COMPLEX SYSTEMS FAILURE (CSF) COLLABORATORY AT PENN SATE

PRINCIPAL INVESTIGATOR: Professor Asok Ray

The Complex Systems Failure (CSF) Collaboratory has been constructed over the past ten years under research and equipment grants from Army Research Office (ARO), NASA Glenn Research Center (GRC), National Science Foundation (NSF), and NASA Langley Research Center (LaRC). The Collaboratory has been significantly expanded over the last four years under a five-year Multidisciplinary University Research Initiative (MURI) grant on *Mathematics of Failures* [ARO Grant No. DAAD19-01-1-0646; Program Manager: Dr. Mou-Hsiung (Harry) Chang]. The MURI grant has been supported by four additional grants under the Defense Research Instrumentation Program (DURIP). The CSF Collaboratory will be further expanded with special purpose equipments that have been requested under the 2006 DURIP.

The objective of the Complex Systems Failure (CSF) Collaboratory is to experimentally validate the results of theoretical research and disseminate a knowledge base of science and technology to enhance dependability of complex engineering systems that include both human-operated and unmanned weapon systems and platforms. It envisions a fundamentally new approach to anomaly characterization and real-time decision-making in complex dynamical systems to achieve *pervasive fault tolerance* and *self-healing control* capabilities based on the real-time information. Dependability of complex systems is achieved by identifying and mitigating the origins of chaos and disorder at a very early stage through dynamic coordination and control of the critical subsystems. At present, the major role of the CSF Collaboratory is to support the above-mentioned ARO MURI project; accordingly, the laboratories are being expanded with state-of-the-art apparatuses.

Extensive experimental research is being conducted to validate the theoretical results, for which special-purpose laboratory apparatuses have been (and also are being) constructed. The following three laboratories have been developed in the CSF Collaboratory:

- ***Electromechanical Systems Laboratory***
- ***Networked Robotic Systems Laboratory***
- ***Systems Simulation Laboratory***

***The Electromechanical Systems Laboratory*:** The laboratory consists of electronic, electro-mechanical, electro-hydraulic, and mechanical systems interconnected by electric and hydraulic power networks and real-time networked computer systems. It has several special-purpose apparatuses of different kinds and is supported by a variety of high precision computer-controlled optical, electromagnetic, and electromechanical instruments.

The goal of the laboratory is to validate engineering and scientific theories of integrated control, communication, and computation in complex electromechanical systems, where the complexity is hidden and cryptic during normal operations and may only become acutely conspicuous when contributing to rare cascading failures. Laboratory apparatuses have been designed and fabricated for experimental research in fundamental aspects of fatigue crack initiation, multi-degree-of-freedom mechanical motion (including chaos and strange attractors), electric motors, and active electronic circuits. A computer-controlled test apparatus and a laser-based material degradation measurement apparatus are planned to be procured in 2005 for early detection of very high cycle fatigue cracks in critical structures of complex electromechanical systems.

Several apparatuses have been constructed or procured to experimentally validate the theories of failure propagation in complex systems, such as rotorcraft and gas turbine engines. Experiments on these apparatuses have been and will be designed to demonstrate how the service life of critical components of complex systems could be enhanced by optimized trade-off between performance and structural durability.

Figure A-1 shows the picture of one of the computerized special-purpose fatigue-damage-prediction apparatus that is equipped with the following sensing devices:

- Questar QM100 Step Zoom Long distance traveling microscope with image resolution on the order of 2 microns at a distance of 15 to 35 mm, and mounted on a 3-axis stepper motor driven precision stage

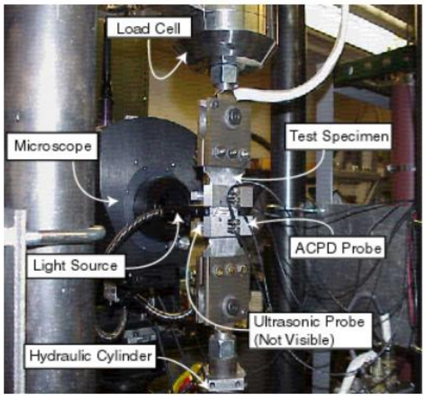

Figure A-1 Fatigue Damage Apparatus

- Piezo-electric crystal ultrasonic flaw detector injecting acoustic waves into the test specimen and deriving the anomaly measure by using a real-time software
- Alternating Current Potential Drop (ACPD) device injecting 100 kHz to 1 MHz electrical energy through the test specimen
- Fiber-optic-based extensometer for measurement of (relatively large) crack lengths
- Load cell for measurement of temporally varying applied tensile forces

