AESS MEETINGS & CONFERENCES

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| | | | http://www.fusion2007.org
22-25 August 2007 | 2007 International Conference on Information Fusion | Xian, China | Y. Li, +86-29-8226-4619
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| | | | http://www.cis.xidian.edu.cn
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| | | | nospovatova@eurocom.com
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| | | | kingw@usna.edu
| | | | (301) 778-6902 F
| | | | williams2@usna.edu
8-11 October 2007 | 2007 IEEE International Conference on Security Technology (ICST’07) | Ottawa, ON, Canada | L. Sampson, 613/563-6646
| | | | sampson@ieee.org
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| | | | framtonescallop.co.uk
| | | | goudet@ntrs.org
1-3 March 2008 | 2008 IEEE Airmesse Conference | Big Sky, MT | D. Zimmerman, (800) 726-8225
| | | | dzimmerman@eistec.com
| | | | bmoore@rfirc.fraunhofer.de
26-29 May 2008 | 2008 IEEE Radar Conference | Rome, Italy | E. Erofeev, +7 951 635-6635, ext. 105
| | | | bermo@rfirc.fraunhofer.de
| | | | gschmitz@rfirc.fraunhofer.de
8-11 September 2008 | AESS Avionics 2008 | Salt Lake City, UT | B. Newton, (310) 444-8370
| | | | nnett@asu.com
| | | | a.yariv@asl.nl
| | | | a.yariv@asl.nl
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OTHER SOCIETY MEETINGS OF AESS INTEREST

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| | | | dolea@uw.edu
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Send all corrections and omissions to Barry C. Breen at his address on the inside back cover.
For latest information: http://www.eew.ieee.org/ksc/AES/conferences.html
This Month's Cover... Marvin the Methane Detector is designed as an autonomous unmanned aerial vehicle for a near-surface methane detection mission on Mars.


This artist's depiction of Marvin was done by M. Emre Gündüz of Georgia Institute of Technology's Department of Aerospace Engineering on a background photograph of Mars taken during the NASA Viking Mission; our cover illustration was derived from the Conference Proceedings cover.

Marvin the Methane Detector is an autonomous unmanned aerial vehicle designed for methane detection on Mars. It is a small, lightweight aircraft capable of flying at low altitudes near the Martian surface to detect methane plumes.

MARVIN – Near Surface Methane Detection on Mars

By K. Shroti, A. Khalid, M.E. González, K. Manyapu, Y.F. Sumer and D.P. Schrag

This artist's depiction of Marvin was done by M. Emre Gündüz of Georgia Institute of Technology's Department of Aerospace Engineering on a background photograph of Mars taken during the NASA Viking Mission; our cover illustration was derived from the Conference Proceedings cover.

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UAV Payload and Mission Control Hardware/Software Architecture

This paper presents an embedded hardware/software architecture specially designed to be applied on mini/micro Unmanned Aerial Vehicles (UAV). A UAV is a low-cost non-piloted airplane designed to operate in D-cube (Dangerous-Dirty-Dull) situations [8]. Many types of UAVs exist today; however with the advent of UAV’s civil applications, the class of mini/micro UAVs is emerging as a valid option in a commercial scenario. This type of UAV shares limitations with most computer embedded systems: limited space, limited power resources, increasing computation requirements, complexity of the applications, time to market requirements, etc. UAVs are automatically piloted by an embedded system named “Flight Control System.” Many of those systems are commercially available today, however no commercial system exists nowadays that provides support to the actual mission that the UAV should perform.

This introduces a hardware/software architecture specially designed to operate as a flexible payload and mission controller in a mini/micro UAV. Given that the missions UAVs can carry on justify their existence; we believe that specific payload and mission controllers for UAVs should be developed. Our architectonic proposal for them orbits around four key elements: a LAN-based distributed and scalable hardware architecture, a service/subscription based software architecture and an abstraction communication layer.

General Aviation Aircraft Flight Operations Quality Assurance: Overcoming the Obstacles

This describes the initiative to introduce a capable yet affordable Flight Operations Quality Assurance (FOQA) program into the general aviation industry. A brief overview of the FOQA concept is given along with a historical perspective to the evolution of such programs. Initial development of a FOQA program for general aviation by the Center for Sensors and Sensor Systems at Saint Louis University is introduced herein. A brief discussion of the obstacles in developing such a system is presented, as well as strategies for overcoming these obstacles. The system consists mainly of a quick access recorder (QAR) that is conceived to be a stand-alone, non-intrusive system that collects parametric flight data, a preprocessor system to analyze initial data sets and validate their use, and post-processor software used in the analysis of available flight parameters. The program concepts are presented for initial determination of the needs and possibilities, and examples are presented along with flight data collected in the University’s fleet of aircraft.

Taming Tornadoes Storm Abatement from Space

Tornadoes represent the most dangerous and destructive of storms. This paper describes a concept for disrupting the formation of tornadoes in a thunderstorm. Beamed microwave energy from a satellite heats cold rain to affect convective forces in the storm cell. This describes a Thunderstorm Solar Power Satellite (TSPS). The TSPS is based on Space Solar Power Program (SSP) concepts and technology.

The concept was evaluated in a numerical simulation using the Advanced Regional Prediction System Code at the Center for Analysis and Prediction of Storms (CAPS). Conditions for tornado formation were affected in the simulation. Additional simulation is proposed to determine the specific areas to be heated and the intensity of directed energy to affect tornado genesis.

Benefits from taming tornadoes provide a basis for initial government investment in TSPS. The potential benefits are balanced by reservations about safety. Demonstration of technology and operations may lead to commercial investment in space solar power. We conclude that the TSPS concept merits additional analysis, numerical simulation, and demonstration testing.

Tetrahedral Robotics for Space Exploration

A reconfigurable space filling robotic architecture has a wide range of possible applications. One of the more intriguing possibilities is mobility in very irregular and otherwise impassable terrain. NASA Goddess Space Flight Center is developing the third generation of its Addressable Reconfigurable Technology (ART) Tetrahedral Robotics Architecture. An ART-based variable geometry truss consisting of 12 tetrahedral elements made from 26 smart struts on a wireless network has been developed. The primary goal of this development is the demonstration of a new kind of robotic mobility that can provide access and articulation that complement existing capabilities. An initial set of gaits and other behaviors are being tested, and accommodations for payloads such as sensor and telemetry packages are being studied. Herein, we describe our experience with the ART Tetrahedral Robotics Architecture and the improvements implemented in the third generation of this technology. Applications of these robots to space exploration and the tradeoffs involved with this architecture will be discussed.

Flight Operations in the New Millennium

New approaches are being studied for real-time interaction, and related supporting processes, with spacecraft and instruments in deep space. Spacecraft are evolving, improving in many ways, and generally becoming more robust. Operations is changing also, and will be more automated in the future. However, there is a challenge. Deep space missions are not all alike. The Operations phases of discovery and exploration are an extension of the research that creates the mission; they are the time of obtaining results.

This examines the historical role of flight operations and its evolving processes to develop an understanding of the operational methods that will be effective in the future.

It takes people, equipment, software, space, and connectivity for Operations success. A balance has to be struck between improving technology, gaining knowledge, automation, and realistic expectations.

Finally, the recommended methods to gain efficiency in Operations are system-wide services and shared resources. These common processes will meet the challenge of varied missions.
UAV Payload and Mission Control
Hardware/Software Architecture

Enric Pastor, Juan Lopez & Pablo Royo
Technical University of Catalonia

ABSTRACT

This paper presents an embedded hardware/software architecture specially designed to be applied on mini/micro Unmanned Aerial Vehicles (UAV). A UAV is a low-cost non-piloted airplane designed to operate in D-cube (Dangerous-Dirty-Dull) situations [8]. Many types of UAVs exist today; however with the advent of UAV’s civil applications, the class of mini/micro UAVs is emerging as a valid option in a commercial scenario. This type of UAV shares limitations with most computer embedded systems: limited space, limited power resources, increasing computation requirements, complexity of the applications, time to market requirements, etc. UAVs are automatically piloted by an embedded system named “Flight Control System.” Many of those systems are commercially available today, however no commercial system exists nowadays that provides support to the actual mission that the UAV should perform.

This introduces a hardware/software architecture specially designed to operate as a flexible payload and mission controller in a mini/micro UAV. Given that the missions UAVs can carry on justify their existence; we believe that specific payload and mission controllers for UAVs should be developed. Our architectonic proposal for them orbits around four key elements: a LAN-based distributed and scalable hardware architecture, a service/subscription based software architecture and an abstraction communication layer.

INTRODUCTION

An Unmanned Aerial Vehicle (UAV) is an expression that identifies an aircraft that can fly without pilot; that is, an airframe and a computer system which combines sensors, GPS, servos, and CPUs. All these elements combined have to pilot the plane with no human intervention. Another usual definition is that of an aircraft which is capable to fly in an autonomous way and operates in a wide range of missions and emergencies that can be controlled from a ground base station. The UAV’s size, type, and configuration could be different and depend on the actual application.

There is no doubt today that a huge market is currently emerging from the potential applications and services that will be offered by unmanned aircrafts. More precisely, UAVs can be applied in so-called “D-cube” missions [8], i.e., missions identified as Dangerous, Dirty, or Dull. If we pay attention to civil applications, a wide range of scenarios appear. For instance; remote environmental research, pollution assessment and monitoring, fire-fighting management, security; e.g., border monitoring, agricultural and fishery applications, oceanography, communication relays for wide-band applications. In general, all of these applications can be divided into four large groups: environmental applications, emergency-security applications, communication applications, and monitoring applications.

Nowadays, and after many years of development, UAVs are reaching the critical point in which they could be applied in a civil/commercial scenario. However, we believe that there is a lack of hardware and software support to effectively develop such potentialities. Basically a UAV is automatically piloted by an embedded computer called the Flight Control System (FCS) [6]. This system reads information from a wide variety of sensors (accelerometers, gyro, GPS, pressure sensors) and drives the UAV mission along a predetermined flight plan.

Even though reliable autopilots exist, the main purpose of the UAV is the actual mission that should execute with its required payload (sensors, etc.) The thesis of this research is that mission and payload control are the main bottlenecks that may prevent the actual development of UAVs in the civil sector. Military UAVs use specific control designs specially tailored to the particular surveillance mission that they will implement. However, a civil UAV should be able to implement a large variety of missions with little reconfiguration time and overhead, if it must be economically viable.

This paper presents a novel hardware/software architecture [9] specially designed to operate as mission and...
payload controller in a mini/micro UAV. We will call this system the Mission Control Computer. Our architectonic proposal orbits around four main innovative elements: 1) a LAN-based distributed and therefore easily scalable hardware architecture, 2) a service/subscription-based software architecture, 3) an abstraction communication layer, and 4) a workflow-based mission planning.

The paper is organized as follows: the section entitled Background and Motivation details the structure and components inside a UAV system and explains the reason a mission/payload is necessary. The System Architecture section introduces the proposed hardware architecture, and following, software application architecture is explained; the Service-Based Software Architecture details the architecture of the communication mechanisms inside the UAV and between UAV and base station. For example, our Mission Control Computer prototype is detailed in the Operational Scenario. The final section concludes this paper and identifies some of our future developments.

BACKGROUND AND MOTIVATION

A UAV is a complex system composed of six main sub-modules that work coordinately to obtain a highly valuable observation platform [5]. Figure 1 depicts a schematic view of each sub-module.

The UAV Airframe
A simple, lightweight, aerodynamically efficient and stable platform with limited space for avionics, and obviously no space for a pilot.

The Flight Computer
The heart of the UAV. A computer system designed to collect aerodynamic information through a set of sensors (accelerometers, gyros, magnetometers, pressure sensors, GPS, etc.), in order to automatically direct the flight of an airplane along its flight-plan via several control surfaces present in the airframe.

The Payload
A set of sensors composed of TV cameras, infrared sensors, thermal sensors, etc., to gather information that can be partially processed on-board or transmitted to a base station for further analysis.

The Mission/Payload Controller
A computer system on-board the UAV has to control the operation of the sensors included in the payload. This operation should be performed according to the development of the flight plan as well as actual mission assigned to the UAV.

The Base Station
A computer system on the ground designed to monitor the mission development and eventually operate the UAV and its payload.

The Communication Infrastructure
A mixture of communication mechanisms (radio modems, satcomm, microwave links, etc.) that should guarantee the continuous link between the UAV and the base station.

Current UAV technology offers feasible technical solutions for airframes, flight control, communications, and base stations. However, if civil/commercial applications should be tackled, there are two elements which limit the flexibility of the system: human intervention and mission flexibility.

Too much human control from the ground station is still required. Flight control computers do not provide additional support beyond basic flight plan definition and operation. Additionally, payload is most times remotely operated with very little automation support.

Economical efficiency requires the same UAV to be able to operate in different application domains. This necessity translates into stronger requirements onto the
mission/payload management subsystems, with increased levels of flexibility and automation.

SYSTEM ARCHITECTURE

The hardware architecture of the proposed Mission Control Computer is built as a set of embedded microprocessors connected by a local area network (LAN), i.e., it is a purely distributed and therefore scalable architecture (see Figure 2). Even though this is a simple scheme it offers a number of benefits that motivates its selection in our application domain.

The high level of modularity of a LAN architecture offers extreme flexibility to select the actual type of processor to be used in each sub module. Different processors can be used according to functional requirements, and they can be scaled according to the computational needs of the application. System modules can be awakened on-line when required at specific points of the mission development. Modules can be added (even hot plugged) if new requirements appear.

Module interconnection is an additional extra benefit because the complex interconnection schemes needed by parallel buses do not fit properly with the space and weight limitations in a mini/micro UAV.

Finally, development simplicity is the main advantage of this architecture. By using techniques inspired by Internet communication protocols, computational requirements can be organized as services that are offered to all possible clients connected to the network. These communication schemes will be further described below.

A number of specific computational modules have been identified as “a must” in any real life application of UAVs. These modules are depicted in Figure 2. On top of these modules several applications will be executed providing specific services to other applications.

Even providing the computational support to these applications will be scaled according to the requirements, but without requiring major modifications in the communication schemes. Critical services to be offered include the following elements: an interface with the Flight Computer System, the Mission Control service, a communication service with a selection of communication infrastructures, video and photo management as a data gathering system or even with real time processing, a data storage service, and a motor control service in case mobile components should be controlled.

SERVICE-BASED SOFTWARE ARCHITECTURE

Over this LAN infrastructure, we implement a software layer that allows each computation module to support multiple applications by providing services to the network. Each application could create and subscribe to the available services. The services could be discovered and consumed in a dynamic way like web services in the Internet domain. Applications could interchange information transparently from network topology, application implementation, and actual data payload. This approach together with the hot-pluggable LAN offers interoperability of different modules and applications.

Service-oriented architectures (SOA) are getting common in several domains, for example Web Services [1] in the Internet world and UPnP [2] in the home automation area. SOA is an architectural style whose goal is to achieve loose coupling among interacting components or services. A service is a unit of work done by a service provider to achieve the desired end results for a service consumer. Both provider and consumer are roles played by software agents on behalf of their owners. The results of a service are usually the change of state for the consumer but can also be a change of state for the provider or for both.

The idea of these architectures is to increment the interoperability, flexibility, and extensibility of the designed system and their individual components. In the implementation of any system, we want to reuse components from the existing system, however in doing that we usually introduce additional dependencies between the components. Service-oriented architectures tries to minimize these dependencies by using loose coupled components.

SOA achieves loose coupling among interacting components by employing two architectural constraints. First, a small set of simple and ubiquitous interfaces to all participant components with only generic semantics encoded. Second, each interface can send on request descriptive messages explaining its functioning and its capabilities. These messages define the structure and semantics of the services provided. These constraints depart significantly from
that of object-oriented programming, which strongly suggests that you should bind data and its processing together.

When a component needs a functionality not provided by itself, it asks the system for the required service. If another component of the system has this capability, its location will be provided, and finally, the client component can consume the service by using the common interface in the provider component. The interface of a SOA component must be simple and clear enough to be easily implemented in different platforms, both hardware and software.

**Proposed Architecture**

In our SOA-based system, services will be provided by different modules, each composed by an embedded microprocessor and the needed hardware to accomplish their assigned task. The designed architecture should fulfill several functional and non-functional requirements.

**Dynamic Discover**

New modules can be attached to the LAN while the system is working and the modules already present on the system will be informed of their presence [4]. In a similar way, when a module needs a service, it can ask the system if any other module is offering this functionality.

**Remote Execution**

Modules will be able to consume services exposed by other modules in the net. A service will offer several functions that can be invoked remotely. The consumer module will send the function and its parameters and will wait for the results returned by the provider module.

