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CRONUS, A DISTRIBUTED OPERATING SYSTEM: Functional Definition and System Concept

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This report consists of four volumes:

Vol I - CRONUS, A DISTRIBUTED OPERATING SYSTEM: Revised System/Subsystem Specification

Vol II - CRONUS, A DISTRIBUTED OPERATING SYSTEM: Functional Definition and System Concept

Vol III - CRONUS, A DISTRIBUTED OPERATING SYSTEM: Interim Technical Report No. 5

Vol IV - CRONUS, A DISTRIBUTED OPERATING SYSTEM: CRONUS DOS Implementation

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1 Introduction

This report details the functional definition and system concepts for Cronus, the distributed operating system being developed as part of the DOS Design and Implementation project sponsored by Rome Air Development Center. The report was the first project deliverable document, originally published in June 1983 and was intended as an overview of the system which we are developing under this effort. <1> It has been revised in October 1984 to reflect the minimal changes in direction taken during the initial phases of detailed design and implementation. The functions and system concepts discussed in this report are the results of a consideration of the current state of distributed system technology and potential uses of the system in a wide variety of command and control environments.

This report is not a design document. The design of a system meeting the objectives described in this report are

<1>. Acknowledgement. In addition to the authors, Dr. William J. MacGregor and Mr. Morton Hoffman participated in writing the original Functional Definition report. During the period of initial system design and implementation a large group of BBNers, too numerous to mention, have contributed their ideas and energy into refining the system concepts and making them work in our system testbed.

covered in other reports. However, the nature of the project dictates that many design, implementation and even test and evaluation approaches be made in a coordinated manner with the system definition. Accordingly, these issues are also addressed where appropriate in the present document.

1.1 Project Objectives

The purpose of the Distributed Operating System (DOS) project is to develop a distributed system architecture and a distributed operating system software for use in command and control environments. The DOS development activity can be subdivided into five major categories.

1. Select the off-the-shelf hardware and software components that represent the foundation of the DOS system.
2. Design the DOS conceptual structure, by defining a) the functions available to users of the system, b) models for pervasive issues such as reliability, access control and system control, and c) the top-level decomposition of the DOS software components into implementation units.
3. Develop the implementation units defined in (2), until they become complete, functioning programs in the DOS Advanced Development Model (ADM).
4. Integrate the implementation units into a coherent and useful system, both by adjustments to the functional definitions and by any optimizations necessary for acceptable performance.
5. Evaluate the concepts and realization of the DOS in the environment of the ADM, by means of formalized test procedures and practical demonstrations.

The DOS is designed as a general purpose system to support interactive information processing. Thus, emphasis is placed on adaptability of the DOS structures along several dimensions, for example:

- Reliability: essential services can be provided with high reliability using redundant equipment, or with lower reliability at lower cost.
- Accommodation: there are well-defined paths for integrating any host under any native operating system, and any special-purpose device into the DOS.
- Scalability: a DOS cluster can be scaled from a few to several hundred hosts, and adjust to a similar scaling of the user population.
- Primary use: appropriately configured, a cluster could be utilized as a program development system, an office automation system, a base for dedicated applications, or a mixture of all three.
- Access paths: the DOS services and applications can be accessed from terminals and workstations attached to a cluster directly, or through the internetwork.
- Buy-in cost: hosts and applications can be integrated into the DOS environment in a variety of ways that offer a range of cost/performance points to the integrator.

The DOS concepts and the software modules that implement the basic system services can be utilized in a wide variety of possible hardware configurations, and in many different operating regimes, to support the requirements of different applications. This makes it difficult to describe the DOS concisely; a complete description must examine each of the dimensions of DOS adaptability. This document presents a top-level view of the

project objectives and DOS design goals further detail will be provided in system design documents