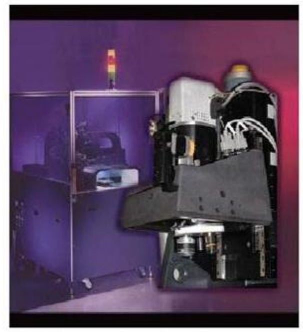
Figure A-2 Optical Metrology Module

The laboratory is being equipped with an optical Metrology Module (OMM) as shown in Figure A-2, which serves as a stand-alone device for measurement of surface deformation and defects. The OMM provides non-contact, gauge-capable metrology that meets the critical measurement requirements of magnetic recording heads, print rolls, fiber optics, optical filters and other applications. This equipment will be used for fundamental research in early detection of very small fatigue-induced cracks in ductile alloys. This device will also interface easily with the existing mechanical, electrical and data acquisition systems of other apparatuses in the CSF Collaboratory.

The effects of pervasive faults will be emulated by combining the resources of Electromechanical Systems Laboratory and Systems Simulation Laboratory. The computer-coded structural models of critical components, located at the Systems Simulation laboratory, generate time series data of cyclic stresses. These data will be transmitted as real-time information to the Electromechanical Laboratory over a network. The time series data of (computed) stress cycles can be interpreted as load cycles to the specimens, made of plant component materials, which are installed on a fatigue damage sensing and control apparatus. These signals are processed in real time to obtain the anomaly measure that, in turn, is used to compute the damage. The damage information, generated by the sensing devices, are feedback signals to the fatigue test apparatus(es) for active damage control, health monitoring, and maintenance planning. The (remotely located) supervisory control system will receive this information and accordingly issue appropriate commands to the lower layer control system. The video data of fatigue damage in specimens, made of plant component materials, will also be generated from the optical microscope for on-line transmission to the remote site at the Systems Simulation laboratory.


Figure A-3 Pioneer 2 AT Robots

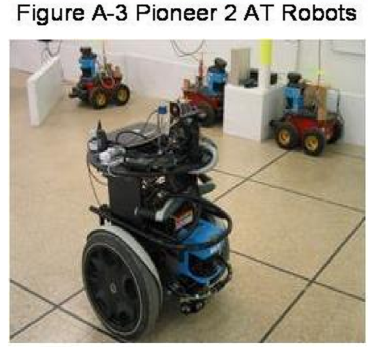
Figure A-4 Team of Segway and Pioneer 2 AT Robots

The Networked Robotic Systems Laboratory: The laboratory, in its current configuration, consists of three Pioneer 2 AT mobile robots; Figure A-3 shows a pair of instrumented robots. Each robot is equipped with a SICK LMS200 laser range finder for obstacle avoidance and distance measurement. The laser range finder provides depth information for a 180^{o} field of view with an angular resolution of 0.5^{o} and an accuracy of 1 cm (± 15 percent). Each robot uses a SONY EVI-D30 pan-tilt camera in conjunction with a Sensoray 311 PC104 frame grabber for object recognition and tracking. For communication between the robot and a remote computer for the purpose of monitoring, a Lucent Technologies WaveLan 11 Mbps radio ethernet (2.4GHz) is employed. In practice, a bandwidth of up to 2Mbps is achieved. An Advantech on-board computer, powered by a Transmeta Crusoe Processor TM5400 500MHz CPU, performs all real-time computations. It has 320MB memory including 256MB PC133 RAM and 64MB flash memory, and a 20GB hard disk. These devices are powered by three 12 Volt sealed lead acid batteries; DC/DC converters are used to provide appropriate power to various devices. The major actuators available on the robots are motors for wheel drive, gripper, and camera. Figure A-4 shows a Segway Mobile Robot Platform (RMP) that has been procured for demonstration and validation of advanced discrete-event supervisory control capabilities for a team of heterogeneous robots.

The Networked Robotic Systems Laboratory emulates multi-level battlefield Command, Control, Computer, Communication, Intelligence, Surveillance, and Reconnaissance (C^4I) systems, where the robots represent autonomous ground vehicles. In general, coordination of robots in a more complex mission is realized through integration of several computer-controlled mobile robots at the execution level, computer-controlled coordinators at the supervision level, and the simulated Commander at the coordination level. The robots represent various mobile platforms (with on-board sensing capabilities) at the battle front. The information from these robots is communicated via wireless transmission to the Coordinators. The battlefront scenarios are emulated at a higher level based on the real-time processed information from the Coordinator. The Commander computer makes decisions based on this information and issues commands to the Coordinators that, in turn, transmit instructions to the individual robots under their control. The challenge here is to formulate and validate decision and control policies for failure accommodation and mitigation in the uncertain operating environments with partial information being available from sensors and other sources. These complex tasks are realized by combining the resources of the Networked Robotics Laboratory and the Systems Simulation Laboratory.