**Module Self-Description**

Each module will provide on request a description of the services it offers. This will help on the development of complex functionalities and will offer modules the possibility of using services that did not exist when built/programmed.

**Get/Set Data From Modules**

Modules will be able to expose their inner state using variables. Other modules can ask for this information or send changes to it in a synchronous way. These variables contain information from sensors or inputs to the different UAV actuators.

**Data Streaming**

Some variables will change at high rates. It will not be efficient for a module to ask constantly for new values from such a variable. For handling this sort of data, our architecture provides data streams that efficiently send information to multiple modules using the multicast capabilities of the network.

**Two Naming Policies**

The users of our system will want to use clear and sound names for the variables, streams, and services like “adf compass,” “fuel flow,” or “lights on.” However at the network layer it will be more efficient to use numeric identifiers occupying fewer bytes. One of the responsibilities of the software layer we provide is to discover and cache the numeric identifiers used internally by the network while the modules can be developed thinking in terms of external human-understandable identifiers.

**Subsystem Grouping**

Information transmitted in our network can be related to different subsystems and our protocol is able to keep this relationship. This allows us to mix and group data from different subsystems. For instance, this will be useful in a ground base station to select data from different UAVs, or inside the UAV itself for grouping information from several engines, etc.

**Distributed Architecture**

Our system should avoid centralized nodes to guarantee its correct global operation. In our vision, each module is responsible for announcing its capabilities and for providing its services without help from any other module.

**Lightweight Protocol**

There exist some protocols common in other areas that could be extended and modified to be used for our intention,
i.e., RTP [3] for the transmission of streamlined information. However, we decided to implement a very lightweight brand-new protocol, capable of obtaining real-time behavior in microcontrollers with limited computational resources.

**OPERATIONAL SCENARIO**

Imagine the following scenario: the mission control decides to take a geo-referenced video. For this task it will need the services provided by storage, flight computer system, and the camera & sensing modules. In Figure 3, we show how these different modules interact and interchange messages with the system to accomplish this complex task.

- **1-2.** The Mission Control asks the system for the module which generates the variable or stream GPS data and the Flight Computer System responds with its location.

- **3-4.** The Mission Control asks the system for the module which generates the stream video camera and the Camera & Sensing module responds with its location.

- **5-6.** The Mission Control asks the system for the module providing the service store stream and the Storage module responds with its location. Now, the Mission Control knows the location of all the services and it will subscribe to those streams.

- **7.** The Mission Control subscribes to the stream GPS data generated by the Flight Computer System.

- **8.** The Mission Control subscribes to the stream video camera generated by the Camera & Sensing module.

- **9-10.** The Mission Control commands the Storage module to store both the GPS data and video camera data streams. From this point on, the Storage Module stores the data without Mission Control intervention.

The software layer we have designed allows the development of complex and collaborative services that can be easily reutilized among several UAV applications. The available modules in our UAV provide an extensive set of services, covering an important part of the generic functionalities present in many missions; therefore, to adapt our aircraft for a new mission, it will be enough to reconfigure the mission control to use the adapted services without adding new software or hardware. Furthermore this abstraction layer provides some desirable capabilities to our system: redundancy, parallelism, fault tolerance, and scalability. When a module distributes a data stream, multiple modules can be receiving it. The processing of this information could be done then in a parallel or redundant way; for example, by processing alternate video frames in two modules or by storing two copies of the sensor data in two different storage modules.

In an analogous way, different modules can offer the same service, variable, or stream. When a module asks the system for a particular action, it does not exactly know (and it does not need to know) which node is going to answer. This permits that, in case of a module failure, another module with equivalent functionalities can attend its responsibilities transparently. This architecture also allows an important degree of scalability and flexibility because it’s not needed to know in advance in which hardware nodes the services are mapped. A hardware node can initially offer several services, and if a low performance is detected we can distribute their services among several nodes. The applications implementing the mission will be unaware of these changes.

**COMMUNICATION GATEWAY**

In a UAV, several communication links may be available, i.e., RF-links, SATCOM links, or wireless links. However, not all links may be available at the same time, and moreover the cost of using each link could be completely different. Depending on the flight stage and application, some links may be more appropriate than others. Therefore, in a flexible architecture, it should be possible to dynamically choose the most convenient or reliable network link.
Our system includes a communication gateway that monitors all communication links and routes the traffic between the UAV and the base station through one or more communication links. Network capabilities, their link quality (bandwidth and latency), the required throughput and the cost (both economical and power requirements) should be taken into account. The gateway should have enough intelligence to select the appropriate routing decision in a real-time and autonomous way.

One of the key elements of this communication gateway is the fact that it provides an homogenization mechanism to hide the actual infrastructure. A data router at the entry point of the base station and another at the Mission Computer will redirect all traffic between the air and ground segments through the best available link. Figure 4 depicts a possible architecture of the ground station and the gateway that will provide connectivity to the UAV in flight. The gateway will concentrate all traffic from the available links and re-inject it into the LAN at the ground station.

PROTOTYPE DEVELOPMENT

We are currently developing a prototype of our architecture using ARM9 hardware modules involving the following components: an autopilot module, a camera & sensing module, a communication manager with two network interfaces: an RF modem and a Wi-Fi device, and finally, a storage module.

The AP04 is used as the autopilot [7]. AP04 is a fully integrated autopilot with manual override, automatic take-off, waypoint-based flight plan, and landing. It has integrated GPS/INS navigation systems providing positioning data for other subsystems. It also provides a 900MHz RF modem for long-range communications.

We could sense the environment using several sensors and cameras. A camera and sensing module are in charge of interfacing with these devices and providing their data to other modules in the system. For this first prototype, our sensor device will be a standard digital USB camera. In addition, the core modules will provide temperature and voltage sensors to monitor their state.

For the communication links we will use an RF modem operating in the 2.4 GHz band and a commercial off-the-shelf (COTS) Wi-Fi network card. The first will be used for long-range telemetry and the latter for close-range configuration and data downloading without connecting cables to the UAV. We are also studying the possibility of using Line-of-sight directional Wi-Fi antennas for increasing the coverage.

Some modules will have higher bandwidth requirements and we will not be able to transmit the information to ground base station nor process it directly in the UAV. Therefore, we will provide a storage module to save permanent information in a Compact Flash media for later processing on-ground.

This prototype has the essential modules to demonstrate the viability and capabilities of our proposed architecture.

CONCLUSION

This paper introduced a hardware/software architecture designed for use as avionics for mission and payload control in the area of Unmanned Aerial Vehicles. The design tackles a number of elements critical for the operation of these systems. The architecture is a LAN-based pure distributed system, being therefore highly modular and scalable according to the requirements of the applications. A small connectivity infrastructure is required among the modules, but yet enough connectivity bandwidth could be obtained. The applications architecture is service-based, following WEB-based/Internet paradigms, offering low developing complexity through a number of standardized protocols.

An initial prototype is currently being completed, the Mission Control Computer. This system will cover basic services that exist to provide support to any UAV civil application like: a homogeneous communication mechanism through a heterogeneous infrastructure, a massive storage service, an image/video recording service, a Flight Computer interface service, and the mission control service itself.

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General Aviation Aircraft Flight Operations Quality Assurance: Overcoming the Obstacles

Kyle Mitchell, Beshara Sholy & Alan J. Stolzer
Saint Louis University

ABSTRACT

This describes the initiative to introduce a capable yet affordable Flight Operations Quality Assurance (FOQA) program into the general aviation industry. A brief overview of the FOQA concept is given along with a historical perspective to the evolution of such programs. Initial development of a FOQA program for general aviation by the Center for Sensors and Sensor Systems at Saint Louis University is introduced herein. A brief discussion of the obstacles in developing such a system is presented, as well as strategies for overcoming these obstacles. The system consists mainly of a quick access recorder (QAR) that is conceived to be a stand-alone, non-intrusive system that collects parametric flight data, a preprocessor system to analyze initial data sets and validate their use, and post-processor software used in the analysis of available flight parameters. The program concepts are presented for initial determination of the needs and possibilities, and examples are presented along with flight data collected in the University’s fleet of aircraft.

INTRODUCTION

A form of flight data monitoring, a Flight Operations Quality Assurance (FOQA) program is an airline-based initiative for the identification and remediation of aircraft operations-related problems prior to their leading to disasters. A FOQA program provides insight into the flight operations environment through selective automated recording and analysis of data generated during line operations. FOQA involves the collection of flight parametric data sets that are collected by the traditional digital flight data recorder (DFDR) systems. At the heart of a FOQA program is the enabling hardware that includes quick access recorders (QAR). QARs are available commercially and are designed to collect data from various systems on-board the aircraft.

A QAR accesses and collects raw data, and provides an easy access to the data via removable media, or via secure real-time RF-data-link. The collected data is then converted to interface with data processing software that is used in a particular FOQA software program. The FOQA software aids an experienced operator in the reconstruction of all aspects of a particular flight for analysis and problem reporting. While the reporting of incidents by pilots and other aviation personnel is subjective, the data collected via a FOQA program is considered to be an objective, unbiased recording of a actual flight scenario. FOQA analysis software is commercially available, is expensive, and is used mainly by the airline industry.

In the US, FOQA programs are voluntary and are used by air carriers for the identification and remediation of potential risks in flight operations, as a tool to promote safety and to increase efficiency and productivity of operations. FOQA data are not intended for use for identifying non-compliance with flight operations rules and regulations, nor is the program intended to be used by regulators as a punitive tool.

In contrast to the FOQA programs implemented at many airlines, the general aviation (GA) industry does not enjoy similar access to flight data monitoring programs. GA would benefit from a similar system to not only improve safety and operational performance, but also for use in training new pilots and for improving maintenance procedures. The high cost of commercially available FOQA analysis systems is driven predominantly by development and certification costs, and the relatively small market that exists for these tools. In effect, the cost of these tools renders them inaccessible to the GA industry.
This paper provides a conceptual approach to address this issue by proposing a feasible FOQA program for GA use (FOQA-GA). The developments discussed herein pertain to an autonomous system that is independent of the aircraft platform. This system reports on a number of in-flight parameters of interest that are captured by calibrated embedded sensors. The captured data is then pre-processed by an on-board computer and recorded to a QAR. The system accommodates the recording of digital data of a variety of parameters including pitch, roll, yaw, acceleration, velocity, distance, position, altitude, cabin temperature and pressure, and others, as needed. The system is self-contained, thus autonomous, and is easily secured in a location in the aircraft flight cabin. The recorded data is retrieved by the operator for later translation and analysis by FOQA software similar to those used by commercial aviation (but appropriately less sophisticated).

A FOQA-GA system can aid small operators, such as flight schools, in providing a cost-effective maintenance monitoring program. A visual flight reconstruction program can also assist in the instruction of pilots by comparing actual flight paths to scheduled flight paths and allowing instructors to critique solo flights by discussing the flight reconstruction with the pilot trainees. Recording of flight dynamics can aid maintenance and flight personnel and students in identifying flights exceedances; i.e., events that exceed predetermined parameters or conditions within which the aircraft is designed to operate.

BACKGROUND

In January 1995, the aviation community held a safety summit to discuss the need for additional safety programs, including a flight data monitoring program similar to those that have been in place in European airlines for decades. One of the significant conclusions of the summit was that the voluntary implementation of FOQA might be the most promising initiative to reduce the number of accidents (Federal Aviation Administration, DOT, 1998). Upon the recommendation of the conference attendees, the FAA sponsored a FOQA demonstration project with the following objectives: to develop hands-on experience with FOQA technology in a US environment; document the cost-benefits of voluntary implementation of FOQA programs; and initiate the development of organizational strategies for FOQA information management and use. The three-year, FAA-funded, $5.5 million demonstration project began in July 1995; today thirteen US airlines have approved programs.

Depending upon the capabilities of the airplane involved, FOQA collects parameters from hundreds of sensors and data sources on the airplane. On a typical Boeing 757 manufactured 15 years ago, for example, FOQA records and stores 200 to 300 parameters per second. Sophisticated airplanes produced today are capable of capturing over 2,000 parameters per second [7]. Parameters recorded include: altitude, airspeed, heading, control surface position, engine and system condition information, cockpit switch positions, information from navigation equipment, and so on. Many FOQA systems are capable of indicated such things as whether the cabin seat belt light is illuminated, the amount of turbulence the airplane is in (using g-load/accelerometer sensors), and the wind drift angle. Using expert software tools, these data are explored to detect single events or exceedances (i.e., deviations from defined expectations) that may have occurred, and the data are aggregated to learn about trends that may indicate areas that need further attention [9].

The data collected in a FOQA system is virtually the same as that collected in the digital flight data recorder system – the so-called “black box” – that investigators use to determine the cause of aircraft accidents. In the case of the flight data recorder, data from the last 25 hours of flight are stored in a crash-resistant container, typically in the tail section of the aircraft. The data are almost always retrievable in the event of a crash, but otherwise the data are difficult to access. By contrast, FOQA is designed to use the data for purposes other than crash investigation, so the data medium, such as an optical storage device or PCMCIA card, is readily accessible and is retrieved during routine maintenance events.

Several companies produce the special software tools needed to analyze FOQA data, including: Aerobyte (FDM), Austin Digital (Event Measurement System), Sagem Avionics (Analysis Ground Station), Simauthor (FlightAnalyst), Teledyne Control (Flight Data Replay Analysis System), and others. While these tools vary in the features offered, most include the following as a minimum: data storage and management capabilities (e.g., data de-identification, airport/aircraft libraries available, raw data storage, data export to external tools); monitoring and analysis capabilities (e.g., event detection, statistical analysis, graphical analysis of flight parameters, identification of trends); and report generation and querying (e.g., automated report generation, customized outputs, export analysis results to other tools) [3].

Commercial air carrier FOQA systems consist of two main components: the recorder (i.e., QAR), and the analysis (and possibly visualization) software. Both of these components are expensive and difficult to implement or use. For an air carrier with about 30 aircraft, a FOQA program costs about $500,000 for the airborne and ground software; a typical QAR costs over $10,000 alone [1]. The QAR operates by connecting to the data bus which is normally a standard ARINC 429 or an ARINC 629 type. GA airplanes lack the consistency of using the ARINC standards, which renders the commercially-available QAR useless for GA purposes.

Developing a new system designed for GA aircraft is most prudent. During development, the system will be used on a local fleet to examine its usability and effectiveness. The system is designed to accommodate a large number of recordable parameters, and can be expanded indefinitely to include more when needed. The cost of such a system will be dependent on the number of parameters chosen for a given
application, but is anticipated to be a fraction of the cost of a commercial system.

Flight data recorders for commercial airliners record the status of most sensors and instruments on the aircraft, including the avionics systems, flight control positions, engine performance, and many other parameters. Installation of a device capable of this level of recording in a GA aircraft would require significant redesign, reconstruction, and recertification of the aircraft. This would limit installation of FOQA-GA devices to aircraft undergoing major maintenance. As an alternative, the proposed FOQA-GA device is non-invasive and does not require retrofitting or recertification of the aircraft, and it can be installed in any aircraft without modification in a matter of minutes.

Limiting the FOQA-GA device to a non-invasive installation places limitation on the measuring capability of the recording device. Since the device cannot interface to the communications taking place on existing sensor data buses, the FOQA-GA device will contain a separate set of self-contained sensors capable of generating many important parameters of the flight. A set of these parameters has been identified for the current study, and include ground speed, latitude, longitude, elevation, engine speed, cabin temperature, cabin pressure, time, roll, yaw, and pitch.

FOQA-GA

Importance of Developing a FOQA-GA System

FOQA has become a valuable tool in the safety, training, and management programs of commercial air carriers. Although general aviation airplanes are not equipped with the systems necessary to collect FOQA data in the traditional sense, new technologies have emerged that enable the collection of basic flight data that can be extremely useful in a number of ways. The development of a FOQA-GA QAR to collect, in the minimum, exact position, altitude, ground speed, vertical and horizontal positions, horizontal and lateral accelerations, and cockpit communications, and pilot view video can be affordable and possible. The collected data can be used in training of pilots and maintenance personnel on the uses of the data in determining allowances and exceedances of flight parameters. The data can also be used in the management of flight scheduling, downtime for maintenance scheduling, and other management-related issues.

The accident rate for GA has been steadily decreasing over the past decade – 9.08 accidents per 100,000 flight hours in 1994 to 6.22 in 2004 [6]. While this trend is encouraging, there is much room for improvement. The determination of probable causes of aircraft accidents often leads to even greater improvements in safety, but investigators are often frustrated in their efforts to draw conclusions due to the absence of flight data. A FOQA-GA system can also provide the necessary data to reconstruct a flight when and if needed, provided the system is encased in a crash-proof container. In fact, the parameters collected in the proposed system are not greatly dissimilar to those used in early-generation flight data recorders in airliners.

