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Computer Networks for Remote Laboratories in Physics and Engineering

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As we embark on a new era in engineering education, we must exploit technological advances which offer opportunities for improving the educational process. One area of technology which offers opportunities for enhancing the manner in which research is conducted and ultimately affects scientific and engineering education is computer networks. As computer hardware has become less expensive, more numerous and more capable, individuals and organizations have developed a keen interest in connecting them together in order to form networks. This in turn has had an impact on the manner in which laboratory research is conducted. This paper addresses a relatively new approach to scientific research, telescience, which is the conduct of scientific operations in locations remote from the site of central experimental activity. A testbed based on the concepts of telescience is being developed to ultimately enable scientific researchers on earth to conduct experiments onboard the Space Station. This system along with background materials are discussed in this paper.

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Computer Networks for Remote Laboratories in Physics and Engineering

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1. Background

In July of 1987, an international conference sponsored by the American Association of Physics Teachers (AAPT) was held in Oaxtepec, Mexico to address the theme, "Creating Physics Education Networks in the Americas." Over three hundred individuals attended the conference among whom were approximately fifty attendees from the United States. Twelve working groups were established for the purpose of investigating different issues in and aspects of physics and engineering education. The results of this conference have been reported regularly in the AAPT Anouncer. By "networks", what is meant is cooperative groupings of individuals, organizations, and governmental agencies for the purpose of advancing specific improvements of physics education by means of better communications and/or cooperative projects.

As a result of the Oaxtepec meeting, a number of topical network groups were established by the AAPT to review the status of educational networks in the United States. Activities of the topical network groups are currently supported in part by funds granted by the National Science Foundation and the AAPT. The topical network groups have been chartered to survey the present status of networks in particular subject areas and to begin to consider recommendations for improvements it will make to AAPT, the American Physical Society, and the scientific community at large.

A topical network group on Physics and Technology was established by AAPT for the purpose of investigating among other topics the impact of modern technology on physics education and research. As a result of deliberations on this subject, the group prepared a report which summarizes the major findings and recommendations of the group. During deliberations on the impact of modern technology on the manners in which physics, engineering and technolgy are taught, the group explored the rapid and drastic changes which have taken place in the areas of telecommunications and computer networking. The group expressed a consensus that advances in the fields of computer databses, computer networks and telecommunications can greatly relieve the tasks of collecting, manipulating, analyzing and distributing data and information in support of physics and engineering education.

The group also considered that the current technolgy in computer networking and data communications has given use to a new way of looking at scientific experimentation. Presently, the technology exists to enable scientist to conduct operations in real time at locations, such as a home institution, remote to a central scientific experimation site. This new concept of remote scientific experimentation has been given the label, telescience [1].

Included in the report issued by the topical network group were two recommendations which provide motivation for this paper. The first recommendation was that telecommunications and computer network be examined closely as a possible infrastructure for facillitating the flow of information among the various members of the network in physics and technology. The second was that the concept of telescience be examined as a means for providing access to major scientific experiments to individual researchers in remote areas. The group also considered that the current technology in computer networking and data communications has given scientists new tools to enhance their scientific productivity. The formulation and development of those networking and information system technologies into a useful integrated set of research tools can only be achieved by, first, understanding the scientific method of research with its inherent iterative, trial and error process.

2. Fundamentals of Computer Networks

Prior to our discussions about the topic of telescience, it is important that we describe some of the fundamental characteristics of computer networks. This is due to the fact that computer networks are the key enabling technology vital to the implementation of the telescience testbed which is discussed later in this report.

For many applications today, centralized computing systems are yielding way to computer networks. Throughout the country and world-wide, many organizations possess a significant number of computers which are often separated by geography. One of the reasons for the trend toward computer networking is that organizations wish to make software, data, and other resources available to users on a network without regards to the physical location of the user or the desired resource. The mere fact that a potential user is located miles from a desired resource should not prevent him from utilizing that resource as if it were indeed local. A major goal of computer networking is to combat the so-called ''tyranny of geography'' [2]. Another major goal of computer networks is to enhance the overall reliability of a system by providing alternative sources of supply. In the absence of networking, failures in isolated computer hardware may prevent local users pursuing their work. On the other hand, a computer network might alleviate this problem by providing the user with access to different machine.