***The Systems Simulation Laboratory*:** This laboratory consists of two large-scale system simulation facilities: (i) Rotorcraft Dynamics based on the Sikorsky GENHEL model of UH-60 Black Hawk as shown in Figure A-5; and (ii) Gas Turbine Engine Dynamics based on the General Electric model of a typical gas turbine jet engine as shown in Figure A-6. The objectives of this laboratory are to design and validate new concepts of anomaly detection, health monitoring, and life extending decision and control for future-generation rotorcraft, gas turbine engines, and other weapon systems and their subsystems. Figure A-7 shows the architecture of a reliable and high performance control scheme for future generation rotorcraft. Figure A-8 shows the architecture of a discrete-event supervisory control scheme for health management and life extending control of gas turbine engines.

Figure A-5 Black Hawk UH-60 Rotorcraft

The hardware and software resources at this laboratory are adequate for interactive simulation of weapon systems and mobile platforms in battlefield environment. The laboratory has the capability for hardware-in-the-loop simulation with spatially distributed subsystems that interact over computer communication networks. To experimentally demonstrate the theories of early detection, accommodation and mitigation of pervasive faults in complex systems, the resources of this laboratory are combined with those of other laboratories. For example, emulation of Command and Control operations with armored vehicles and rotorcraft in a battlefield environment requires the joint resources of the Systems Simulation Laboratory and the Networked Robotic Laboratory. Similarly, investigation of life extending control and self-healing control in complex weapon systems would require the joint resources of the Systems Simulation Laboratory and the Electromechanical Systems Laboratory.

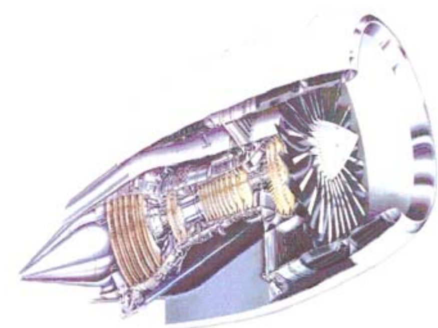

Figure A-6 Typical Gas Turbine Jet Engine

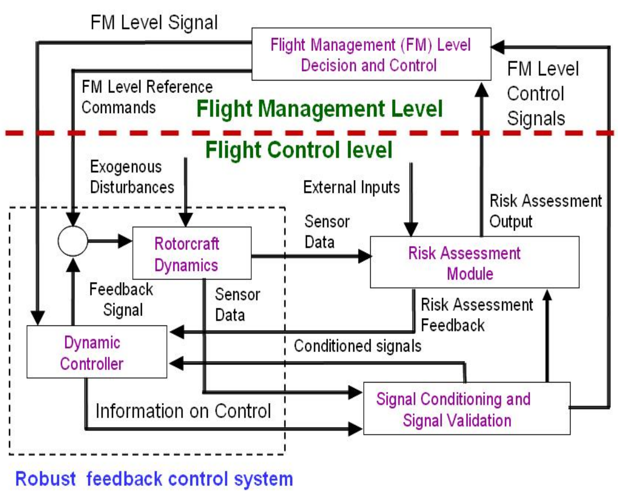

Figure A-7 Reliable High Performance Control of Future Generation Rotorcraft

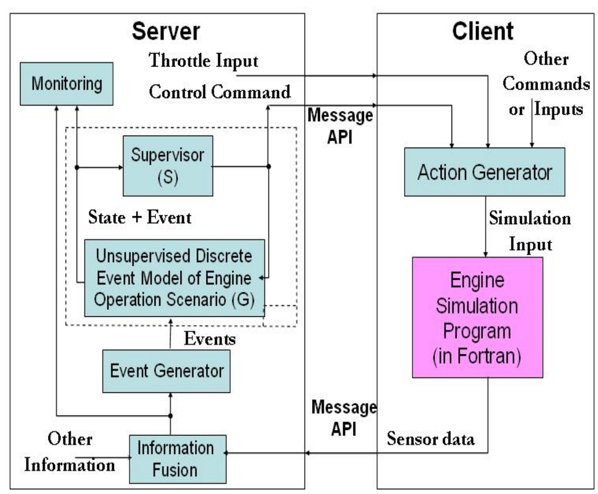

Figure A-8 Discrete Event Supervisory Control of Gas Turbine Engines