Potential Benefits for FOQA-GA

The general aviation industry stands to benefit in several areas from the adoption of a FOQA-GA device. In flight training, solo flights can be reconstructed and critiqued in a flight simulator situation. In maintenance, issues surrounding loading during training operations can be monitored and incidents of exceeded ratings can be used to schedule maintenance. In accident reconstruction, information not currently available, such as attitude and engine speed, can be provided to investigators.

Flight Training

Playback of a dual or solo training flight can be used by instructors to critique flight maneuvers. This is currently being done using systems that contain GPS data, however, GPS-only data limits the critique to whether or not a path was followed and maintained. With the addition of attitude and engine speed a much clearer picture of how the aircraft was being operated can be viewed and discussed.

Aircraft Maintenance Scheduling

Real-time monitoring of the forces the airframe is subjected to can lead to better fleet maintenance. Monitoring of the G-loading of the aircraft and performance of the engine can help identify aircraft that have experienced loads beyond their design limits. Aircraft that have been subjected to such loading need to be inspected for structural damage or deformity. Currently there is no method to monitor when these exceedances occur. Additionally, monitoring of performance loading coupled with damage detected during inspection can be used by aircraft manufacturers to design systems more tolerant of stresses.

Accident Reconstruction

Current general aviation accident reconstruction relies on retrieving all the components of the aircraft, determining their position and condition at the time of the crash, and forming hypotheses about the cause(s) of the crash. If the investigators are able to view a simulation of the last minutes of a flight they would have considerably more information from which to form conclusions.

Table 1 depicts the parameters that will be useful for various purposes. Personnel in flight training and accident investigation will be interested in all the available measurements. Personnel in maintenance will be more concerned with how the aircraft is performing and what stresses have been placed on the airframe, and less concerned with where the aircraft was flown.

Obstacles to Implementing a FOQA-GA System

As described above, there are several obstacles to implementing a FOQA-GA system. First and foremost is the high cost, both for the requisite hardware and analysis software. The absence of an ARINC bus in GA aircraft renders the commercially available QARs useless, so a QAR that is not dependent on an ARINC bus must be developed. Finally, software programs that contain the necessary
algorithms to interpret aircraft characteristics based on the parameters available, to analyze the data, and provide visualization of the data are needed.

Table 1. FOQA-GA Parameters

<table>
<thead>
<tr>
<th>Flight Training</th>
<th>Maintenance Scheduling</th>
<th>Accident Investigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitude</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Latitude</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Ground Speed</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Altitude</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Direction</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Roll</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Yaw</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Pitch</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Engine RPM</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Cockpit Sounds</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Structural Loading</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

PRESENT EFFORTS

Previous work on general aviation flight monitoring and replay has primarily relied on GPS data to analyze the flight path of the aircraft. GPS data is excellent for determining whether an aircraft flew a correct path but provides very little information about other conditions encountered along that path. GPS data only provides longitude, latitude, elevation, and ground speed; it does not provide aircraft attitude or engine speed indication. The proposed FOQA-GA device will extend the current work being done with GPS data by adding sensors to measure roll, yaw, pitch, temperature, pressure, and engine speed to allow additional flight properties beyond position information.

Current research into acceptable systems for accurately measuring these properties is underway. Static quantities like temperature and pressure will be acquired through the use of commercial off-the-shelf (COTS) transducers. Engine speed will be acquired through signal processing of a microphone placed in the cockpit. Roll, yaw, and pitch cannot be directly measured with a high enough accuracy using low cost sensors. These quantities will be estimated using measurements from COTS accelerometers.

Needed Parameters and Parameter Limits

The development of a FOQA-GA device requires identifying those attributes that are of interest for flight reconstruction and airframe stress determination. Flight reconstruction requires knowledge of the aircraft’s position, heading, and attitude. Airframe stresses can be inferred from the aircraft’s position, heading, and rates of roll. Table 2 enumerates those attributes currently identified for the first generation FOQA-GA device and the sensors being studied to measure these quantities.

The currently identified flight parameters are those required to visually recreate the flight of the aircraft. These include parameters for ground position, aircraft attitude, and additional measurements such as engine speed. The current target set of measurements is limited by those readings which can be measured or inferred from instruments that do not interface, intrude, or come in contact with flight surface, controls, or instrumentation. The set of direct-measured parameters based on an available prototype system are shown in Table 2.

The parameters and parameter limits are by no means bounded by the above list. The listed parameters are the minimum needed to reconstruct a simple flight with the aid of commercial processing software.
Table 2. Parameter Limits

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Limits</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airspeed</td>
<td>0 to 200 knots</td>
<td>GPS</td>
</tr>
<tr>
<td>Altitude</td>
<td>0 to 15000</td>
<td>GPS and Altimeter</td>
</tr>
<tr>
<td>Position Longitude, Latitude</td>
<td>N/A</td>
<td>GPS</td>
</tr>
<tr>
<td>Heading</td>
<td>0° to 360°</td>
<td>GPS</td>
</tr>
<tr>
<td>Flight Time</td>
<td>0 to 5 hours</td>
<td>GPS</td>
</tr>
<tr>
<td>Acceleration</td>
<td>−1.5 to 4.0 G</td>
<td>Accelerometer</td>
</tr>
<tr>
<td>Cabin Temperature</td>
<td>−20° to 40°C</td>
<td>Thermocoupe</td>
</tr>
<tr>
<td>Attitude:</td>
<td></td>
<td>GPS Combined with</td>
</tr>
<tr>
<td>• Pitch</td>
<td>• ± 60°/sec</td>
<td>Accelerometer</td>
</tr>
<tr>
<td>• Roll</td>
<td>• ± 60°/sec</td>
<td></td>
</tr>
<tr>
<td>• Yaw</td>
<td>• ± 60°/sec</td>
<td></td>
</tr>
<tr>
<td>Engine Monitoring</td>
<td>0 to 4000 RPM</td>
<td>Microphone</td>
</tr>
</tbody>
</table>

Present testing is being performed with a laptop and a data acquisition card in both a laboratory setting and in an automobile to ascertain the stability and dynamic range needed from the sensor subsystems to acquire adequate performance. The lessons learned on the bench will be translated into a prototype, self-contained, strap-down FOQA-GA device.

The FOQA-GA system under development is composed of flight monitors and recorders and the post flight analyzers. Figure 1 illustrates the minimum set of functionality needed to record flight data. Sensors that can measure attitude of the aircraft directly are desirable; not all attitude measurements can be sensed directly. In the absence of direct measurement, sensors that measure quantities which can be used to model that actual attitude are chosen and their data manipulated offline to calculate the aircraft attitude. The outputs from sensors often are not in the correct domain for direct attachment to an analog-to-digital converter (ADC) or digital system directly. The analog conditioning circuitry is responsible for adjusting the voltage range of the sensor signal to make full use of the range of the ADC and for removing frequency components that are incompatible with the sample rate of the ADC. The analog sampler combined with the preprocessor manipulates the sensor signals into a form that can be stored in a non-volatile memory. The non-volatile memory (e.g., compact flash card) stores sensor values even in the event of power loss, ensuring that the data will be available to the ground-based analysis system.

When the aircraft is back on the ground, the recording media is removed and reconstruction of the flight can take place. Figure 2 depicts the data flow of the flight sensor data to the various personnel that have an interest in monitoring the flight. Data about engine performance and airframe stresses will be used to calculate a need-based maintenance schedule for each aircraft. These same data will be used to predict when an aircraft is due for inspection. Data about location and attitude will be further processed and sent to a visualization system for flight reconstruction. This reconstruction will be used by pilots and trainers to assess what happened during cross-country solo flights. This same visualization can be used by accident investigators to replay the last minutes before a crash.

![Fig. 1. Major Components of a Flight Data Recorder](image_url)

**Work in Progress**

Currently sensor selection and algorithm development is taking place. Figures 3, 4, 5, and 6 depict data recorded from various sensors during initial testing. Sensors are initially tested using a laptop computer outfitted with analog and digital recording equipment. Figure 3 is a travel path as generated from the longitude and latitude recorded from a Garmin GPS. The path traveled was 5 miles of Interstate 64 through St. Louis County. When overlaid on a topographical
map the path was found to be nearly exact down to the lane of the highway. Figure 4 is the data recorded from an Analog Device thermocouple amplifier measuring the temperature

![Diagram](image1)

**Fig. 2. Depiction of Data Collection and Usage in a FOQA-GA System**

![Graph](image2)

**Fig. 4. Temperature Profile from a Car with Air Conditioning**

**Proposed Future Work**

Acoustic sampling using air source microphones and frame source acoustic transducers are planned to monitor engine speed and landing gear and flap actuation. Mechanical systems produce vibrations which can be detected and recorded by microphone-style recording systems.

The cockpit of a small aircraft is filled with the drone of the engine. The frequency content of this noise can be used to estimate the rotation speed of the engine. Noises present in the audible range can be recorded with a standard voice grade recording system. Mechanical systems create vibrations that can lie outside – either above or below – the audible range. These vibrations can be recorded by monitoring the vibrations in the frame of the aircraft. Vibration of a metallic structure creates stress and strain in the structure. By treating these stresses and strains as acoustic emissions, different mechanical systems of the aircraft can be monitored in much the same way as one listens for acoustic signatures in the ocean to track vessels. It is anticipated that landing gear can be monitored for both motion and locking by monitoring the acoustic emissions present in the airframe.

A data visualization tool will be necessary in order to gain maximum value of FOQA-GA for flight instruction purposes. A system where a simulated aircraft flies through a simulated terrain is envisioned. This system will be developed in C language using open GL for graphic rendering. The choice of this software development environment will facilitate easy porting to different computing platforms as the need arises. The envisioned system will allow viewing of the flight from the perspective of inside the cockpit with a simulated instrument panel and from outside the aircraft. During viewing from outside, the analyst will be able to fix the view to a location in space to enable watching the aircraft fly by, or to lock the view to follow the aircraft from any orientation and distance.
future for the general aviation industry. The system will collect the raw data that will be pre-processed and later analyzed with a low cost analysis tool based on a SQL database. A data visualization tool will also be developed using C language and open GL for graphic rendering.

Additional parameters, unavailable without integrating sensors into the airplane, will be enabled by developing air source microphones and frame source acoustic transducers that may provide estimates of the operation of certain systems, such as flaps and landing gear. Future work may also include data conversion tools for use by operators with access to commercial FOQA software. Other future work on this subject will address the possibility of providing an ARINC 429 transceiver for total system integration in GA aircraft.

REFERENCES


SUMMARY

It is our intention to develop a flight operations quality assurance recording system that will aid in the maintenance of general aviation fleets, assist in the training of pilots, and possibly serve as a useful tool for accident investigation. In doing so, we expect our system to be feasible in the near future.
Taming Tornadoes

Storm Abatement from Space

Bernard J. Eastlund & Lyle M. Jenkins
Eastlund Scientific Enterprises

ABSTRACT

Tornadoes represent the most dangerous and destructive of storms. This paper describes a concept for disrupting the formation of tornadoes in a thunderstorm. Beamed microwave energy from a satellite heats cold rain to affect convective forces in the storm cell. This describes a Thunderstorm Solar Power Satellite (TSPS). The TSPS is based on Space Solar Power Program (SSP) concepts and technology.

The concept was evaluated in a numerical simulation using the Advanced Regional Prediction System Code at the Center for Analysis and Prediction of Storms (CAPS). Conditions for tornado formation were affected in the simulation. Additional simulation is proposed to determine the specific areas to be heated and the intensity of directed energy to affect tornadogenesis.

Benefits from taming tornadoes provide a basis for initial government investment in TSPS. The potential benefits are balanced by reservations about safety. Demonstration of technology and operations may lead to commercial investment in space solar power. We conclude that the TSPS concept merits additional analysis, numerical simulation, and demonstration testing.

INTRODUCTION

Annual loss of hundreds of lives and property damage in billions of dollars is the result of severe weather in the United States. Tornadoes and hurricanes are the principal agents of this damage through the extreme winds in these mesocyclones. There are theories that global warming will increase the frequency and intensity of these storms. The capability for providing warning of hazards from these storms has improved. This paper presents concepts for abatement of the most severe aspects of such storms.

Eastlund Scientific Enterprises Corporation investigated the potential for active intervention in storm systems [1]. One concept calls for the application of atmospheric heating using electromagnetic waves. These microwave beams are similar to those used in ground- and space-based diagnostic systems. The frequency range required is similar to that of police radar (26–37 GHz). Flux levels about 1000 times that of a police radar would be focused on fine structure in the storm to disrupt the convective shear forces that produce tornadoes. In particular, the microwaves would heat structures such as the cold rain downdraft. The process of heating cold rain in the storm will reduce the beam flux to a safe level at the earth's surface.

A solar power satellite is proposed as the source of the microwave beam. The proposal is derived from the concept of a Solar Power Satellite proposed by Peter Glaser [2]. It is described as a Thunderstorm Solar Power Satellite (TSPS). The concept requirements were presented at the Workshop on Space Exploration and Resource Exploitation-Explospace, 20-22 October, 1998, Cagliari, Sardinia [1]. The systems analysis indicates that power levels on the order of $5 \times 10^8$ to $10^9$ watts could prevent tornado formation in smaller mesocyclones. These results are based on numerical simulation of mesocyclones using the Advanced Regional Prediction System (ARPS) code [4] at the Center for Analysis and Prediction of Storms Center (CAPS) at the University of Oklahoma.

CONCEPT DESCRIPTION

Tornadogenesis, the process of tornado formation, is not well understood. There is a complex interaction of the relative motions within the storm. The shear interface between updrafts and downdrafts acts to concentrate energy in one or more tornadoes. The fact that most mesocyclones do not generate tornadoes is the basis for speculation that the injection of a small amount of energy can disrupt tornadogenesis in the at-risk storms. Doppler radars on the ground and in space must identify the precursors to tornado
formation and direct the energy beam into the critical structure. The extensive ground-based system of Doppler radar provides extensive data on storm development. However, the ground-based systems primarily measure horizontal rain motion. The overview of a space-based Doppler radar could directly measure the vertical velocity components of the draft structure. The uncertain occurrence of storms in time, location, and motion are also best observed from the overview of an orbiting space system.

The Thunderstorm Solar Power Satellite concept focuses on the mesocyclone storm systems. Initial concentration on the fine structure of mesocyclone systems identifies the elements for disrupting tornado formation. A phased-array microwave antenna is expected to perform a dual function. First, it is a Doppler radar for defining the critical structure of the storm. The antenna then forms the concentrated beam to heat the designated volume of the storm. Targeting of the beam will be dependent on accurate real-time identification of the location of the appropriate fine structure.

Current understanding of tornadogenesis does not support specific designation of critical volumes. Improvements are required in numerical modeling and correlation with storm condition sensing. For example, the ARPS code does not include some important microphysics, such as the size of rain droplets. The choice of microwave frequency is dependent on droplet size. This improved modeling and sensing provides a basis for TSPS requirements and technology development needs. The results would have immediate benefits in improvement of forecasting and timely hazard identification.

PROPOSED PROGRAM OBJECTIVES

In order to define a program for the reduction of the number of tornadoes produced by super-cell thunderstorms, a series of objectives are proposed. Initially, there must be an evaluation of the concept for feasibility and practicality. The central activity is the numerical simulation of tornadogenesis and the interaction with the application of directed energy. Then the research and tasks necessary for demonstration of critical elements of the process are defined. Having characterized these elements, the needed resources will be estimated. An interdisciplinary funding structure will be necessary, as weather modification is not presently the focus of any one government agency. NOAA would likely lead with responsibility for computer simulations and monitoring the weather. DoE has a role in application of space solar power. NASA provides the capability to develop space-based systems.

SCIENTIFIC ISSUES

The science of tornadogenesis is the subject of considerable research and analysis. The complex process is not well understood. Numerical simulations are not yet reliable in predicting tornado formation. Project VORTEX (Verifications of the Origin of Rotation in Tornadoes Experiment) collected storm data indicating occurrence of significant tornadoes on the cool side of pre-existing, low-evel boundaries. Other precursors to tornadogenesis include lightning, rain patterns, convective shears, and storm motion. These elements define the fine structure of super-cell thunderstorms that are integrated with updrafts and downdrafts. These parameters show the difficulty of adequately dealing with variables in the numerical models. Research on concentration of energy in the vortex of a tornado is important to the capability to interact with a storm. Are there "Achilles' heel" zones that smooth the concentration of energy when stimulated? Determination of the effect of external energy input on the convective forces is the key to the "taming" of tornadoes.