With regard to DOS adaptability we distinguish between accommodation the ability of the DOS to incorporate new host types new constituent operating systems and new application subsystems (services) and substitution the replacement of a hardware or software module critical to the provision of DOS essential services It is a project goal to achieve as wide a range as possible of accommodation i e to be able to integrate many types of existing or future host operating system or application subsystems within the DOS concepts Substitution in contrast will be much more tightly constrained because the new hardware or software module must correctly implement the external interface of the old module in order for the DOS to continue to function correctly Certain critical interfaces e g the interface to the local network will be carefully defined to make substitution feasible and convenient Both forms of adaptability accommodation and substitution are important but we expect accommodation to occur much more frequently

In general the DOS design is influenced more by available and projected technology than by the specific requirements of any application since to do otherwise would violate the general-purpose nature of the DOS The temper of the DOS design is

pragmatic The project aims to design build and evaluate a useful system over a period of approximately 3 years The following problem areas are not considered to be important project objectives

1 Development of high reliability or fault tolerant hardware

2 Development of minimal-cost solutions to distributed processing problems

3 Research into low-level communications hardware and protocols

4 Development of support for distributed, real-time applications.

By stating (1) as a non-goal we emphasize the project orientation towards software, rather than hardware, reliability techniques We note the mention of specific, non-fault-tolerant commercial processors as DOS constituent hosts in the Statement of Work the implication that non-fault-tolerant machines will often be included in DOS configurations is evidence in support of (1) as a non-goal

By stating (2) as a non-goal we express a bias towards general-purpose operating system facilities For some applications, high-volume production (hundreds or thousands of units) may be anticipated, economic pressures will then encourage tailoring the systems to provide the required function at minimal cost per unit. General-purpose systems, on the other hand, tend

to provide more functionality than is necessary for any particular application. They are thus more cost effective for small production volumes of application systems (their generality makes programming less costly), and less cost effective for large production volumes (since each replicated system contains unused general-purpose mechanisms). Because simply achieving the required distributed operating system function is to a large degree still a research problem, we do not believe a major emphasis on cost effectiveness is desirable or even possible at this time.

By stating (3) as a non-goal we recognize the large investments in low-level communication protocols and hardware already made by the Department of Defense and the private sector. In the interests of interoperability and a rapid rate of progress on the other, higher-level issues of distributed operating system design, we will directly utilize the DoD IP and TCP protocol standards and commercial local network technology.

By stating (4) as a non-goal we identify a conflict between the distributed operating system structures required for high performance in real-time systems, and the structures which support a modern, general-purpose computing utility. Again, the project orientation is towards the more general-purpose concepts; however, the presence of individual hosts in a DOS cluster

performing real-time processing is entirely within the DOS concept of operation, and is readily supported

1.2 System Environment

To define the focus of the DOS project it is useful to classify distributed systems along architectural lines according to the physical extent of distribution the systems exhibit. We can identify three major architectural areas of interest:

1. Node Architecture
2. Cluster Architecture
3. Inter-Cluster Architecture

Each of these is related to the emerging technology of distributed systems, but the technology of distribution tends to be different in the three areas, as explained below:

Node Architecture

The development of a processor architecture, configuration, and operating system for a single host or processing node is a large-scale undertaking, usually accomplished by computer manufacturers. A host is typically physically small (can be contained in one room), is designed by computer hardware architects as a single logical unit, and is concerned with maximum event rates of approximately 1 to 1000 million events per second. Although dual-processor nodes have been common for some time, nodes with many-fold internal distribution are just now becoming commercially available. The

structure and efficient utilization of such hosts is at the forefront of computer architecture research.

Cluster Architecture

A cluster is a collection of nodes attached to a high-speed local network. At present, technology limits the speed of local networks to approximately 1 to 100 megabits aggregate throughput, and the physical size of the network to a maximum diameter of about 4 kilometers. The host systems are made to work together through the agency of the distributed operating system, which provides unifying services and concepts which are utilized by application software. The maximum event rate at the DOS level is related to the minimum message transmission time between hosts, and is on the order of 10 to 1000 messages per second. The cluster configuration and applications supported by it are typically under the administrative control of one organizational entity.

