneous vehicles for coordinated attack;
iv) cooperative timing of tasks;
v) rendezvous/join-up;
vi) simultaneous target intercept;
vii) task sequencing

(2) Partial observability and asynchronous communication

The proposed architecture does not take into account the issues of partial observability and asynchronous communication. In the examples listed above, vehicle, target and threat information need to be exchanged, in real time, among vehicles on network links, which are likely to have limited bandwidth. These data are subject to randomly varying delays as packets are lost and retransmitted. In addition, network connectivity may be limited because of geographical constraints or electronic countermeasures. Unfortunately, emerging cooperative decision and control strategies are often designed on the unrealistic assumption of idealized information flow between the vehicles, which could lead to degraded performance or even failure to complete a cooperative task. For the control system designer, such treatment is undertaken to reduce algorithmic complexity and obtain a real-time solution. Consequently, communication constraints and their effects on the control algorithms are quantified *a posteriori*. While vehicle communications provide the opportunity to enhance the system performance, the cost associated must be payed. Therefore, decision and control laws must be synthesized with due regard to their associated communication needs or effects.

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Appendix A. A brief exposure to complex systems

This appendix recapitulates salient properties of a complex dynamical system as the background information for decision and control of such systems in the main body of this paper. The website of the Santa Fe Institute, which is a leading authority on the subject, lists over three hundred definitions of complex systems. Instead of attempting to provide a precise definition, it is more meaningful to grasp the basic concept of complex systems in terms of one or more of the following properties that they might possess.

- *Emergence*
  What distinguishes a complex system from a merely complicated one is that some behaviours and patterns emerge in complex systems as a result of the patterns of relationship between the elements.
- *Short-range relationships*
  Typically, the relationships between elements in a complex system are short-range. That is, information is normally received from the nearest neighbours. Richness of connections implies communications pass across the system but are probably modified on the way.
- *Non-linear and (possibly) time-varying relationships*
  There are rarely simple cause and effect relationships between elements. A small stimulus may cause a large effect or no effect at all. The butterfly effect is a phrase that encapsulates the more technical notion of sensitive dependence on initial conditions. The idea is that small variations in the initial conditions of a dynamical

system can produce large variations in the long-term behaviour of the system.

- *Nested structure*
  Another key aspect of complex systems is that the components of the system—usually referred to as agents—are themselves complex systems. For example, an economy is made up of organizations, which are made up of people, who are systems of organs controlled by their nervous systems and endocrine systems, which in turn, are made up of cells, all of which, are complex systems, at each level in the hierarchy.
- *Feedback loop configuration*
  Both negative (damping) and positive (regenerative) feedback are key ingredients of complex systems. The effects of an agent's actions are fed back to the agent and this, in turn, affects the way the agent behaves in the future. This set of constantly adapting non-linear relationships lies at the heart of what makes a complex system special.
- *Open architecture*
  Complex systems are open systems, i.e. energy and information are constantly being imported and exported across system boundaries. This causes the complex systems to be subjected to fluctuations. Under normal circumstances, complex systems are at quasi-static equilibrium in the thermodynamic sense (Badii and Politi 1997) and are subjected to small fluctuations. Under abnormal situations, these fluctuations may rapidly grow and the equilibrium (or stability) condition is lost. The goal of the decision and control system is to forecast such a situation and take appropriate actions to circumvent potential instabilities.
- *The whole not being sum of the parts*
  There is a sense in which elements in a complex system cannot know what is happening in the system as a whole. If they could, all the complexity would have to be present in that element. A corollary of this hypothesis is that no single element in the system is capable of individually controlling the system.
- *Imprecise boundaries*
  It is usually difficult to determine the boundaries of a complex system. The decision is usually based on the observer's needs and prejudices rather than any intrinsic property of the system itself.

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