TECHNICAL ISSUES

The design of a space system to monitor a storm and to generate a microwave beam is within the aerospace experience base. To achieve the capability to track the storm structure and to direct the microwave beam is a significant challenge. Diagnostic and heating microwave beams must have focal patterns of 50 meters or less. The beam frequency for greatest heating effect is dependent on raindrop size. Techniques for sensing absorption of the beam and the effect on convective forces must be determined [9]. Modeling of storms will define the requirements for duration and intensity of the heating beam. Initial experiments will aid in evaluating the interactions with actual storms. The design of TSPS must accommodate safe operations and include interlocks against improper use.

CONCEPT NUMERICAL SIMULATION

The initial analysis is based on results of the Advanced Regional Prediction System (ARPS) code at the Center for Analysis and Prediction of Storms (CAPS) center at the University of Oklahoma [4]. This systems analysis assesses the effect of electromagnetic wave heating in a mesocyclone (thunderstorm) and estimates the energy requirements for tornado-mitigation concepts.

The ARPS numerical model is a three-dimensional, non-hydrostatic, compressible model in generalized terrain-following coordinates. It is run on a CrayC90 at CAPS. The governing equations of the atmospheric model component of ARPS include conservation equations for momentum, heat (potential temperature), mass (pressure), water substance (water vapor, liquid, and ice), subgrid scale turbulent kinetic energy, and the equation of state of moist air.

The study, Systems Considerations of Weather Modification Experiments Using High Power Electromagnetic Radiation [1] focused on the hypothesis that cold downdrafts in proximity to hot updrafts (the hook-echo region) play a role in tornadogenesis. The ARPS model was modified [8] to study effects on a "standard storm" of electromagnetic radiation beamed from a Thunderstorm Solar Power Satellite. The results of this study indicated significant
effect on the simulated storm from the microwave heating [1]. This result was achieved with the application of heating over most of the cold area of the hook-echo. Refinements in the numerical simulations in the next phase will include microphysics, now missing, and will be oriented toward the reduction of the required energy input and its application to specific fine-structure regions. First experiments would be diagnostic-related. A small volume of the storm would be heated and then the motion of the heated air would be followed with real-time radiometers to obtain correlation with the improved numerical models.

OVERALL SYSTEM REQUIREMENTS

Certain parameters will drive the requirements for the space system. For instance, the elimination of a downdraft involves a volume within the thunderstorm. The volume heated may range from less than 1 to more than 100 km³. Corresponding linear dimensions are a few hundred meters up to 10 kilometers. Typically, the region of high rainfall, 6g/Kg or greater, is about half a cubic kilometer. Heating rates of .01 °K/second-meter² to .05 °K/second-meter² appear adequate for significant heating on a time scale of 30 minutes. The electromagnetic wave generation requirements for total power range from a maximum 5 x 10¹⁴ watts to a minimum of perhaps 5 x 10¹² or less. The duration of heating may range from one minute to thirty minutes and will be a factor in selecting the operational orbit for the TSPS.

Depending on the target raindrop size, the microwave frequency may be from 20 GHz to 96 GHz. If numerical simulations indicate a fifty-meter resolution in the horizontal plane, specific phased array antenna dimensions are required. In geosynchronous orbit, the antenna radius is 3100 meters @ 13.5 Ghz or 500 meters @ 85 Ghz. For a low earth orbit, the antenna radius is 75 meters @ 13.5 Ghz or 30 meters @ 85 Ghz. Although space construction of structures on this size is challenging, studies indicate their feasibility. In order to track the moving storm, it may be necessary to reposition the microwave beam in microseconds.

The microwave beam from a Solar Power Satellite is targeted on the receiving rectenna array by locking on a pilot signal from a transmitter located at the rectenna array. Targeting a specific cold, rainy downdraft in a mesocyclone will be more difficult. The downdraft can have a horizontal velocity of up to 70 m/sec. It also is embedded in a complex mesocyclone system. The diagnostic package of the TSPS will need to reliably locate this downdraft on a time scale of seconds, with a resolution of about 60 meters in the horizontal direction and about 200 meters in the height.

Considerable cloud and rain cover can occur over the downdraft region. The region we wish to heat will most likely have a high rainfall concentration. However, if the rainfall in the top of the cloud is below 2 g/Kg, then there will be little attenuation before the beam enters the greater rainfall density.

NUMERICAL SIMULATION AND ASSESSMENT

A more complete understanding of tornadogenesis must be developed before the feasibility of mitigation by heating fine structure, such as cold downdraft regions, can be determined. Also, the present severe storm diagnostic capability and numerical simulation codes are not yet suitable for real-time assessment of electromagnetic heating results.

The ARPS numerical simulation is presently used to make weather predictions for the Southern Plains on a daily basis and for the entire US Continent during special experimental periods. Important input parameters are temperature and wind velocity distribution data. Presently the WSR-88D Doppler radar network is used for input on rain distribution. Wind shear is inputted using data obtained from rawinsonde balloons. Data are available only every 12 hours with the few wind profilers that are presently in operation.

The large-scale prediction runs usually use grid sizes of 1 to 5 km and thus, the available data is serviceable for these types of simulations. By using a nested grid with smallest dimensions of 58 meters in the horizontal direction, ARPS has been used to study the conditions suitable for tornado formation [8]. These simulation codes show the conditions thought to be critical for tornadogenesis. Specifically, development of strong updrafts and downdrafts separated by a “hook-echo.” The “hook-echo” regions were the targets in the initial simulations documented in [1]. These simulations showed significant changes and reduction in the conditions required for tornadogenesis. Additional simulations using this code and other codes will refine our understanding of the interactions with the beamed energy.

We suggest the following numerical code requirements for use in a tornadogenesis mitigation system:

- A. **Real-time calculations.** It would be desirable to predict the development faster than real-time to be able to provide better targeting.

- B. **Continuously updated with fresh data** from diagnostic systems. Validation using extensive field data.

- C. **Nested grid calculations** down to 58 meters or less in horizontal grid dimensions.

- D. **Ability to calculate heating patterns** with complex electromagnetic heating beam geometry.

- E. **Inclusion of important microphysics** considerations.

The diagnostics must also be capable of real-time operation, a one-second or less response time.
meters/second, the mass in one grid point can move entirely to another grid point.

The WSR-88D Doppler radar system has a beam width of 9° and a typical resolution of 1 km to 10 km. This would be adequate to locate a candidate mesocyclone. The TSPS would be designed with Doppler radar imaging systems to identify and quantify the velocity of the rain downdraft. The TSPS system must be able to distinguish rainwater densities of between 2 and 6 g/Kg. Spatial resolution of 10-50 meters will be desirable.

At geosynchronous orbit, a 13.5 GHz Doppler Radar with an aperture radius of about 3.1 km would give a focal spot radius of about 50 meters. For a 350-km altitude orbit, an aperture radius about 75 meters would give a focal spot radius about 50 meters at 13.5 GHz. These dimensions are consistent with the required dimensions of the power beam; therefore, the power beam antenna could have a diagnostic dual use.

Microwave Doppler radiometers with response time of less than 1 second could take real-time measurement of the actual heating patterns. The information would be fed in real-time into the numerical code to predict heating results. The beam direction and intensity would be continuously corrected with the input data from the diagnostics.

SPACE SOLAR POWER SYSTEMS

A fundamental source of the microwave beam to interact with the cold rain downdraft is expected to be a version of the solar power satellite invented by Peter Glaser [2]. The overview capability of an orbiting system is an effective approach to locate, track, and direct energy into the sensitive region of the mesocyclone. Ground-based alternative systems have little chance to be in an optimum position to interact with a threatening storm. Even so, there are a number of potential design concepts that can be evaluated.

Much of the SSP technology [6] will be common to many of the TSPS concepts. This commonality extends to the commercial space solar power concepts. Current SSP studies provide a level of confidence that the TSPS can be designed, constructed, and operated without requiring any technological breakthrough. Still, improvements in technology will reduce the cost of SPS. Examples of these technologies are solar cells (mass and efficiency), power management and distribution (super-conductivity), microwave generation (solid-state) [5], space construction (robotics), flexible structure (control systems), high specific impulse propulsion (solar-electric thrusters), and reusable launch vehicles (launch cost reduction).

An initial version of TSPS could be much smaller than a full scale SPS. The TSPS development program might be integrated with that defined for commercial space solar power. For example, experiments for diagnostic purposes (as described above) could be performed with the present International Space Station. One or two payloads of energy storage devices, such as batteries, could be trickle-charged from the station’s solar panels. Heating times of 10 minutes could be provided by such a system.

SYSTEM ECONOMICS

The predicted cost of power from an SPS is subject to a wide range of uncertainty. Not only is the mass of the system dependent on many advanced technologies, the transportation cost for delivery to orbit must be reduced an order of magnitude below current cost of access to orbit. For example, the European Space Agency has defined the technological and economical development considerations necessary for an “economical” SPS system. Electricity could be provided for $0.30/Kw-hour if the mass-specific power of an advanced technology SPS were about 200 watts/Kg, transportation costs were about $1000/Kg and hardware costs were $5000/Kg. [10]. NASA study projections are lower than $0.10/Kw-hour using other parameters. However, the SPS cost must compete with the World Bank predicted generation cost at about 5.5 cents per Kw/hour.

By providing tornado-mitigation services to the insurance industry, the revenue from the service decreases the net cost of power delivery. The TSPS application could provide additional revenue for a 1 GW SPS of about $500 million per year. This could decrease the net cost of electricity generation and increase the potential for near-term economic competition of space solar power with fossil fuels [7].

The potential for saving lives with TSPS supports government investment in initial development and deployment. A value per life saved might be used to make an economic justification for the TSPS. Furthermore, a project such as the TSPS provides a significant market for launch services and faster development of economical launch vehicles.

Nearly all of the elements of a commercial SSP system are required in the TSPS program. Demonstrated engineering and operations allows credible projection of efficiency for commercial SSP’s. These projects provide a level of risk reduction needed to attract commercial investment. The larger commercial power systems will provide clean, renewable energy to benefit the Earth's environment.

SAFETY, LEGAL, AND POLITICAL CONSIDERATIONS

Paramount to evaluating the potential for active intervention in natural weather processes are the safety, legal, and political aspects. Some guidelines for developing weather mitigation concepts were defined in the 1992 NAS (National Academy of Science) study on greenhouse warming. The study suggests steps for mitigation research as follows [3]:

1. Theoretical modeling and simulation analysis of the physics, chemistry, and biology of the
relevant geophysical, geochemical, climate, and ecological system.

2. Study of potential for instability and chaos.

3. Small-scale mitigation experiments to determine physical, chemical, and biological properties where they are known.

4. Detailed design, development, and cost analysis of deployment systems.

5. Study of related natural events to understand their relevant properties including the statistics of their occurrence.

6. Study of possible ecological, geophysical, geochemical, and atmospheric side effects, including consideration of reversibility.

The NAS guidelines described above form part of our recommended guidelines for weather control by space means. However, fear of such research has to be dealt with. One of the most damaging concerns is weather manipulation for military purposes to the detriment of the world’s population. The UN Convention on the Prohibition of Military or any other Hostile Use of Environmental Modification, which went into effect 5 October, 1978, applies only to “widespread, long-lasting or severe” environmental modifications, and specifically allows local, non-permanent changes, such as precipitation enhancement, hail suppression, fog, and cloud dispersal. Even so, there is concern that techniques will be applied to military objectives. This fear may be justified; however, such concern should not deter responsible scientists from pursuing research that saves lives and property. We propose three additional guidelines to address this issue:

7. Systems design shall include provisions that preclude military or harmful applications.

8. Oversight committees with international representation will review all plans and experiments.

9. Space systems for severe weather modification shall operate under International control.

CONCLUSIONS

Throughout history, mankind has sought to minimize the impact of the unpredictability and severity of violent storms such as tornadoes. To date, solutions have focused on development of fortified buildings made to withstand the strong forces that are the hallmark of these atmospheric events. Sophisticated prediction methods have been developed to warn populations of potential storm danger. These “warn and seek shelter” mechanisms have clearly reduced, to some extent, the loss of life and, to a lesser extent, property damage associated with these natural events. However despite our best efforts, loss of life and costly property damage are still strongly associated with severe weather phenomenon. This paper has presented a new paradigm that seeks mitigation of these violent weather systems. By using beams of electromagnetic radiation from satellites to heat the fine structure of a mesocyclone, the formation of tornadoes may be disrupted. The objective is to prevent concentration of storm energy and diffuse it over a larger area. The anticipated result is minimum impact on overall weather without the death and destruction from tornadoes.

The systems analysis performed so far is rudimentary. To assess concept feasibility, more research is required, especially in the areas of numerical simulation and beam propagation analysis. A program to pursue such goals must rest on firm public support in which the risks and benefits are clearly set forth.

Near-term benefits to the industrialization of space are likely. By providing a significant market for launch vehicles, the TSPS program can contribute to the advancement of launch technology and to a consequent decrease in the cost of space systems.

If it does prove possible to prevent tornadoes, then systems are envisioned for intervention in other severe storm phenomena. Hurricanes and typhoons may be modified in some beneficial fashion, and weather modification could be a routine operation in the twenty-first century.
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Tetrahedral Robotics for Space Exploration

Steven Curtis, Matthew Brandt, Greg Bowers, Gary Brown, Cynthia Cheung, Caner Cooperider, Mike Desch, Noah Desch, John Dorband, Kyle Gregory, Ken Lee, Allan Lunsford, Fred Minetto, Walt Truszkowski, Richard Wesenberg, John Vranish
NASA Goddard Space Flight Center
Miguel Abrahantes
Hope College
Pamela Clark, Tom Capon, Michael Weaker, Richard Watson
Catholic University of America
Philip Olivier
Mercer University
&
Michael L. Rilee
Computer Science Corporation

ABSTRACT

A reconfigurable space filling robotic architecture has a wide range of possible applications. One of the more intriguing possibilities is mobility in very irregular and otherwise impassable terrain. NASA Goddard Space Flight Center is developing the third generation of its Addressable Reconfigurable Technology (ART) Tetrahedral Robotics Architecture. An ART-based variable geometry truss consisting of 12 tetrahedral elements made from 26 smart struts on a wireless network has been developed. The primary goal of this development is the demonstration of a new kind of robotic mobility that can provide access and articulation that complement existing capabilities. An initial set of gaits and other behaviors are being tested, and accommodations for payloads such as sensor and telemetry packages are being studied. Herein, we describe our experience with the ART Tetrahedral Robotics Architecture and the improvements implemented in the third generation of this technology. Applications of these robots to space exploration and the tradeoffs involved with this architecture will be discussed.

INTRODUCTION

Irregular and unknown environments pose critical problems for space exploration. Mission goals may lead to requirements for access to areas or spaces that are difficult to reach and hard, or impossible a priori, to characterize. Such goals can involve obtaining data pertaining to scientific questions and can also involve providing access to irregular, undeveloped environments in contingent situations; for example, involving search and rescue or forensic analysis. Developing systems with extra degrees of freedom that allow systems to adapt to and move around in complicated environments would provide an important new capability providing access to currently inaccessible regions, see Figure 1.

Addressable Reconfigurable Technology (ART) is an approach to developing systems with multiple degrees of freedom that is being studied at the NASA Goddard Space Flight Center (GSFC). ART features multiple reconfigurable systems acting together to provide advanced capabilities. These advanced capabilities include improved packing factors for deployable structures, active control and increased redundancy for reliability, and new possibilities for structural reconfiguration enabling mobility, multiple use, or configuration optimization. Addressable means that the individual elements of these parallel systems can be accessed and commanded individually and do not require a
high-degree of subsystem autonomy. This means that ART systems can be implemented with current and near-term technologies, see Figure 2. More advanced applications have been discussed elsewhere [1,2,3,4], including for example, systems with the Autonomous Nano-Technology Swarm (ANTS) architectures [5]. These include discussions of the use of adaptable overdetermined trusses for solar sails, radiowave reflectors, manipulators, and modular and monolithic deployable structures.