Inter-Cluster Architecture

An inter-cluster architecture typically deals with geographically distributed clusters (or in the degenerate case, hosts) which are not under unified administrative control. Because of administrative issues and the greater lifespan of inter-cluster architectures, they tend to be composed of parts from many different hardware and software technologies. The communication paths between widely separated clusters have much lower bandwidth and higher error rates than local networks, the maximum event rate for cluster-to-cluster interactions is on the order of 0.01 to 10 events per second. In the inter-cluster case, emphasis is on defining protocols for interactions between clusters, and on the appropriate rules for the exchange of authority (for access to information and consumption of resources) between clusters.

The boundaries between these areas are often indistinct, and sometimes simply the result of unrelated design efforts. Nonetheless each area has a unique set of requirements and

solutions for system design. For a given area, these aspects combine to form an outlook that encompasses not just the functional properties of a system, but also many "system level" issues relating to development, administration, training, operations, documentation, and maintenance.

The initial principle concern for the DOS project will be the development of a system for a cluster architecture. Because a cluster is composed of nodes and connected to other clusters, the relationships between node, cluster, and inter-cluster architectures must be considered in order to produce the DOS cluster architecture. In certain specific but limited regards, problems concerning node or inter-cluster architecture will be important. For example, it must be possible to integrate a wide variety of nodes into the cluster system, and the cluster system must be able to interact with other clusters. Where feasible, we would like the design to be extendable to include the areas of node and inter-cluster architecture. Standardized node components and standardized connections to the internetwork environment will both contribute to the applicability and longevity of the DOS design. However, it is outside the primary scope of this phase of the project to attempt the development of unified approaches to problems of distribution in all three areas, which would involve addressing three different sets of issues at once. We do believe that over time, many of the same

concepts used in handling cluster-width distribution can when suitably adopted also be applied to problems in intra-node and inter-cluster distribution All three diversions ultimately need to be integrated in a truly global architecture

It is important that the DOS project take full advantage of the best available off-the-shelf component technology A 'component' in this sense may be hardware (e g processors and storage devices) or software (e g the commercial UNIX or VMS operating systems and the ARPA-sponsored internet gateway software) The current technological trends should also favor continued development of the components in applications apart from the DOS project so that the parallel evolution of node and inter-cluster architectures can potentially benefit the DOS cluster architecture The DOS project can be expected of course to provide useful concepts and services for the other areas synergism results from a blend of diversity and commonality among the three architectural levels

1 3 System Goals

The overall objective of developing a cluster operating system can be broken down into a number of system design goals along the lines of the characteristics the system should exhibit

The resulting design goals can then be prioritized and used during the design process as a means for focusing the design effort and as a basis for making various design choices.

The system design goals for the DOS, in order of decreasing priority are:

Primary Goals

1. Coherence and Uniformity

   To be usable as a system the DOS should provide a coherent and uniform integration of its collection of systems and subsystems.

2. Survivability and Integrity

   The operation of the system and the integrity of the data it manages should be resilient to outages of system components.

3. Scalability.

   It should be possible to configure the system with varying amounts of equipment to accommodate a wide range of user population sizes and application requirements. It should be possible to grow the system incrementally as the demand for individual resources grows over time.

Secondary Goals

4. Resource Management.

   The system should provide means for system administrators to establish policies that govern how resources are allocated within the entire collection of policies and it should work to enforce those policies.

5. Component Substitutability.

The ADM DOS will be built on a specific equipment base. The system should be structured to permit system components to be replaced by functionally equivalent equipment to the largest extent feasible.

6 Operation and Maintenance Procedures

The system should provide features which facilitate routine operations and maintenance activity by system operations personnel.

Each of these design goals is discussed in more detail in the sections that follow.

2 Coherence and Uniformity

The DOS project aims to develop a coherence and uniformity among otherwise independent computer systems and services attached to a cluster in such a manner that the effort required to integrate existing applications, or to develop new, explicitly distributed applications, is small.

This section discusses "coherence and uniformity" as the phrase applies to the DOS. First, an important dichotomy in the domain of anticipated DOS applications is explained, and the dichotomy this places on the design process are described. Second, the cluster architecture is described in more detail. Third, several design principles which are the basis of the design process are presented and discussed as they apply to the goal of coherence and uniformity. Finally, specific approaches to some of the issues which are believed to be well understood at the current time are given.