An emerging trend which has supported the rise of distributed versus local sytems is the relative expense of computing resources to that of communication facilities. A computer network provides a powerful communication medium among people widely separated by geographical distance. Using a computer network, it is easy for numerousojects such the task of writing a report or of developing a piece of software. For example, groups of individuals in different geographically distant locales can continuously have access to the most current version of the text of a report or program listing which could be stored online. Under such an approach, it is not necessary for the authors to wait long amounts of time during the revision process which is often the case when groups are restricted to using the mail or other means to disseminate changes.

In the most general sense, a computer network may be described as a collection of computers and terminals connected together by a communications system. However, the use of a single term to describe such a wide variety of processing facilities blurs an important distinction that exists among networks. This distinction is based upon the different ways in which a user may view a given network. It is cogent to classify computer networks according to the degree of transparency presented by the network to the user. By doing so, we typically can categorize networks into two different classes. The two classes differ in terms of the management of computer resources. In the first class of networks, the responsibility for resource management falls upon the user. In the second, the user can depend upon the aid of a network operating system in the acquisition and handling of needed resources. Networks in each of the two classes share an important characteristic; in both cases, it is the network which is responsible for the management of the communications system.

In any network there exists a collection of machines, which are called hosts, that are intended for running user application programs. Hosts are interconnected by a communication subnet. The job of the subnet is to carry messages from host to host. In nearly all networks, the subnet consists of two basic components. These are switching elements and transmisssion lines. Switching elements are generally specialized computers which are called Interface Message Processors or IMPs. Transmission lines are often called circuits or channels. An excellent presentation of examples of these network components can be found in [3].

3. Telescience

In the past three years the U.S. space research community, lead by the Space Station Task Force for Scientific Uses of Space Station (TFSUSS), has addressed this issue for Space Station era research and has developed an operational concept to maximize scientific productivity. Although this concept and approach has been formulated for space research, it is equally applicable to any terrestrial research activity where the scientists and research capabilities are geographically distributed. TFSUSS determined that the baseline networking and information system capabilities should be such that Space Station research operations must be able to emulate the adaptive science methodology used in terrestrial research laboratories. To address this issue, the TFSUSS has coined the term telescience, which they describe as the interactive acquisition of new scientific knowledge through remote observations and xperiments. The Office of Space Science and Applications (OSSA) as part of the Science and Applications Information System (SAIS) activities has further defined telescience as follows:

> Telescience is the direct, iterative and distributed interaction of users with their instruments, data bases, specimens and data handling facilities, especially where remote operations are essential.

The distributed interaction is meant to include all members of a investigation team, in space and on the ground, and may involve either manned or unmanned operations. It is the general desire of the science community to conduct their operations from their home institution by on-line computer networking. To cover the entire life-cycle of a research investigation, telescience was divided into three phases, centered on pre-flight, flight, and post-flight activites:

1. Teledesign - The ability to send drawings, documents and specifications, to plan, manage, and coordinate science investigations among geographically distributed investigators, to perform interactive design with remote facilities, and to conduct interface and other tests of instruments by remote computer access.
2. Teleoperations - The ability to conduct remote operations by making rapid adjustments to instrumental parameters and experiment procedures in order to obtain optimum performance.
3. Teleanalysis - The ability to access and merge data from distributed sources and to perform analyses and studies on computers that may be located at other institutions.