A cutting-edge technology is Tetrahedral Robotics (TR), which involves active trusses made up of extensible structural members (struts) and interconnections (nodes) arranged in a tetrahedral mesh [6, 7]. The number of tetrahedra, or TETs, is an indicator of the complexity of a TR robot and the behaviors and shapes it can take on, see Figures 1-5. Using an ART-based design philosophy, changing the lengths of the struts in concert allows the truss as a whole to reconfigure itself into a variety of different shapes. The concept is scalable, depending on the technologies used to provide actuation and control, including power, communication, and computation. In the longer-term there are exciting possibilities for MicroElectro-Mechanical Systems (MEMS)-based systems with large numbers of struts enabling an essentially continuous, reconfigurable material. In the near-term, a set of technologies must be developed to enable these active overdetermined structures to take on useful behaviors. The current work focuses on using ART/TR adaptive trusses for mobility and access in irregular and complex environments.

In such environments, especially in the context of exploration, mobility and access mean more than covering distance. They also mean transporting and deploying payloads through and into difficult, even vertical, terrain. For science missions, data relating to important questions usually require access to new and unfamiliar locations that require adaptation during the mission. Without such adaptation, scientific return can be greatly limited. With the increase in the human element of exploration systems, improved capabilities for mobility, access, and adaptability can provide important new capabilities, particularly contingencies where human lives may depend on the ability to adapt equipment for unforeseen and unplanned activities.

All mobility technologies have their limits, the technologies we have been studying aim to enable access to regions that are not accessible by wheeled vehicles. Wheeled vehicles and legged vehicles (and creatures) can adapt to a wide variety of terrain, yet irregular, vertical, subterranean, and similarly hazardous locales push the limits of these modes of locomotion. In the natural world, evolution has driven the development of species that “finesse” such difficulties, e.g., birds that fly to nests on cliffs. Evolution has also led to species that deal more intimately with irregular environments, e.g., snakes which by fine control of their shape can seek prey in tunnels or bury themselves by flexing their bodies. These natural examples have inspired research into a variety of mobility technologies. The reconfigurable trusses that are the subject of this work seek to use structural

Fig. 1. Conceptual 12-TET Rovers with 26 large extension ratio struts integrated as 12 tetrahedra

Fig. 2. First Generation 1-TET behavioral model
reconfiguration to reach for new levels of flexibility and adaptability.

It is worthwhile to note that adaptability need not focus only on the environment in which a mechanism is deployed. Our current focus is on bringing together control, communication, and actuation to enable tightly coupled parallel robotics and using these systems to adapt to external constraints to provide system mobility. This same capability is also applied inward, that is to constraints arising because of the mechanisms and subsystems constituting these tetrahedral robots. Should a strut fail; e.g., by seizing, there are sufficient degrees of freedom remaining to allow the rest of the system to continue to reconfigure and function. This does place novel demands on control algorithms, but a single failure will not cripple these parallel systems. In fact, it is clear that multiple struts may fail and as long as they do not form a pathological “substructure” within the structure, the structure as a whole will still be able to reconfigure and move albeit perhaps in a suboptimal way.

Previous work with Tetrahedral and adaptive trusses has been outlined in a previous paper [8]. The current line of work at GSFC on ART/TR began in 2004 with the development of the 1-TET, a one-tetrahedron reconfigurable truss that demonstrated basic movement and control of a determined system. The struts used in the 1-TET featured an extension ratio of about 2:1, which was enough to allow the 1-TET to topple from place to place by moving its center of gravity. To provide more varied and useful locomotion, a follow-on effort sought to develop a 12-TET, a twelve-tetrahedron truss, with struts with a 5:1 extension ratio. Nicknamed “Arnold” because of its weight, this second-generation 12-TET was deficient in a number of
Table 1. Goals for the Third-Generation 12-TET

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Desired</th>
<th>Achieved (12/06)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strut extension ratio (each)</td>
<td>5:1</td>
<td>5:1</td>
</tr>
<tr>
<td>12-TET Behavior</td>
<td>Complex shapes</td>
<td>Simple shapes</td>
</tr>
<tr>
<td></td>
<td>Climb a 40° Slope</td>
<td>First movements</td>
</tr>
<tr>
<td>Overall mass of 12-TET</td>
<td>&lt; 60 lbs</td>
<td>~92 lbs</td>
</tr>
<tr>
<td>Control</td>
<td>Remote, open loop</td>
<td>Yes</td>
</tr>
<tr>
<td>Strut Length</td>
<td>Self-Maintained</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Individually Commandable</td>
<td></td>
</tr>
<tr>
<td>Strut Telemetry to Central Computer</td>
<td>Enough for monitoring and</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Generating Gaits</td>
<td>Yes</td>
</tr>
<tr>
<td>Strut Extension / Retraction Speed</td>
<td>Fully deploy in 10 sec.</td>
<td></td>
</tr>
<tr>
<td>Total Budget</td>
<td>$100 K</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 5. Second Generation “Box Tet”
A 12-TET precursor lacking the central node.
Note the point-like connections or nodes between the struts.

making a truss with active struts extensible, strong, and smart enough to be able to act in concert to reconfigure the overall shape of the truss. We have endeavored to develop a commandable system that can be used as a test bed to study control algorithms and different mobility strategies.

In this paper, we describe our experience with the second-generation 12-TET Arnold and its successor, the third-generation 12-TET. In the following sections, we briefly discuss Arnold’s structure and performance. Arnold’s successor features a complete redesign, which we will outline. In parallel with the prototyping efforts reported in this paper, we are studying technologies for adapting these structures for use on the lunar surface; for example, our electrostatic dust-mitigation research and its application to our prismatic joints will be discussed elsewhere [9].

PREVIOUS GENERATION TET ROBOTS

The first ART/TR was the 6-strut 1-TET which formed a single-cell mechanism with a flopping gait, see Figure 2. It featured nested, telescoping aluminum tubes with nylon top and bottom pieces, and changed their lengths by Kevlar fishing-line string-pulley actuation. As stated above, the ratio of these struts’ fully extended to their fully compact length was about 2:1, which was enough to allow the simple structure to move its center of gravity out of its base, initiating a tumble. The electronics and motors were all Commercial-Off-The-Shelf (COTS). Kit development microcontroller prototyping boards were used with hobby
Table 2. Comparing the second and third generation struts

<table>
<thead>
<tr>
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<th></th>
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<tbody>
<tr>
<td>Bandolier, steel cable &amp; pulley system</td>
<td>Nested screws with exoskeleton</td>
</tr>
<tr>
<td>One motor driving both “substruts”</td>
<td>Two motors for independent “substrut” actuation</td>
</tr>
<tr>
<td>Commercial stock aluminum square tubes</td>
<td>Custom stereo lithographic fabrication</td>
</tr>
<tr>
<td>Virtual nodes from wire loop connections</td>
<td>Node cluster of ball &amp; socket joints</td>
</tr>
<tr>
<td>Weight transferred to motor box</td>
<td>Weight transferred directly to ground</td>
</tr>
<tr>
<td>Motor box transfers weight to ground</td>
<td>String pull-potentiometers</td>
</tr>
<tr>
<td>Photodiode and sector wheel for length sensing</td>
<td>3-Axis accelerometer</td>
</tr>
<tr>
<td>Motor current monitoring and limiting</td>
<td>Battery level measurement and auto-shutoff</td>
</tr>
<tr>
<td>Ground sensor</td>
<td>Motor current monitoring and limiting</td>
</tr>
<tr>
<td>Low battery sensor</td>
<td>2 Force gauges for tension and compression</td>
</tr>
<tr>
<td>Central computer handles commands and telemetry</td>
<td>Board temperature sensor</td>
</tr>
<tr>
<td>BlueTooth with custom multiplexing</td>
<td>Central computer handles commands and telemetry</td>
</tr>
<tr>
<td>Mass 26 lb, Min/Max 28” / 116” , Section: 28” × 18”</td>
<td>Fast strut-to-strut communication is in development</td>
</tr>
<tr>
<td></td>
<td>ZigBee using standard protocols</td>
</tr>
</tbody>
</table>

shop motors with incremental encoders implemented with chopper wheels and optical couplers to monitor strut lengths. The 1-TET onboard microcontrollers maintained a simple model of its orientation which it updated after performing a commanded action. Upon an external command executed a timed sequence of strut length changes calculated to cause a single step (or fall) in one direction immediately followed by a return to a similar, regular, initial state ready for another step. This simple procedure, open loop commanded and performed by rote, has allowed operators to direct the TET to maneuver about during many demonstrations around the world.

Though falling over is a feature and not a failure of 1-TET locomotion, finer control is desired for most scientifically motivated planetary operations. To move a step closer to a system that could carry and position a science instrument package more precisely, it was desired to have a system that could move about quasi-statically when desired and that could place an instrument package near or over interesting features such as cracks, crevices, or stones. To move to a quasi-static gait without (much) dynamic tumbling is realized by moving to more complicated TET robots with more tetrahedral cells, see Figure 3. One of the most exciting possibilities fitting within this paradigm is the possibility of putting together a 26-strut 12-TET ART/TR robot that is capable of a quasi-amoeboïd motion, see Figure 4.

At this point we decided to redesign the ART/TR struts to account for the limitations of the 1-TET. To eliminate twisting and binding of the nested cylindrical tubing, nested square tubes were used. Friction of the Kevlar strings over the ends of the strut tube segments was deemed a problem, so for the new struts steel cable and pulleys were used. To lift itself and a science payload robustly a power electric motor with a planetary gearhead and worm gear were used. A potentiometer was used to keep track of strut extension. Excessive compliance and “flop” of the 1-TET’s node end

Fig. 6. Third-generation strut fully retracted
plates was eliminated by creating a “virtual node,” by tying wire loops together in a tight cluster. A custom electronics board on each strut created an ART addressable communications and control architecture. The struts could be queried and controlled by user-friendly interface software running on a laptop communicating with the struts via wireless links. To increase the variety of structural configurations the extension ratio of these new ART/TR struts was increased from 2:1 to 4:1, not quite reaching the goal of 5:1 but still sufficient to start exploring our gait concepts. A number of gaits and motions were designed to take advantage of these new capabilities, but the new strut did not meet our expectations.

Due to our limited resources, time budget, and our focus on using COTS wherever possible, the final weight of the struts greatly exceeded our initial estimates. Furthermore a small design change that greatly eased assembly of the struts turned out to have a dramatic effect on the mechanical behavior of the struts leading to the storage of a great deal of internal tension in the struts’ actuation mechanism. In addition to this tension, the “bandolier” string-pulley system used in the 1st-generation and 2nd-generation ART/TR robots has an amount of “slop” in the length of the strut. For example, in the transition from compression to tension our robust struts would change length, sometimes significantly, perhaps 10%. Even in the face of these difficulties, the new strut design did allow us to examine strut communication, command, and control, and provided us with a look into how these ART/TR robots reconfigure themselves as their struts move around and reconfigure the trusses.

For example, we examined the simple augmentation of the 1-TET as a 4-TET in which a science package is held by 4 ATR/TR struts to the corner nodes of a 1-TET, see Figure 3. We used the 4-TET configuration to learn about the requirements for reconfiguring an over-constrained structure by moving the “central” science node around and outside of the tetrahedral volume. Such motions are an analogy for moving around any science package integrated with an ART/TR framework.

With the 2-TET ART/TR robot, we used the second-generation strut to take a few simple quasi-static test steps or reconfigurations. Most of our motion studies were with the 2-TET and 4-TET configurations. Because of the weight and tension we were careful not to perform, 1-TET style flopping gaits. A fully configured 26-strut 12-TET with the 2nd-generation struts (see Figure 5) weighs over 740 pounds! This presented a number of logistical problems in addition to the problems during test operations. At this point we stress that, so far, the ART/TR robots are to be considered behavioral models and technology demonstrators. These technologies are to be light-weighted and hardened for flight once the behaviors are demonstrated: we do keep in mind how to and maintain plans for a transition to flight-capability.
THIRD GENERATION TET ROBOTS

Requirements for a Small 12-TET

During our final integration and test of the 2nd-generation 12-TET, we had already started a trade study and requirements analysis for the third-generation ART/TR robots. Broadly, a more portable 12-TET that stressed the structural, mechanical, and material aspects of the system was desired. Again resources, budget, and time were also drivers, see Table 1. The basic goals of achieving a 5:1 strut extension ratio with the 12-TET structure able to take on complex shapes while in remote communication with a central computer were carried forward from the 2nd-generation TET. Constraints on weight and the ability to climb a 40 degree slope separate the 3rd- from the 2nd-generations. Speed of strut extension and retraction was also an important consideration. Finally, the availability of summer interns for parts finishing and assembly were also important for determining the 12-TET’s overall timetable.

Mechanical Overview

Based on our experience from previous builds and on the trade studies, we decided to rework the node design for the 3rd-generation strut, see Table 2. The geometry of the struts are similar to the second generation, a back-to-back double sided geometry expanding in two directions, improving the extension ratio with fewer segments and reducing crowding at the nodes, see Figures 6 and 7. For actuation we have developed a system of nested screws within an exoskeleton, which has a greater extension ratio than we believe has previously been achieved. The 2nd-generation ART/TR robots transmitted the weight of the trusses to the ground by loading the ends (nodes) of a strut while its central pulley box rested on the ground. Anyone who has held a book for any period of time at arms length will understand the nature of the stresses involved. Therefore, for the 3rd-generation ART/TR structures, the node was redesigned so that the 12-TET would walk on the node, transmitting the weight to the ground through the node. A cluster of 2- and 3-degree-of-freedom (DOF) joints at each node were designed to strike a balance between rigidity and node freedom and provide a rigid relation between points to improve predictability and control, see Figure 8.

Exoskeleton

The exoskeleton with the nested screws is probably the major change in the 3rd-generation strut. The exoskeleton has three telescoping segments that extend and contract at the same time as the nested screws. The shape of the exoskeleton provides a brace against which the screws themselves turn, and the exoskeleton itself takes the bending loads of the structure to keep the screws from binding. For low-cost and rapid production of the exoskeleton, they were fabricated using stereo lithography, which allowed light and low-friction components with useful built-in features to be conveniently produced.

Actuation

These ART/TR struts feature two independent nested-screw/exoskeleton devices, that could work as one-side “substruts.” Each substrut has its own motor which drives the screws via a pulleyshaft mechanism. Our gearbox/pulley mechanism provides sufficient resistance to backdrive to support the ART/TR mass and movement, and also provides some mechanical advantage, as well. Integrated pull-pots provide excellent strut-length sensing and the entire
package fits within a 3.13 inch diameter by 8.4 inch-long cylinder, but can extend to 44.26 inches with a compression ratio of 5.29:1. A summary of strut characteristics, as built, are in Table 1.

Nodes
The ART/TR nodes also received a great deal of attention. The desire was to provide “feet” for the TET that would assure the struts would stay off of the ground while allowing as much maneuverability to the struts as possible. At the same time, however, we wished for the nodes to add as little as possible to our uncertainty in the configuration of the ART/TR 12-TET as a whole, i.e., to minimize sag and slop. We came up with a 9-faceted design involving 2- and 3-DOF joints that eliminates play when struts are fixed, yet allows full mobility when struts are moving, see Figure 8. This node design also provides space in which a payload may be placed.

Payload Node
A special payload-node was designed to carry a 1 kg “science” payload that allows the same ART/TR struts to be used for all 26 struts of a 12-TET, see Figure 9. Like the feet, the payload design eliminates play while struts are fixed, but allows full TET mobility while moving. The payload is small enough so that the wrapping angle for each strut about the payload is the same.

Command and Sensing
For the first moving behaviors of the 3rd-generation 12-TET, commands are transmitted from a central computer via ZigBee™ wireless communication links to PIC microcontroller-based custom control electronics on each strut. The central computer, in our case an external laptop computer, sends a command sequence of strut lengths vs. times to each strut, and then broadcasts a universal “GO” command to the entire structure. Built-in sensors provide 3-axis accelerometer to measure strut inclination, string pull-potentiometers to provide strut length data, force gauges to measure tension and compression, as well as electronics board temperature. The battery level is also monitored and an automatic shut-off is implemented to save the Lithium Polymer batteries. The sensors and communication when coupled with the central computer provides a powerful framework for developing together a parallel computer that has a space-filling and behaviors for the 12-TET and other ART/TR structures. The integrated system can be seen in Figure 10.

Behaviors
The first behaviors to be developed will all be implemented via open-loop command sequences first tested in simulation. We have added a MATLAB-based simulation of the 12-TET to our existing kinematic and dynamic TET simulations, see Figure 11, [8]. These models incorporate a variety of strut parameters and provide a tool to investigate gait and control algorithms. One such algorithm we have recently studied is the Decentralized Adaptive Controller, and we have found that DAC may provide an efficient means to control TET motions without depending on a centralized processor or burdening interstrut communication bandwidth.