2.1 The Outer System and Inner System Views

The interpretation of the phrase "coherence and uniformity" is ultimately subjective, and should reflect the users opinions of the system concepts and realization. Thus it is fitting that this section begin with a discussion of how the DOS concepts

might be used in different applications. Rather than attempt a thorough treatment of the (very large) domain of applications, two important classes of applications are considered in the abstract.

The first class of application views the DOS as an external entity, a supplier of services and communication facilities. This orientation is referred to as the outer system view of the DOS, since the applications already exist or are built outside the context of the DOS concepts of operation. The second class of application is built to run in the DOS context, with full knowledge of the DOS environment and a bias towards its full exploitation. This orientation is referred to as the inner system view of the DOS. The outer system view is most closely related to the problem of achieving connections among existing functional components built on heterogeneous hosts and operating systems; the inner system view should prevail in the design of new, distributed applications, whether they are built on a homogeneous or heterogeneous base.

We presume that applications satisfying an organization's needs will often be developed independently of each other. During their development, these applications will frequently come to depend upon particular hardware and software objects in their environment, e.g., the host instruction set, the host operating

system, and one-of-a-kind peripherals attached to a particular host. The applications may reach operational status with no explicit use of the DOS concepts, and they could be built either on conventional, stand-alone hosts or on a host attached to a DOS cluster.

At some point in time it may be necessary to form a logical connection between application programs which have been developed independently--that is, to achieve interoperability among the functional components. There may be many obstacles to interoperability; a few of the more prevalent and difficult obstacles are:

1. Incompatible data structures.
2. Application interfaces designed for program-to-human rather than program-to-program communication.
3. The absence of a suitable program-to-program communication facility in the host operating system(s).
4. An inadequate structure for the transfer of authority (for access to information and resources) between programs.
5. Poor reliability as the system becomes more and more vulnerable to single-point failures.
6. Poor reliability due to high error rates on communication channels between components.
7. The high cost of performance optimizations involving several complex software components.
8. Disparate software development environments--both automated tools and manual procedures.

In the outer system view, the primary role of the DOS is to

reduce these and other obstacles to interoperability by providing a core of common concepts and functions that become the focus of component interactions

As an example of the outer system view suppose there is a need to link a graphics display function executing on a personal workstation to a database management system running on a standard mainframe operating system Initially the database management system and the graphics support may have no relationship to the DOS whatsoever relying entirely upon the hardware and software resources of their own hosts In order to accomplish the logical link the hosts must be physically attached to a DOS cluster communication software must exist on each host and the applications must be prepared to properly utilize the host-to-host communication path The DOS can assist this integration by defining the common concepts required for the logical connection to be formed In this simple example the only requirement is for communication but in more complex situations the DOS may supply other services (e.g., user authentication data storage and encryption terminal multiplexing)

The inner system view in contrast assumes that new applications are constructed within the framework of the DOS and use DOS mechanisms in preference to local host mechanisms whenever practical A new application designed from the inner

system perspective may or may not be distributed, and may be built on homogeneous or heterogeneous machines and operating systems Whichever the case by adopting the DOS conventions for system decomposition, object definition and handling, access control, file storage and cataloging etc such applications avoid many of the interoperability problems listed above and can take advantage of the distributed nature of the environment In fact, the process of building an application on the DOS inner system is akin to program construction on a single conventional host, in that the system concepts are generally understood by all of the components to mean the same thing independent of the distribution of the underlying system The new application not only achieves uniform connections among its constituent pieces, but also inherits the ability to interact with other inner system tools which also conform to the common concepts Thus inner system applications enrich the DOS environment in an incremental way, and form the basis for the continued orderly evolution of the DOS environment.