4. Systems Engineering Methodology for Telescience

Telescience, as defined above, clearly defines the functional needs of the Space Station science community but it does not identify the systems engineering methodology needed to implement it. All systems engineering methodologies begin with mission requirements definition and specification. Generally, there are three major players in this initial requirements activity: the systems engineer, the system user (either in person or a surrogate), and the technologist. Most space projects use a linear phased approach (Phase A: mission needs and objectives defined, Phase B: mission definition and specification, Phase C: design, and Phase D: development) to carry out the systems engineering. Although there may be involvement of all three major players in the Phase A activities, the system users and technologists have minimal involvement beyond Phase A. Systems which use this engineering methodology make the basic assumption that system needs and requirements are fully understood and that the technology is identified during Phase A and they will remain essentially static during the other phases.

The process moves efficiently along from engineering to design to development whereby budget and schedule are managed carefully. System performance is judged against the initial Phase A requirements. Changing user needs or utilization concepts, evolving technology, and operations cost modeling are not allowed to influence the design or development of the system. If the system requirements are not well known in Phase A and/or the system technology or operations concepts are dynamically evolving, the operational system will not be functionally satisfactory or cost-effective.

Too often the linear approach neglects to define fully what the system is. Design engineers generally believe that the system is the design and development of the hardware while others may think that the primary objective is the functional operation of the hardware for some purpose. This generally results in optimizing the design for the wrong functions. Optimizing for development efficiencies instead of operational efficiencies can many times lead to costly, unproductive and unuseable systems.

A second approach to the problem is nonlinear systems engineering. The basic assumption for nonlinear systems engineering is that requirements and technology will be evolving throughout the life of a project. This requires the formulation of a engineering methodology which allows this dynamic evolution of requirements and technology to influence the system design and development. The process begins with the formation of an engineering/users/technologists team to begin preliminary system requirements definition from best guess user functional needs. This team also derives its membership equally from the university, industry and government sectors. Each sector will gain unique benefits from this working level interaction. The team establishes a set of evaluation criteria for various proposed concepts which were formulated to meet the preliminary requirements. At this point the concepts can take one of two paths. With either path, the primary objective of the process is to validate the concepts in terms of satisfying the preliminary requirements and to educate the team. Some concepts can be functionally tested in a modeling or computer simulation environment while others must be placed in a rapid prototyping testbed where "quick and dirty" point designs can be operated in a hands-on mode by the team. With both paths, rapid iteration is essential to success of the methodology. When several competing concepts satisfactorily meet the system requirements, then a formal trade-off process must occur to arrive at the optimum concept. Before formal specification can begin, care must be taken to distill all functional specifications from the concepts such that vendor specific specifications from the point designs are removed. It should be stated that not all requirements will be fully specified at the end of Phase B in engineering design terms. Any RFPs for the Phase C/D should fully identify which requirements have not been fully specified and proceed into Phase C/D with additional prototyping to fill in any additional information that will be needed to complete the system design.

5. Space Station Telescience Testbed

As a proof of concept, the NASA Office of Space Science and Applications has initiated a Space Station Telescience Testbed Pilot Program involving fifteen universities under subcontract to the Universities Space research Association (USRA) [4]. The universities (Arizona, UC-Berkeley, UC-Santa Barbara, CalTech, Colorado, Cornell, Maryland, MIT, Michigan, Purdue, Rensselaer, Rhode Island, Rochester, Stanford and Wisconsin) are conducting a variety of scientific experiments using advanced technology to determine the requirements and evaluate trade-offs for the communications and information system of the space station era. The goal is to allow scientists to interact with potential space station technologies in a manner that will allow resolution of design and specification questions without having to wait until space station hardware is available. The experiments all share the characteristic that they are attempting to apply new technologies and concepts otion to ongoing scientific activities. Through such an experimental prototyping activity actively investigating various technical and procedural trade -offs, a better understanding will be gained of the future scientific modes of operation and the systems architectures, concepts and technologies required to support such operational modes. At this early phase of the program a great deal has already been learned concerning the needed technical infrastructure to carry out not only the testbed activity but also the types of multidisciplinary scientific activities represented by Space Station. The following findings are the results of this early work.