CONCLUSION
In this work, we are exploring the synthesis of computation and actuation into integrated parallel systems that provide truly novel capabilities. Figure 12 gives an impression of the progress that we have made since the start of this work. We have learned a great deal about how to put together a physical mechanism capable of executing what amounts to a parallel computer program that has physical and geometrical implications. Note that components of the 3rd-generation struts have been fabricated by computer driven stereo lithography 3D plans constructed using Computer Aided Design software. Computer animations, stills from which are seen above in Figures 1, 4, and 12, show in a kinematic sense the motions that are possible, at least given their own level of detail and physical fidelity. The first of these two deals with constructing static structures and controlling that process via computer. The latter, the animations, controls the motions and geometries mostly kinematically, but as the technology goes forward with increasing fidelity and dynamics. We are working through the natural evolution of mechanical systems, adding computation and communication to operate many tightly coupled mechanical subsystems in parallel. In one sense, we are putting together a parallel computer that has a space-filling and reconfigurable geometry.

As of this writing, several ART/TR robots have been assembled from 3rd-generation struts, including most recently, a 12-TET, see Figure 10. All of the nonbehavioral requirements for a 3rd-generation 12-TET mentioned above have been met except for the 60 pound mass goal: the 12-TET as-built weighs in at just over 90 pounds. Full motion trials for the current generation 12-TET have begun, starting with simple reconstructions that change the robots shape, but do not necessarily show mobility. In December 2006, we demonstrated mobility by a simple open-loop commanded step of the 12-TET.

We are being exceptionally careful during these trials with the 3rd-generation 12-TET, principally because the plastic parts generated via stereo lithography (SL) have proved more brittle than expected. This does not rule out SL for fabrication in the future, but does constrain material choice. Furthermore, we are learning that feedback adjustment of ART/TR behaviors is going to be very important for use in the field. The ART/TR structure tends to “settle” into configurations that differ from ideal “sticks & nodes” models from which kinematic commands are most easily generated. Incorporating sensor feedback into our ART/TR control is a natural next-step beyond kinematic open-loop commanding, and we believe that this will help the system deal with such non-ideal aspects. Though for flat or sloping terrain such feedback may not be necessary, it will certainly be required.

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ZigBee™ is a trademark of the ZigBee Alliance, Inc.
Fig. 12. The evolution of the most basic tetrahedral structure, the 1-TET, used for strut research and development.

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Robert E. Ryan
Jet Propulsion Laboratory, California Institute of Technology

ABSTRACT

New approaches are being studied for real-time interaction, and related supporting processes, with spacecraft and instruments in deep space. Spacecraft are evolving, improving in many ways, and generally becoming more robust. Operations is changing also, and will be more automated in the future. However, there is a challenge. Deep space missions are not all alike. The Operations phases of discovery and exploration are an extension of the research that creates the mission; they are the time of obtaining results.

This examines the historical role of flight operations and its evolving processes to develop an understanding of the operational methods that will be effective in the future.

It takes people, equipment, software, space, and connectivity for Operations success. A balance has to be struck between improving technology, gaining knowledge, automation, and realistic expectations.

Finally, the recommended methods to gain efficiency in Operations are system-wide services and shared resources. These common processes will meet the challenge of varied missions.

INTRODUCTION

Space exploration is going through a cycle of rapid evolution. There are a number of reasons, but possibly the most significant has to do with cost. At a time when the desire for exploration is increasing, the cost factors are becoming ever more restrictive. The very history of National Aeronautics and Space Administration (NASA) space exploration explains why innovation and technology improvements are proliferating at the present. Even though spacecraft were tested in an end-to-end mode on the ground prior to launch, there were always surprises during flight. Operations personnel learned to patch and correct, finding effective ways to accomplish a task. However, complaints about high overall mission costs usually pointed to Operations as being proportionally too expensive a phase. One could argue that, in the past, the amount of funding allocated to Operations was justified. Operations was truly at the cutting edge and it took a lot of people and equipment to accomplish a mission. At that time, we, in Operations, always pressed on looking for other opportunities, as long as the spacecraft and money held out. The situation is changing... the goals are the same... but we have to work smarter.

We must become more efficient in Operations. The challenge is there. By applying new operations concepts and by using advanced technology, both on the ground and in space, we can provide the means for continued scientific exploration.

THE CHANGING ROLE OF OPERATIONS

Spacecraft systems, both hardware and software, are going through a transformation of their own. The technology advancements and cost limitations mentioned above are causes in themselves, forcing ground operations to innovate and evolve along with the flight system. While this document is directed at ground operations, it is important not to separate ground operations from flight system operations. They need to be looked at as a complete end-to-end system. As spacecraft become more automated and more fault-tolerant, the ground operations portion, most especially the uplink process, has to adapt to the flight system. So the two operating systems must be considered as a complete system. Flight and ground software need to be designed, developed, tested, and operated together for success. This need for concurrent engineering is making a significant change in Operations.

Automation of the downlink data flow means that it does not take a team of people to ensure that all available data get to the right project’s computers.

The uplink process has always been the more labor-intensive, being the most critical of the two activities. Newer automatic uplink functions, with all their checks and verification capabilities, coupled with the improved ability of the on-board flight system to protect itself, have greatly...
simplified the process, and provided the assurance of command quality.

The push to reduce operations costs has also caused organizational changes. The traditional dedicated specialty teams of the past are giving way to multi-tasking within a project; a multi-mission service, defined as “function sharing,” across a number of projects; or the possibility of institutional operations services.

Another option for consideration is the use of multi-mission teams. Personnel and equipment can be shared – spread among a small grouping of missions. The obvious advantage is reduced cost while having a semi-custom team. The disadvantage is difficulty with any deviation from a plan. Will there be sufficient response to any circumstance? Team members might be busy with other planned tasks. The risk of this disadvantage generally remains small and is usually outweighed by the cost advantage.

Operations services can be very useful and can be performed efficiently at low cost. They can be a real advantage in the downlink process: seeing that data are collected, complete, and routed to project computers. In a limited manner, they can handle simple uplink operations. Generally, they are spread over a broad spectrum of missions, and do not have individual mission details. They can provide the alert in case of alarms or any deviation from a plan. They are an excellent adjunct to automation, providing the human interaction for the next level of decision-making.

DIFFERENCES IN MISSIONS

Standardization will certainly help efficiency; and it is needed in Operations; but missions are not all alike. In the past we had simple and complex missions. Some were relatively low in cost while others were expensive, flagship class. The flagship class is becoming a thing of the past as funding tightens. We still have a variety of mission classes, as represented by Midex, Discovery, New Millennium, and others. They represent different mission types and different methods to explore space. Operations needs to perform the same basic functions for all. We need to watch over them, performing the monitoring function that looks at the end-to-end system to make sure everything is going according to plan. We need to direct them, performing the uplink function that starts with planning and verifies that the required functions have been performed. We need to collect data, which is the downlink process, ensuring that all available data are safely on the ground and distributed as required. That suite seems relatively standard and should be standardized to the extent possible. The challenge is to be adaptable to the needs of each of the missions and to balance that adaptability with following standards, using common equipment, and taking advantage of available services. Stardust is a case in point. The original operations concept was to use multi-tasking and institutional services. Various factors have changed that concept, giving it a strong multi-mission flavor, as seen in the teaming of Stardust Operations with the Mars Surveyor Operations Program. The strong commonality of the Stardust and the Mars Surveyor flight systems and the missions’ use of the same ground system made this change the obvious choice for efficient operations.

DRAWING ON PAST EXPERIENCE

It is quite natural to use past experience when approaching a new task or challenge. The most obvious reason is that it tells us what works. We also learn what does not work. Sometimes there is resistance to change, but this tends to be rare in space operations. Technology advancement rapidly provides new opportunities. People are eager to try new process innovations and devise new organizations. For a while in deep space exploration, when money was more available, we began to drift into new approaches just for the sake of change – not because an idea was better, but just because it was different. In some cases, this was appropriate, because it brought in new technology that might not otherwise have been affordable. Often it was time and money wasted because someone just wanted to do the job differently. Efficiency was not a requirement. The danger lay in not carefully taking a systems approach. In space operations, you do not get too many second chances. Everything has to work together, finely meshing in a system, to fly the mission successfully. As space funding tightened, new projects looked to find what was available, or what was adaptable, to keep their new launches going. History shows that the Pioneer-class missions, managed out of Ames Research Center, led in early deep space exploration by being a series of missions that operated under one management structure, and used essentially one Operations group and an evolving ground system, thus making a good contribution to a model of low cost and efficiency [1]. These mission innovators started in 1965 with Pioneer 6, went to Venus with probes and orbiter, and are looking at the last of Pioneer 10 as they prepare for the Discovery Lunar Prospector. By contrast, the Clementine mission and the Mars Pathfinder missions tried new management structures and adapted parts of other ground systems for their operations. Both made radical changes to the proven Operations Process to accomplish successful and efficient missions. Stardust, which will be the next of the Discovery class, will realize most of its efficiency by adapting an existing ground and flight system, and simplifying the operations processes. The most common thread in all of these mission classes has been the use of experienced personnel in key roles: these personnel draw on their past experience to know what needs to be done and how best to do it.

OPERATIONS PROCESSES

The purpose of Operations is to complete the mission, to obtain the results. It is a two-phase process of supplying direction, then getting the effect of the directions. Operations can be defined as two functions, which are split into two
Operations. This is concurrent engineering. Test it as you will fly it. Concurrent engineering actually starts with the concept, gets refined in the design, does match-mating in the development, and tests the whole package during assembly and pre-launch testing.

Another factor of efficiency for Operations comes in here: documentation. Certainly it is important to have requirements, plans, procedures, and rules well-documented; but it is also important to know where to draw the line. Mars Pathfinder and the Lunar Prospector went almost too far in drawing the line. They went "bare bones" on the documentation, but the necessary agreements and procedures were there. Some documentation tips:

- Avoid the elaborate documentation tree with many volumes, condense the volumes into sections, and forget all the boilerplate. This saves time and effort and makes for easier consumption of the important parts.

- Putting the documentation online, in a database, is much more efficient than providing multiple printed copies and mail distribution. Also, if you find what you want on a server, it will be the latest version.

These ideas lead to other considerations:

- Resources for operations are limited. Map out operability designs for both the spacecraft and the ground system. It is a mistake to squeeze development money at the cost of driving operations, because the life-cycle cost will end up being higher.

- One area often overlooked in the concept and design phase is the amount of Deep Space Network (DSN), or telecommunication time that will be needed. Each mission will present unique requirements, but a good general rule is: The more DSN tracking required, the more expensive the operation will be. This will be especially true when full-cost accounting becomes a reality and station time will be charged to the project. Therefore, try to design for flight automation and large on-board storage, and plan to use a "data dump" mode for retrieval.

- Once the plan has passed the development stage, the rest of the Operations Process should be just a matter of implementing it. This is, of course, a great over-simplification, but if costs are to be
kept under control, stick with the plan. Implementation then becomes a matter of attending to the details of what was demonstrated during system test. It is known and expected that adjustments will have to be made in the post-launch, or check-out, phase. This is where Operations’ “Process” loop is very active, as it involves correcting and adjusting for how the spacecraft actually operates.

- Whereas every part of the Operations Process was carefully monitored in the past, we know from experience that we can use automation to monitor most functions. Therefore, the process of monitoring what is happening throughout the system will depend much more on raising the alarm when a deviation occurs, recording the events, making adjustments, and individual notification or posting of results.

OPERATIONS PROCESS TRENDS

The Project Team

The typical project team has already become smaller and will probably continue to shrink. Multi-tasking will likely be more prevalent as personnel take on additional duties, aided by process automation.

Multi-tasking has worked and can work well. It does depend on the talents and personalities of the individuals involved. The term “generalist” has been applied to those who have a penchant for doing and handling multiple tasks on the same project. Here, the value and depth of the individuals’ knowledge is focused on a single mission. If more in-depth technical knowledge is required, use on-call or consulting services working in the needed specialty, on a case-by-case basis. Buy only what you need. Keep the direct costs for Operations to a minimum.

Multi-mission Teams

Multi-mission teams have a distinct advantage where there is commonality among missions. These teams tend to be shared over several missions rather than among all missions, since the commonality extends over the smaller grouping. Multi-mission teaming allows a greater depth of mission knowledge than can be expected in; for instance, a service environment. Sharing personnel has some limitations when the same operation is going on in parallel in different missions. While Murphy’s Law says that parallel, high-activity operations will happen, there is at least some limitation imposed by the number of antennas in the DSN and its supporting system, which will help to keep multi-mission personnel from being overwhelmed. Multi-mission teams were used in the Pioneer missions and were demonstrated in the cases of Magellan and Voyager real-time operations. The Mars Surveyor Operations Program (MSOP) will be operating all the current and planned Mars missions, because of the missions’ common flight system. MSOP will handle a portion of the Stardust mission also, providing flight and spacecraft support at the mission’s industry partner’s site (Lockheed Martin, Denver). Stardust is a good example of common-usage sharing. It shares a common flight and ground system with the Mars missions; yet the mission itself is quite different.

Future operations will be more distributed. Large mission-support areas, and all their related costs, are already becoming history. Smaller areas that have special capabilities are replacing them; these areas are devoted to specific disciplines, such as navigation, image processing, data management and distribution, and the like. Other operations, like command generation, sequence building, scheduling, and subsystem analysis, can be done in a distributed manner within a project server network. Newer, more powerful workstations provide more information more rapidly. Personnel can focus more on the decision-making process.

Operations Services

The Telecommunications and Mission Operations Directorate (TMOD) at the Jet Propulsion Laboratory, which manages the Deep Space Network, is developing a Flight Engineering Services program that will provide a set of standard services or processes to any user of this tracking system. The program will take a catalog approach, allowing a project to pick and choose from a full spectrum of mission operations services. The concept is that a project user would only need to bring in his or her mission objective and basic operations plan, and the service would provide full mission life-cycle support, extending, that is, from concept through the end of mission. Reality, or old experience, says that it may come to pass. However, it also warns that what may happen instead is that a lot of the program’s services will be developed, and be of great benefit to the flight missions, but that the program itself may never reach full maturity. Technology advancements will keep pushing development efforts, constantly bleeding away the limited funding that will be available. Whatever the outcome, there will be distinct gains. The best of these is the downlink data capture and delivery. Strides are already being made in the automation of this service. Using standards, such as the data handling methodology of the Consultative Committee for Space Data Systems (CCSDS), brings missions into a realm that is easily accommodated by this service. The monitoring task now performed by project personnel will not be necessary any longer. All the data will be in the right locations for analysis.

Depending on the requirements, the uplink side is usually much more interesting. Theoretically, the more automated spacecraft, the less need there is for uplink commanding. Still, the uplink side is the most critical aspect of mission operations. The execution of the mission plan is the focus of the uplink process. This holds true when there is deviation from the plan and correction is needed. Such deviation can be caused by some change in the spacecraft, or it can be caused by a difference between a prediction about the medium being
examined and the medium itself. Careful planning and preparation of the uplink file to allow for either contingency are required. These seem, for the foreseeable future, to be in the realm of mission personnel. Usually joint decisions, i.e., decisions that can include mission science, management (if it entails cost), engineering, and operations are made. The service system can then provide for the actual uplink process details, including verification of the results.

Another option, also a service, is referred to by the TMOD organization as the "Beacon" mode. There are applications, such as long cruise to an encounter destination where this can be very cost-effective. Essentially, it is a check-in type of process in which the cruising spacecraft transmits a continuous signal. The DSN takes a quick peek at the spacecraft periodically, and, based on the modulation tone, can tell what the spacecraft status is and react if necessary. If the spacecraft has an autonomous navigation system, this is very useful. An interim phase of the service is just to have periodic navigation tracks that gather radiometric and angle data while collecting some limited engineering telemetry, thus accomplishing the same status check. This procedure can be relatively cost-effective, also. Stardust is using this method for its long cruise. One short navigation track per week is planned, so as to verify the trajectory and plan for maneuvers. Since the mission is six years long, and the spacecraft’s comet encounter will take up less than one-tenth of that time, the procedure represents a significant benefit to Operations efficiency. As so often happens, a benefit is tempered, in this case by the need to collect low-volume cruise science which means occasional downlinks of stored data from the on-board memory.

Suggestions

Be sure to weigh each of these methods carefully before choosing.

When the Operations team is dedicated, its whole focus is on a single mission, even when the members are multi-tasking. With multi-mission teams, there is still the sense of focus, at the very least because of mission commonality, but each member’s time allotment to any one mission is less than 100%. There are other demands on their efforts.

The service approach can be very efficient and effective, but it carries the strengths and limitations of a service. Personnel are directly involved only at the contact points and they are guided by the requirements and agreements.