The DOS inner system is unlike a conventional operating system, however because it addresses issues of distribution--the development of distributed programs, the possibility of survivable operation through host redundancy, and the potential for configuration scaling beyond the limits of shared memory architectures. These system aspects motivate the development of

a powerful and coherent inner system architecture

An assumption of the DOS project is that both the outer and inner system views are important and must be considered in the design Because the two views imply different system requirements this represents a burden to the design process

2 2 DOS Cluster Physical Model

Before discussing the major system design principles the equipment configuration for the DOS cluster is briefly reviewed .

The DOS cluster is composed of three types of equipment

1 A communication subsystem The subsystem consists of a high-bandwidth, low-latency local network, hardware interfaces between hosts and the local network, device driver software in the host operating systems, and low-level protocol software (the data link layer) in the hosts

2 DOS service hosts These machines are dedicated entirely to DOS functions, and exist only to provide services to DOS users and applications In general, they represent modules with specific, system-oriented functions (e g archival file storage) and are not user programmable Requirements for the DOS service host types and operating systems will be specified in the DOS design documents <1>

<1> The DOS design will permit the substitution of different service host types for the hosts actually used in the Advanced Development Model.

3 Application hosts These may be general-purpose hosts (e g , timesharing machines) providing services to many DOS users, or workstations providing services to one user at a time, or special-purpose hosts (e g signal processing computers) required by just one DOS application. Application hosts are often user programmable. In general, they have many characteristics which are not under the control of the DOS, the DOS must be sufficiently flexible to incorporate application hosts of almost any kind

Application hosts will be connected to the communication subsystem in one of two ways 1) directly by means of a host-to-local-network device interface, or 2) indirectly through an intermediary DOS service host called an access machine The intent is that standardized access machine software and hardware can reduce the integration cost for a new application host The electrical interface between the application host and the access machine, for instance, need not be as complex as a local network interface it need only be mutually acceptable to the two machines <1> Access machines may have other functions as well they could play a role in the DOS security model, for example, by isolating untrusted hosts from the (presumed secure) local network The tradeoffs arising in direct and indirect host integration are not presently well understood an exploration of this topic is anticipated during the DOS project

<1> As a concrete example, the access machine planned for the Advanced Development Model will utilize the HDLC protocol over an RS-422 or RS-423 machine interface

General-purpose application hosts will usually operate with standard operating systems (e g., a Digital Equipment Corporation VAX computer running the VMS operating system) which are enhanced and or modified to integrate the host into the DOS. Thus application hosts will support some DOS software components at a minimum those required for communication with DOS service hosts Some DOS services may also be partially or completely implemented on application host to realize performance advantages (by locating applications and required DOS services together) or cost advantages (through resource sharing)

2 3 Design Principles

2 3 1 Provide Essential Services System-Wide

At the heart of the DOS concept is the availability of selected essential services to all of the applications in the DOS The coherence and uniformity of the DOS is directly enhanced when applications and application host operating systems embrace the DOS-supplied services as the single source of these services To the extent that applications and application host operating systems choose to utilize parallel but incompatible services, coherence and uniformity is lost.

At this time the essential services are believed to be

- User access points (terminal ports workstations) providing a uniform path to all DOS services and applications
- Object management (cataloging and object manipulation) for many types of DOS objects
- Uniform facilities for process invocation control and interprocess communication for application builders
- Cluster-wide user identifiers and user authentication as the basis for uniform access control to DOS resources
- Cluster-wide symbolic name space for all types of DOS objects
- A standard interprocess communication (IPC) facility supporting datagrams and virtual circuits
- A user interface that provides access to all DOS and application services
- Input/output services for the exchange of data with people and systems apart from the DOS
- Host monitoring and control services, and additional mechanisms needed for cluster operation

2.3.2 Utilize Recognized and Emerging Standards

The DOS design will incorporate recognized and emerging standards whenever practical at many levels of the system The adoption of standards both enhances the uniformity of the system and contributes to the likelihood of pre-existing compatible interfaces The longevity of the DOS concept of operation is extended by attention to standards that are the foundation of contemporary research and development activities, the possibility of interaction with other projects to the mutual benefit of both

is maximized

2.3.3 Preserve Choices

The DOS design will preserve choices for the application host integrator and the application builder.