The value of computer networking capabilities such as electronic mail, file transfer and remote access to computers has been well established. Each of the Federal agencies is establishing a computer network to serve its community of researchers. In particular, NSFnet, ESnet (DOE), and NSI (NASA) are all being established based on similar requirements and approaches. The NASA Science Internet (NSI) in particular is being established to ensure that satisfactory basic and enhanced networking service is provided in a cost-effective manner through use of a number of networks (including Space Physics

Analysis Network (SPAN) and the NASA Science Network, a new TCP/IP based network.) The NSI program is aimed at cost-effectiveness and ubiquitous connectivity through the use of shared communication resources both internally to NASA (using SPAN and NSN) and with other agencies and through the use of interoperability approaches such as gateways between the various networks.

The science community, though, is multidisciplinary and multi-agency. Typical science activities require operation across agency boundaries. For example, exploration of global environmental issues requires cooperation amongst oceanographers, climatologists, atmospheric scientists, and earth scientists. Such activities are funded by several agencies including NOAA, NSF, USGS and NASA. Networking approaches based on discipline specific or agency specific requirements alone will not provide the widespread connectivity and interoperability needed by such multidisciplinary activities, nor will it provide for the effective cost-sharing required if the needs are to be satisfied within feasible resources.

For these reasons, activities such as NSI have been addressing the sharing, interoperabilty and cross-support requirements through joint discussions with other agencies. These discussions must continue with the goal of providing a single "virtual" network to all scientific activities. This network should allow for transparent interaction between scientists and the resources they require, including access to remote computers, databases, experimental laboratories, and other scientists. Such interaction should only be limited by permission to use the resources rather than limitations in the network connectivity. It is imperative that OSSA take the lead in providing such services to NASA scientists as the space science community has need for communications with scientists' resources beyond those reachable through normal NASA communications (such as PSCN and NASCOM).

Recognizing the need to provide such ubiquitous networking capability to the scientific community, the FCCSET Committee on Computer Research and Applications has developed a set of recommendations in conjunction with the White House Office of Science and Technology Policy for putting in place such a national research network. To achieve this goal, questions of circuit sharing, access control, accounting, interoperability standards, and gateways will have to be addressed. The agencies involved are continuing discussions at the working level to resolve these issues and move forward to establish this broad based network. We recognize these ongoing activities, believe they are critically important to the science community, and recommend that they continue.

In the process of providing ubiquitous networking to the scientific community, particular attention should be paid to providing the required administrative functions needed for facilitating electronic mail.

The Pilot Program has made heavy use of electronic mail to carry out the distributed program. This started with the development of the initial concept papers on the testbed and continued through today where the activities are coordinated through the use of such structures as monthly informal electronic mail reports.

USRA has attempted to facilitate this ongoing electronic interaction by maintaining a list of electronic mail addresses for the various participants and interested parties, and providing automatic mailing to subsets of interest groups. (For example, a list is maintained for participants involved in earth sciences.) In maintaining this list, USRA has had to validate the various electronic mail addresses to insure that they result in reliable delivery.

This has turned out to be a non-trivial task due to the large variety of electronic mailing systems being used (e.g., Internet, SPAN, telemail, nasamail, gsfcmail, OMNET, Bitnet) and the need to deal with changing routing and gateways between systems. For example, the cutover from telemail to nasamail caused a considerable effort in assuring accuracy of addresses in the mailing lists.

Based on this experience, we believe that any attempt to provide for and use electronic mail to support multidisciplinary scientific research will require administrative support of the gateways and directory services. Rather than asking the individual scientific researchers or their organizations to provide this function, we believe it would be much more cost -effective to provide such functions on a community wide basis.

6. Summary

As we embark on a new era in engineering education, we must continually look toward better and more efficient ways to improve science and engineering education. Realizing that scientific and engineering research is inseparable from science and engineering education, it is essential that we endeavor to examine new ways to improve the manner in which research is conducted. By capitalizing upon advances in technology, we can develop new methodologies for research such as telescience. In the upcoming years, telescience can be expected to benefit from the expanding technology base of computer networks, automation and robotics. It is reasonable to expect that telescience will provide a means for increased interaction among earth-borne investigators and space-borne experiments.

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