SUMMARY OF EFFECTIVE OPERATIONS

This document has tried to make the reader more aware of what works in flight operations, what new methods are being developed, and what to look for in the future. The main message is: Involve Operations early if you want low cost and efficiency.

There was discussion of the early design trade-offs to be made. While you should use the latest hardware and software, be sure to look at what already exists and works. Consider Commercial-Off-The-Shelf (COTS) software as much as possible. Consider adaptation of existing systems. These practices will reduce development time and cost. Make use of a distributed ground system, especially for science-related interaction. Take advantage of institutional and system-provided services, especially communications services. Try to keep the documentation streamlined, and use an online documentation system.

The Operations Process was briefly reviewed. This review is an important factor during the design phase. Equally important during the design phase are the decisions made about the Operations Process methods.

The flight service system will be the main force in operations in the new era. A service method can provide the most efficient and cost-effective means to carry out mission operations so as to accomplish the desired purpose of the research.

The push will be toward standards-based systems. Commonality will be equated with low cost for operations. Flexibility will be the key to making mission operations work. Those common systems must be able to accommodate different types of missions and different phases of any given mission.

All these factors come together as a recommendation that you provide a flight-control service that is effective and adaptive, that interacts with new technology, and develops tools and processes of its own, so that you will be successful in the many and varied missions that offer the challenge of the future.

And, finally, if you want low cost with innovation and reasonable risk, mix experience with some of those new ideas. Designing a mission in a vacuum will not be successful. Get the right inputs; and get them early.

ACKNOWLEDGMENT

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Target Tracking

Target tracking is an area of research that addresses a long list of topics that include nonlinear estimation, maneuvering targets, multiple sensors, multiple targets, low observable targets in the presence of clutter, sensor fusion, sensor resource allocation and management, particle filters, and sensor control. Many members of the IEEE Aerospace Electronics Society (AESS) are actively involved in the area of target tracking, and while the conferences and publications of the IEEE Control Systems Society and Systems, Man, and Cybernetics Societies include contributions in the area, the IEEE Transactions on Aerospace Electronics and Systems is the premier IEEE publication for papers that fall in the area of target tracking. However, no IEEE Society or group clearly identifies with the area of target tracking systems and the many related topics.

In order to address this need for an IEEE group that supports the area of target tracking, the Target Tracking Systems Panel was organized under the IEEE Aerospace and Electronics Systems Society. The purpose of the panel is to promote the area of target tracking through the creation of standard terminology, specification formats and test procedures, and promulgation of an understanding and appreciation of algorithms and components of target tracking systems. The panel is composed of representatives from industry, government laboratories, educational institutions, and professional societies involved in target tracking systems and the application of the concepts to real-world problems.

The Target Tracking Systems Panel meets twice a year and is comprised of four committees:

- Terminology,
- Implementation,
- Test and Evaluation, and
- Technology.

The Terminology Committee addresses the development and maintenance of standards for terminology. This will be realized in a publication such as an IEEE Dictionary for Target Tracking Systems. Philip West and Lisa Ehrman chair this committee.

The Implementation Committee is concerned with the establishment of standards for implementation of algorithms, interfaces, and specifications for hardware for sensor data processing. Amy Smith-Carroll and Aubrey Poore chair the committee with support from Darin Dunham.

The Test and Evaluation Committee is concerned with methods for test and evaluation of algorithms and components of target tracking systems. The committee is pursuing standards for modeling and simulation, performance metrics, and performance assessment methodologies. Erik Blasch and Oliver Drummond chair this committee.

The Technology Committee is concerned with the promotion of the technologies, algorithms, and concepts involved in target tracking systems. Additionally, the Technology Committee is concerned with the execution of seminars, workshops, conferences, and other activities that promote the exchange of information and education of the research community. They will also seek to recognize individuals for specific career achievements and teams for specific achievements. It is the intent of this committee to establish awards and recognition programs through the IEEE. Chee Chong and John Gray chair this committee along with support from Mohammed Farooq and Rabinder N. Madan.

An organizational meeting of the Target Tracking System Panel was held July 14, 2005 in Maui, Hawaii. Seventeen researchers and engineers attended and proposals for the charter and bylaws were reviewed and revised. Chairs were identified for the four panels. The panel held two meetings in 2006. The first in Gatlinburg, Tennessee, June 21, 2006; and the second in Florence, Italy, July 10, 2006. Key topics of discussion in Gatlinburg included standards for performance metrics, multilevel interface standard for tracking algorithms, and a tribute to Fred Daum. Key topics of discussion in Florence included standards for performance metrics and an IEEE conference on target tracking and terminology.
Currently, the *Terminology Committee* is pursuing the development of the first phase of a *Target Tracking Dictionary*. The *Implementation Committee* is pursuing the development of an IEEE Standard for a multilevel interface for target tracking algorithms to address different levels of sensor data available and tracker output desired. The *Test and Evaluation Committee* is pursuing the development of an IEEE Standard for kinematic-based track-to-truth assignment method for performance assessment of multiple target tracking algorithms. The *Technology Committee* organized a tribute workshop for **Fred Daum**, May 23-24, 2007, Monterey, California.

For 2007, a meeting was held May 21, 2007 in Monterey, California in conjunction with the tribute to **Fred Daum**; and another for July 9, 2007 in Quebec City, Canada, in conjunction with the 2007 10th *International Conference on Information Fusion*.

IEEE members interested in participating in the *Target Tracking Systems Panel* should contact the Panel Chair **Dale Blair** or one of the committee chairs. Memberships in the panel are classified as:

- **Voting**
- **Active**, or
- **Inactive**.

New members enter the panel as active members and, after a year of active service, are elevated to voting members by recommendation of the panel chairs.

**W. Dale Blair**  
GTRI-SEAL  
7220 Richardson Road  
Smyrna, GA 30080, USA  
dale.blair@gtri.gatech.edu

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### 26th DASC Call for Abstracts

Although the abstract submittal deadline has passed for the 26th Digital Avionics Systems Conference, abstracts are still being accepted in selected areas. If you would like to submit an abstract, please contact one of the Technical Program Co-Chairs: Bob Lyons at: technical.chair@dasconline.org; or John Moore at: deputy.technical.chair@dasconline.org.

Abstracts should be 500 words in length. Please avoid the use of acronyms or abbreviations in the paper’s title. Include a short biographical sketch of the author(s), mailing address, e-mail, telephone, and fax numbers.

Final manuscripts of selected papers are due 31 August 2007. Papers that do not meet this date may not be included in the conference Proceedings CD to be provided at the 26th DASC.

For more information, visit: www.dasconline.org.

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### IEEE AUTOTESTCON  
Frank McGinnis Professional Achievement Award

The Frank McGinnis Award is presented at AUTOTESTCON to recognize a career of outstanding leadership, individual initiative, and technical contributions in automated test engineering. Nominees must have demonstrated specified professional achievement and leadership over a career span, and participation in AUTOTESTCON. The award carries a cash prize of $2,000 and a perpetual trophy; a permanent trophy is presented at AUTOTESTCON the following year.

Nominations must include the name, address, telephone, e-mail, professional position and experience, and details of activities that the nominator feels qualifies the nominee for consideration. Nominations may include resumés or letters, but must contain a statement by the nominator specifying why the individual should be honored. Nominations must be signed by the nominator. No self-nomination will be accepted.

The McGinnis Award may be received only once by an individual – and the former AUTOTESTCON Man of the Year Award is considered a predecessor award; those recipients are not eligible; also not eligible are current members of the AUTOTESTCON Board of Directors.

Nominations should be sent to: Walt Downing, IEEE AUTOTESTCON Board of Directors, 6119 Willowridge, San Antonio TX 78249-2462, USA. For further information: telephone (210) 522-3186; F (210) 520-5505, e-mail: w.downing@ieee.org.
Discourse

"From letters one makes syllables, From syllables, words, and From words discourse. Do your duty by them."

From Champ Fleury (1529) by Geoffrey Tighe Translation by George B. Ives

Discourse is “the formal and orderly expression of thought on a selected subject.”

Systems encourages discourse in many forms: papers, contributions, tutorials, reports, and correspondence to name a few. If the subject aligns with society interests, or the contributors (and editors) feel that an as-yet-uncovered subject is worthy of discourse, we gladly welcome it.

Discourse publication by Systems will be handled as follows:

1) One item per issue as an insert;
2) There may be an Introduction by a guest editor if there is more than one section of the subject;
3) If multiple sections, all will be cross-referenced;
4) Discourse will be an “extra” in an issue – it will not replace regular features;
5) Comments on discourse items will appear as correspondence in succeeding issues.

In exceptional cases, with a suitable subject, it will be handled as a Part Two of a regular issue (as we do with Tutorials). For a series, we will include one item per issue, and not necessarily in consecutive issues. Discourse items and any comments thereupon will be cross-referenced and included in our Annual Index.

– Evelyn Hirt

The 10th International Conference on Information Fusion

Quebec, Canada  9-12 July 2007

Topics:

Theoretical and technical advances in information and knowledge modelling; probabilities and statistics; non-classical set theories; possibilities; evidential and other theories; non-classical logical approaches; graph-based approaches; neural networks; genetic algorithms; artificial life and intelligence; nonlinear estimation and filtering; semiotics and ontologies.

Algorithms and Systems Perception and cognition; detection and tracking; recognition and classification; data association; resource management; image or sensor fusion; database fusion; knowledge-based systems; data mining; distributed systems; system design; measures of performance.

Applications of C4ISR; network-centric warfare; networks and communication; robotics and control; autonomous systems; intelligent transportation systems; navigation, positioning and guidance; economy and finance; surveillance and situation analysis; remote sensing; medical and biological diagnosis; decision support; data acquisition and testing; machine vision and learning; security and safety.

Information:

Secretariat: JPdL
Tel: (418) 692-6636; Fax: (418) 692-5587
fusion2007@jpdl.com
IEEE AUTOTESTCON 2007
The Systems Readiness Technology Conference for the Military and Aerospace Industry

Baltimore Convention Center
Baltimore, Maryland
September 17 - 20, 2007

For more than 40 years, IEEE AUTOTESTCON has gathered the military/aerospace automatic test industry together to share new technologies, discuss innovative applications, and exhibit products and services. Major reasons to attend AUTOTESTCON 2007:

- Over 125 quality technical papers presented in 2 1/2 days of technical sessions.
- 143 exhibitors (274 exhibit booths) will display the latest in test technologies and services.
- Timely and topical keynote and plenary session speakers.
- New venue with outstanding social and night-life opportunities in Baltimore’s Inner Harbor.

Now is the time to reserve your room with one of our three very high quality hotels. Register by August 31 and take advantage of the advance registration discount. Conference registration information can be found at www.autotestcon.com
June 2007

**Distinguished Lecturers Program**

**Dr. James R. Huddle, Chair**

All AESS Chapters and IEEE Sections are encouraged to take advantage of the AESS Distinguished Lecturers Program for their regular or special meetings. We have selected an outstanding list of speakers who are experts in their fields. The AES Society will cover up to $1000 of the speaker’s expenses for travel in North America, with any remaining amount normally covered by the AESS Chapter or Section or by the speaker’s organization. For travel outside North America, the AES Society will cover half of the speaker’s expenses per trip, up to a maximum of $2500. The procedure for obtaining a speaker is as follows: If a Chapter or Section has an interest in inviting one of the speakers, it should first contact the speaker directly in order to obtain his agreement to give the lecture on a particular date. After this is accomplished, and if the Chapter or Section wishes to request financial support from the AES, it should contact James R. Huddle on (818) 715-3264, F (818) 715-3976, j.huddle@ieee.org at least 30 days before the planned meeting, in order to obtain approval for the financial support. The list of distinguished speakers who have expressed their willingness to speak to Chapters or Sections, along with their organization, topics, and telephone numbers, is given below.

<table>
<thead>
<tr>
<th>Title</th>
<th>Name</th>
<th>Contact Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Control Technology Applied to Aircraft &amp; Automobiles</td>
<td>Dr. Kimio Kanai, <em>National Defense Academy of Japan</em></td>
<td>81-45-812-1244 (V&amp;F) <a href="mailto:k-kimio@mch.biglobe.ne.jp">k-kimio@mch.biglobe.ne.jp</a></td>
</tr>
<tr>
<td>Avionics for Manned Spacecraft</td>
<td>Dr. Myron Kayton, <em>Kayton Engineering Co.</em></td>
<td>(310) 393-1819</td>
</tr>
<tr>
<td>Evolution of Aircraft Avionics</td>
<td></td>
<td>(310) 393-1261 F <a href="mailto:m.kayton@ieee.org">m.kayton@ieee.org</a></td>
</tr>
<tr>
<td>Navigation: Land, Sea, Air and Space</td>
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<tr>
<td>One Hundred Years of Inertial Navigation</td>
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<td>Practitioner’s View of System Engineering</td>
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<tr>
<td>Bistatic &amp; Multistatic Radar</td>
<td>Dr. Hugh D. Griffiths, <em>University College, London</em></td>
<td>+44 20 7679-7310</td>
</tr>
<tr>
<td>Synthetic Aperture Radar</td>
<td></td>
<td>+44 20-7388-7325 F <a href="mailto:h.griffiths@ee.ucl.ac.uk">h.griffiths@ee.ucl.ac.uk</a></td>
</tr>
<tr>
<td>Current Advances in Radar Technology</td>
<td>Robert T. Hill, <em>Consultant and Lecturer</em></td>
<td>(410) 770-4535 (V&amp;F) <a href="mailto:janebobhill@man.com">janebobhill@man.com</a></td>
</tr>
<tr>
<td>Evolution of Inertial Navigation</td>
<td>Dr. Itzehack Bar-Itzehack</td>
<td>+972-4-829-3196</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+972-4-829-2030 F <a href="mailto:ibaritz@technion.ac.il">ibaritz@technion.ac.il</a></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(315) 463-8261 F <a href="mailto:Dick.Wiley@aol.com">Dick.Wiley@aol.com</a></td>
</tr>
<tr>
<td>Global Navigation Satellite System</td>
<td>Dr. Surendra Pal, <em>ISRO Satellite Center (India)</em></td>
<td>(+91) 80-2520-5275</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(+91) 80-2508-3303 F <a href="mailto:pal_surendra@hotmail.com">pal_surendra@hotmail.com</a></td>
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<tr>
<td>Multisensor Data Fusion</td>
<td>Dr. Pramod Varshney, <em>Syracuse University</em></td>
<td>(315) 443-4013; (315) 443-2583 F <a href="mailto:varshney@syr.edu">varshney@syr.edu</a></td>
</tr>
<tr>
<td>National Missile Defense and Early Warning Radars</td>
<td>Dr. Larry Chasteen, <em>University of Texas at Dallas</em></td>
<td>(972) 234-3170; (972) 883-2799 <a href="mailto:chasteen@utdallas.edu">chasteen@utdallas.edu</a></td>
</tr>
<tr>
<td>Novel Orbits &amp; Satellite Constellations</td>
<td>Dr. Daniele Mortari, <em>Texas A&amp;M University</em></td>
<td>(979) 845-0734</td>
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<td>(979) 845-6051 F <a href="mailto:mortari@cornell.edu">mortari@cornell.edu</a></td>
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<tr>
<td>Radar — Past, Present and Future</td>
<td>Dr. Eli Brookner, <em>Raytheon</em></td>
<td>(978) 440-4007</td>
</tr>
<tr>
<td></td>
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<td>(978) 440-4040 F <a href="mailto:Eli_Brookner@raytheon.com">Eli_Brookner@raytheon.com</a></td>
</tr>
<tr>
<td>Satellite Communication Systems</td>
<td>Dr. S.H. Durran, <em>Consulting Engineer</em></td>
<td>(301) 774-4607 (V&amp;F)</td>
</tr>
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<td></td>
<td></td>
<td><a href="mailto:s.durran@ieee.org">s.durran@ieee.org</a></td>
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<tr>
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<td><a href="mailto:p.gartz@ieee.org">p.gartz@ieee.org</a></td>
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<tr>
<td>Target Tracking and Data Fusion: How to Get the Most Out of Your Sensors</td>
<td>Dr. Yaakov Bar-Shalom, <em>Univ. of Connecticut</em></td>
<td>(860) 486-4823</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(860) 486-2283 F <a href="mailto:ybs@eecs.uconn.edu">ybs@eecs.uconn.edu</a></td>
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</tbody>
</table>

All data on this page is under the purview of James Howard, VP-Member Affairs.
Please send all corrections and omissions to him at the address on the inside back cover.
About the Conference

The latest in the series of the UK’s premier radar event returns in October 2007.
Radar 2007 will cover all aspects of radar systems for civil, security, and defence applications and will showcase the latest developments in radar technology techniques and signal processing.
Radar 2007 provides a unique opportunity to update your knowledge on the latest developments for all involved in advanced radar systems, from the experienced engineer to new graduates seeking to build a career in this field.