There is a complex tradeoff between the cost of host and application integration into the DOS, and the uniformity and power achieved as a result of the integration. Although many issues involved in the tradeoff have been identified, the problem is not sufficiently well understood to make prescriptions confidently. Investigation of this problem is an important objective of the DOS project.

Part of the project's approach is embodied in Principle 3. This principle requires that the DOS concept of operation accommodate not just one, but a range of possible cost uniformity points.

Similar tradeoffs exist among the DOS services supplied to application programs. For example, this principle applied to interprocess communication implies that neither datagram nor virtual circuit service is sufficient for all applications; the DOS should provide both types of communication service.

In general, this principle requires that the DOS design address the problem of how DOS installations will adapt to very different configuration and application requirements

2.4 Specific Approaches

2.4.1 The Communication Subsystem

A high-bandwidth, low-latency local network <1> is the backbone of the DOS. The DOS concept of operation will specify the interface to the local network, so that alternate local network technologies can be substituted for the particular local network chosen for the Advanced Development Model, if they meet the interface specification. The interface specification will be as unrestrictive as possible, so that substitution is a real possibility.

The local network will permit every host to communicate with every other host in the DOS cluster, and will provide an efficient broadcast service from any host to all hosts. The local network interface specification may further restrict the minimum packet size, addressing mechanism, and other local network properties.

<1>. See DOS-Note 21, "DOS Local Network Selection".

2.4.2 Generic Computing Elements

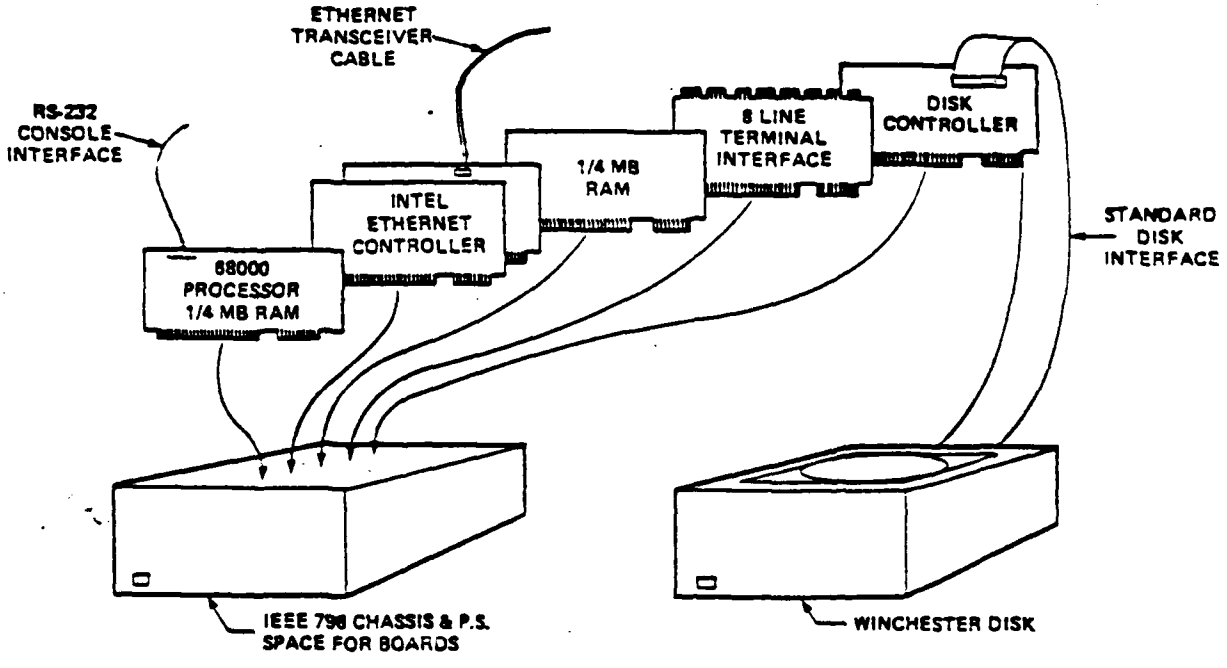
The concept of a Generic Computing Element (GCE) is one aspect of the DOS design <1>. A GCE is an inexpensive DOS host that can be flexibly configured with small or large memory and with or without disks and other peripherals, as shown in Figure 3. GCE's will be configured for, and dedicated to, specific DOS service roles, such as terminal multiplexing, file storage access machines, and DOS catalog maintenance <2>.

The GCE's are a basis for implementing essential DOS services in a uniform, application-host-independent manner. Thus, even hosts which choose to support only a minimum integration to Cronus can obtain essential DOS services remotely from GCE implementations. Because the DOS design will specify the properties of GCE's and also the software components <3> running on them, it is possible to carefully customize and control the performance and reliability characteristics of the DOS services which run on GCE hardware. A configuration consisting of the local network, some number of GCE's supporting the essential services represents the minimum useful DOS

<1> See DOS-Note 17, "A Generic Computing Element for the DOS Advanced Development Model".

<2> A single GCE may support several DOS services simultaneously.

<3> Perhaps the most important software component is the GCE operating system, CMOS.



The Generic Computing Element
Figure 1

instance.

Application programs can be constructed above the GCE hardware and operating system. a single GCE host may support DOS services or user applications. but not both.

2.4.3 Standards Applicable to DOS Components

The DOS design will utilize recognized standards in several key areas. these directly contribute to both the coherence of the DOS and interoperability with other computer systems. The use of recognized standards within the design and implementation of the DOS will extend the effective lifetime of the system and simplify the substitution of alternate but compatible components. The standards which have been identified as pertinent as of this time are

1. IP and TCP internet protocol standards. IP and TCP will be used as a basis for Cronus interprocess communication within the DOS cluster.

2. ARPA standard gateway. The gateway between the ADM cluster and the ARPANET will be an LSI-11 based ARPA standard gateway. developed and supported by BBN.

3. Ethernet. From the hosts' point-of-view the local network in the Advanced Development Model will match the Ethernet transceiver cable compatibility interface <1>.

<1>. As noted above. the DOS concepts will not depend upon any local network properties which are peculiar to the Ethernet. Ethernet-compatible devices will. however. be easily added to the

4 IEEE 796 bus. The GCE hardware selected for use in the Advanced Development Model is based on the IEEE 796 bus standard for circuit board interconnection.

5 HDLC and RS-232C. These communication standards will be used to connect hosts and terminals, respectively, to GCE s within the cluster.

6 Standard programming language. A single programming language will be emphasized, although the DOS concepts are language independent. Initially the C programming language will be used to the maximum extent. Ultimately it is intended that the military standard language Ada will be exploited to the greatest extent practical. Its use will be determined by timely completion of activities outside of the scope of the DOS project.

7 The UNIX Constituent Operating System. The UNIX COS provides an important base for many software development tools used in the development of Cronus. A well integrated UNIX COS is seen as an enduring component of DOS clusters.

Other standards may be applicable to DOS components and are being considered for adoption by the project. Two areas in which existing standards will probably be adopted, rather than developed by the project, are the format of electronic mail messages and the interface between GCE s and mass storage modules.

Advanced Development Model.

2.4.4 Flexible Application Host Integration

When a new host is integrated into a DOS cluster it will assume one of several possible host roles The host roles will occupy different points along the spectrum of integration cost versus degree of adherence to the DOS unifying concepts System administrators are thus presented with a choice of integration paths and can tailor host roles to the needs of specific applications

When a host is integrated with minimum effort, little more than a communication path between the host and other entities in the DOS cluster will be present This host will be able to obtain many DOS essential services through the communication path, but its resources may be unavailable to other DOS processes Further effort must be devoted to assimilate the host partially or fully into the DOS object catalog, process model, and reliability mechanisms Another key issue in integrating Cronus communication into a host is the relationship between Cronus communication and any existing constituent operating system Cronus is designed so that it can be either an adjunct to an existing COS (integrated with a COS kernel or as application wide) or serve as the base operating system for some hardware components

As defined above, the access machine concept is closely

related to the effort required for host integration Minimal effort integration will most likely be achieved through the use of access machines. This host integration path will probably result in lower throughput between the host and the network due to the presence of the access machine. but may be a desirable approach on balance. For special purpose devices with limited programmability. access machines may play the dual role of device controller and DOS interface.