Conference Highlights

• Three days of presentations showcasing the latest worldwide research and development

• A valuable opportunity for you to receive an update on the latest technologies and future challenges facing the radar industry

• A Tutorial day on 15 October – your chance to study a state-of-the-art topic area in greater detail

• An exhibition of the latest, most innovative products and services from key suppliers

• Valuable networking opportunities, including lunch breaks served on the exhibition show floor, a welcome drinks reception, and conference dinner at the prestigious Royal Museum of Scotland

Key Conference Themes

Topics to be covered at Radar 2007 include:

- Dual-Use/Civil Applications
- Environment
- Radar Systems
- Processing Techniques
- ECCM/ECM
- Emerging Technologies
- Advanced Sub-Systems
- Computer Modelling and Simulation

To Register Your Place At This Exciting Conference

Conference registration will be available in April 2007. To register your interest and receive advance information, please contact the organizers on: +44 (0) 1438 765 647 or e-mail: Eventsa3@theiet.org

Main Sponsors: Thales and Selex Sensors and Airborne Systems
Sponsors: BAE Insyte, Raytheon, and UCL

The IEEE Aerospace & Electronic Systems Society (AESS) is a technical sponsor of Radar 2007, one in an ongoing series of International Radar Conferences. The AESS Board of Governors has scheduled its Fall 2007 meeting to coincide with Radar 2007 in Edinburgh.
International Conference on Radar
Adelaide, Australia  ♦  2 - 5 September 2008

First Call for Papers

Conference Theme: *Maritime Surveillance for the 21st Century*

Australia participates in the five-nation series of annual international radar conferences (with France, US, China, UK) and hosted the very successful Radar 2003. Following Radar 2007 (October 2007 in the UK) the international series returns to Adelaide, Australia in September 2008.

Radar 2008 will cover all aspects of radar systems for civil, security, and defence applications. Tutorials will be held in a number of fields of radar technology.

We particularly welcome papers focusing on our maritime surveillance theme but papers will be accepted over a wide range of topics. Topics include (but are not confined to):

<table>
<thead>
<tr>
<th>Radar Systems</th>
<th>Dual-Use / Civil Applications</th>
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<tr>
<td>Radar Studies of the Sea Surface</td>
<td>Processing Techniques</td>
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<tr>
<td>Antenna and Component Technology</td>
<td>Radar EW</td>
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<tr>
<td>Environment and Phenomenology</td>
<td>Emerging Technologies</td>
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<td>Modelling and Simulation</td>
<td>Electromagnetics</td>
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<td>UAV Radar</td>
<td>SAR/ISAR</td>
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<td>Metamaterials</td>
<td>Polarimetry</td>
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<td>Target Discrimination</td>
<td>Netted Radar</td>
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<td>Radar Scheduling</td>
<td>Passive Coherent Location</td>
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<tr>
<td>OTHR – New Directions &amp; New Applications</td>
<td>Radar Test and Evaluation</td>
</tr>
</tbody>
</table>

**Important Dates**

**Receipt of Papers:** January 31, 2008

Author notification of acceptance as an oral or poster presentation: May 2, 2008

Final Papers: June 30, 2008

See www.radar2008.com for further details as they are developed.
Plan now for 2008 in Australia!
The 2008 IEEE Radar Conference is in the series of radar conferences promoted by the IEEE Aerospace and Electronics Systems Society (http://ewh.ieee.org/soc/aes/).

In continuity with the tradition of IEEE Radar conferences, so far always held in the United States, the radar community will gather next year in Italy, in the city of Rome, the beautiful capital of the ancient Roman Empire.

CONFERENECE TOPICS

The 2008 IEEE Radar Conference will focus on the key aspects of radar theory and applications as listed below. Exploration of new avenues and methodologies of radar signal processing will also be encouraged. Tutorials will be held in a number of fields of radar technology. The Conference will cover all aspects of radar systems for civil, security, and defense applications. Topics to be covered include (but are not limited to):

- Radar Systems, Radar Data and Signal Processing, Waveform Design and Trade-Offs, Antenna & Component Technology, Environment and Phenomenology,
  - SAR and Weather Radars, Sonar and Merchant Marine Radar,
  - Radar Early Warning, Radar Simulation, Dual-Use/Civil Applications,

SUBMISSION

Procedures to submit a paper can be found at www.radarcon2008.org. Submitted summaries must be 1000-1500 words long, final full paper, no more than six pages all inclusive and conforming to the format specified on the RadarCon2008 website listed above. In addition to formal presentations, there will be poster presentations. Authors who believe their papers are better suited to a poster format are requested to so note on their summaries. The poster format provides authors the opportunity to display their paper and to discuss their information with conference participants. Both oral presentation and poster presentation papers will be published in the Proceedings.

BEST STUDENT PAPER AWARDS

There will be a student paper contest. Student authors who appear as first authors in a paper may enter the student paper contest.

IMPORTANT DATES

Submission of Summaries: September 15, 2007
Notification of Acceptance: October 30, 2007
Submission of Full Papers and Registration: January 15, 2008

www.radarcon2008.org
The Distinguished Tutorials Program

The Distinguished Tutorials Program (DTP) was established in 2006. Many sections have expressed interest and some are currently in touch with Distinguished Instructors (DIs) to schedule a tutorial.

The Distinguished Tutorials Program allows a Section or an AES Section to invite a Distinguished Instructor to give a tutorial at no cost to the hosts. The AES picks up the travel cost and pays an honorarium. This allows members to benefit from tutorials, normally presented at major conferences that are not available locally, at a date convenient for the hosts.

The Program was approved by the AES Board of Governors in 2006 and budgeted. Due to the better-than-expected response, funds are available for three or more Tutorials in 2007. Similarly, the program started with five Tutorials with four currently available. Tutorials are as listed. Interested parties should contact the Instructor directly.

GPS and Inertial Data Processing
James Farrell, VIGIL, Inc.,
navaide@comcast.net

Systems Approach to Engineering Projects
Paul Gartz, Boeing Corporation,
p.gartz@ieee.org

Design and Use of Small Satellites in Education
Albert Helfrick, Embry Riddle Aeronautical University,
helfrica@erau.edu

Advances in Radar Technology
Robert Hill, Consultant,
janebobhill@msn.net

Navigation – Land, Air and Space
Myron Kayton, Consulting Engineer,
m.kayton@ieee.org

Space-Time Adaptive Processing for Surveillance Radar System
Michael L. Picciolo, SAIC,
Michael.L.Picciolo@saic.com

Digital Avionics
Cary Spitzer, Consultant,
c.spitzer@avionicon.com

Radar Reflectivity
Robert Trebits, Georgia Tech,
bob.trebits@gmail.com

Radar Systems Performance Modeling
G. Richard Curry, Consultant
dickcurry@cox.net

Automated Testing
Michael Ellis, Northrop Grumman Corporation,
mtellis@aol.com
RESPONDING TO OBJECTIONS

My company will not pay for my dues.

We're grateful that some employers reimburse for IEEE membership dues, but IEEE membership is about individuals who desire to take ownership of their career, regardless of an employer's willingness to reimburse dues. Individuals who belong to IEEE take personal responsibility for their careers.

IEEE membership is too expensive.

The cost of IEEE membership compared to most professional associations is significantly lower, as much as 30%, compared to organizations such as the National Society of Professional Engineers, American Medical Association, and the American Bar Association. When you really think about it, IEEE membership dues are quite reasonable when you consider the quantity and quality of benefits offered to members. Also, IEEE membership often pays for itself. The discounts members receive on IEEE products or attending a conference makes membership a good return-on-investment.

The value of IEEE membership does not justify the cost.

IEEE membership offers an array of benefits that may be of interest to you. Perhaps you are unaware of some of these benefits. They include Access to technical publications; Professional and educational development; Unique networking venues; Discounts on conference attendance, insurance programs, IEEE products. And every member has their own, personalized gateway into IEEE membership via myIEEE.

I have no time to read the publications.

It's a constant challenge between finding the time to be informed, and one day discovering that you're not technically current. Our members tell us that reading IEEE publications saves them time, as they do not need to "reinvent the wheel" at work. IEEE publications are the world's best collection of technical information. Taking the time to read this information keeps you technically current. Investing 30 minutes with one publication could save you 40 hours of research at work.

I can find all this information on Google—what's the value of membership?

There's a lot of information to be found on Google, but IEEE publications are not available for free on Google. Moreover, the quality of technical information found via Google is random, and doesn't adhere to any consistent standards of technical excellence. Did you know that 60,000 patents cite IEEE information? These patents cite IEEE, not Google. IEEE membership is much more than access to information. It's about networking, professional development, and you taking personal responsibility for your career. Membership is about meeting new colleagues, and coming into contact with really great people—individuals who join IEEE form friendships that last a lifetime. You wouldn't meet these people on Google.

I can get all of the information through my employer, so why should I belong?

Yes, organizations worldwide rely upon IEEE information to be technically current and competitive—it speaks to IEEE's quality. IEEE membership is more than access to information. IEEE membership is about you being competitive and taking personal responsibility for your career. IEEE's benefits include venues and tools for members to network, build valuable professional connections, and hone leadership skills. These are essential for managing your career. Membership is about meeting new colleagues, and coming into contact with really great people—individuals who join IEEE form friendships that last a lifetime. IEEE membership is more than what you receive—it's also about what you're giving back. When you belong to IEEE, you are supporting a much larger mission—your membership enables initiatives such as public information and policy efforts, affordable student membership, and the introduction of technology careers to young people worldwide.

I've recently been unemployed, and can no longer afford the dues.

IEEE will help you during these times. IEEE has a reduced-dues program for unemployed members, which allows you to keep your benefits, which are very helpful for finding a new job—for example, networking at local Section and Chapter meetings, uploading your resume to the IEEE Job Site, engaging the career navigator.
The Benefits of Membership

Core Benefits - IEEE is the world's largest technical society, bringing Members access to the industry's most essential technical Information, networking opportunities, career development tools, and many other exclusive benefits.

Knowledge - Staying current with the fast-changing world of technology...

IEEE Spectrum Magazine - 12 monthly issues (print) and online
The Institute Newsletter - 12 monthly issues (4 print, 8 online)
IEEE Potentials Magazine - 6 issues (online)
IEEE Xplore - table-of-content and abstract access to 1.2-million documents
What's New @ IEEE - produced monthly, electronic newsletters on technical topics (10 topics to choose from)

Community - Belong to the network and buying power of 365,000 members in 150 countries...

IEEE Sections - network with others in the local member community, and participate in local educational events
Technical Chapters - engage with others through informative technical meetings
IEEE e-mail alias - with virus protection and spam filtering
ShopIEEE discounts - membership paying for itself, with as much as 50% off IEEE products
IEEE Conference registration discounts
Volunteering - opportunities that build leadership skills and networking opportunities
myIEEE - members-only personalized gateway into IEEE membership

Profession - Empowering members to build and own their careers, and venues to give back to society...

IEEE Job Site - locate career opportunities easily and confidentially
Career Alert - a weekly email newsletter containing career advice plus the job of the week from the IEEE Job Site
Continuing Education Partners Program - up to a 10% discount on online degree programs
Awards - recognize the accomplishments of technologists and engineers worldwide
Scholarships - enhance your resume with an IEEE scholarship
Consultants Database - a service available for matching technical consultants with clients
Today's Engineer - monthly webzine devoted to the issues affecting IEEE members' careers

Add-On Benefits

IEEE Member Digital Library - access up to 25 articles a month from any IEEE publication or conference proceeding
Proceedings of the IEEE - leading authoritative resource for in-depth research coverage, tutorial information and reviews
Insurance Services - customized selection of insurance products, designed for the professional engineer
Financial Services - receive discounts on financial services from our partnering companies
Home & Office Services - substantial discounts on products and services for your home and office
Travel Services - enhancing the overall travel experience for IEEE members and their families

Additional Memberships

IEEE Society Membership - expands the scope and depth of your technical knowledge, expanded networks
IEEE Standards Membership - influence the direction and application of standards development
IEEE Women in Engineering Membership - promotes the entry into and retention of women in engineering programs

IEEE A&E SYSTEMS MAGAZINE, JUNE 2007
1. NAME AS IT SHOULD APPEAR ON IEEE MAILINGS: SEND MAIL TO: ̊ Home Address OR ̊ Business/School Address
   If not indicated, mail will be sent to home address. NOTE: Enter your name as you wish it to appear on membership card and all correspondence. PLEASE PRINT. Do not exceed 40 characters or spaces per line. Abbreviate as needed. Please circle your last/surname as a key identifier for the IEEE database.

<table>
<thead>
<tr>
<th>TITLE</th>
<th>FIRST OR GIVEN NAME</th>
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<tr>
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<td>COUNTRY</td>
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<td>STATE / PROVINCE</td>
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</table>

2. Are you now or were you ever a member of IEEE? ̊ Yes ̊ No
   If yes, please provide, if known:

<table>
<thead>
<tr>
<th>MEMBERSHIP NUMBER</th>
<th>Grade</th>
<th>Year Membership Expired</th>
</tr>
</thead>
</table>

3. BUSINESS / PROFESSIONAL INFORMATION

| Company Name | |
| Department / Division | |
| Title / Position | Years in Current Position |
| Years in the Profession since Graduation | ̊ PE ̊ State / Province |
| Street Address | |
| City | State / Province |
| Postal Code | Country |

4. EDUCATION

| Baccalaureate Degree Received | Program / Course of Study |
| College / University | Campus |
| State / Province | |
| City | Mo. / Yr. Degree Received |
| Highest Technical Degree Received | Program / Course of Study |
| College / University | Campus |
| State / Province | |
| City | Mo. / Yr. Degree Received |

5. SIGNATURE OF APPLICANT

| I hereby make application for IEEE membership and agree to be governed by IEEE’s Constitution, Bylaws, Statements of Policies and Procedures and Code of Ethics. |

| Full signature of applicant | Date |

6. CONTACT INFORMATION

| Office Phone | Home Phone |
| Office Fax | Home Fax |
| Office E-mail | Home E-mail |

7. 2007 IEEE MEMBER RATES

| Residence | Pay Full Year ̊ Pay Half Year |
| United States | $161.00 ̊ $80.50 |
| Canada (includes GST)* | $149.38 ̊ $74.69 |
| Canada (includes HST)* | $159.22 ̊ $79.61 |
| Africa, Europe, Middle East | $134.00 ̊ $67.00 |
| Latin America | $127.00 ̊ $63.50 |
| Asia, Pacific | $126.00 ̊ $64.00 |

8. 2007 AESS MEMBER RATES

| Aerospace and Electronic Systems Society Membership Fee | $25.00 ̊ |
| Includes AESS Magazine | (print & electronic included in membership fee) |
| Online access to IEEE/OSA Journal of Lightwave Technology | |
| Publications available only with AESS membership: Transactions on: | |
| Aerospace and Electronic Systems | Print $25.00 ̊ |
| Electronic | $25.00 ̊ |
| Pattern Analysis and Machine Intelligence | Print & Electronic $35.00 ̊ |
| Journal of Lightwave Technology, IEEE/OSA | Print $45.00 ̊ |

9. METHODS OF PAYMENT: Prices stated are in US dollars
   • Credit Card – American Express, VISA, MasterCard, Diners Club
   • Check
   • Bank Drafts
   • Money Orders Payable on a US bank

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<tr>
<th>IEEE Membership Dues</th>
<th>Aerospace and Electronic Systems Society Membership Fee Total</th>
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</tbody>
</table>

| Canadian residents pay 7% GST or 13% HST on Society fees only, Reg. No. 125034188 |

<table>
<thead>
<tr>
<th>AMOUNT PAID WITH APPLICATION TOTAL</th>
<th>TAX $</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prices stated are in US dollars, subject to change without notice.</td>
<td></td>
</tr>
<tr>
<td>̊ Check or money order enclosed (Payable to IEEE)</td>
<td></td>
</tr>
<tr>
<td>̊ American Express</td>
<td>̊ VISA</td>
</tr>
<tr>
<td>̊ Diners Club</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Charge Card Number</th>
<th>Cardholder’s Digit Zip Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp. Date</td>
<td>Billing Statement Address</td>
</tr>
<tr>
<td>Mo.Yr.</td>
<td>USA Only</td>
</tr>
</tbody>
</table>

| Full signature of applicant using credit card | Date |