The host role is decided anew for each host in a cluster It is possible. for example. for two hosts which are physically the same type of machine and which run the same operating system to be integrated to assume different roles

2 4 5 Comprehensive DOS Object Model

The DOS concepts revolve around a group of basic object types files. processes. hosts. users. and directories to name a few of the more important. The DOS design attempts to treat all of these types (and others) uniformly. in accord with an abstract object model The abstract object model recognizes that an object may be designated in a variety of ways

1. **Universal Identifier (UID).** A UID is a fixed-length bitstring. Every object in the abstract object model has a unique UID. over the set of all objects in the cluster

and the entire lifetime of the system A UID is always an acceptable designator for an object from anywhere within the DOS

2. Symbolic Names People often use symbolic object names to designate DOS objects Symbolic names can be context dependent (for example, relative to a directory) or context independent The symbolic name space is hierarchically structured so that the logical grouping of related objects is reflected in a similarity among their context independent symbolic names An object need not have a symbolic name.

3. Address An address is a bitstring composed of a sequence of address portions Users sometimes specify address information to exercise control when referencing objects but most often leave the handling of object location to automatic system mechanisms

Normally, people will refer to objects using symbolic names, and programs will refer to objects using UID's, addresses, and symbolic names The system will provide translation services, the most important supported by the object catalog, to translate among the representations of object names

UID s, addresses, and symbolic names will be used in different ways within the DOS A UID is always a sufficient object name, even for objects which can move from host to host because it is completely context independent An address will sometimes represent the fastest access path to an object, because its representation explicitly contains the routing information needed to reach the designated object It is often used as a hint to underlying system object access software. Symbolic names are most suitable for the user interface

A mechanism will be developed for constructing new composite abstract types from previously defined types. This will allow objects with rich semantics to be built from simpler objects. for example, a 'reliable' file could be assembled from several primitive files on different hosts, containing redundant copies of the same information.

2.5 A Summary of the DOS Architecture

The commitment of the DOS design to support a wide range of equipment configurations makes it difficult to give a concise description of "the DOS". The system will have widely varying characteristics for different DOS equipment configurations. We identify a few possible configurations to help clarify the boundaries of the design.

2.5.1 Level 1: A Minimal System

A minimal DOS system consists of the local network, a small number of dedicated hosts supplying essential services (GCE s), and a host integration guide which explains how the owning agency can integrate their own hosts into the DOS environment. Alternatively, the essential DOS services can often run on

existing hosts to reduce even futher initial buy-in costs

The minimal system supports the user registration and authentication functions, and the essential services pertaining to the object model and the cluster gateway(s). It also supports the basic system monitoring and control functions present in any DOS instance. By itself, it does not provide a user programming environment, a user interface, or the utilities (electronic mail, text preparation, etc.) found in most general system environments.

2.5.2 Level 2: A Utility System

A utility system consists of the minimal system, plus one or more fully-integrated, general-purpose hosts called utility hosts. The utility system will be suitable for developing new applications in the framework of the DOS, and will support the utilities typical of a modern general system environment. The utility system will also support the maintenance of its own software, and the software of the minimal system.

2.5.3 Level 3: An Application System

An application system consists of a minimal system and some number of application hosts, workstations, and special-purpose devices. An application system may simultaneously be a utility system, if utility hosts are present in the cluster. Applications are generally developed in a utility system and operate in an application system. Application systems, therefore, need not be capable of supporting their own software development. Application systems are sometimes configured with redundant components and operated in a high reliability mode. Note that GCE's can be used for application programming, thus a particularly simple application system could consist of just the network, the GCE's required to provide essential services, and some number of application GCE's.

Figures two and three illustrate the components and the context of the current system configuration for the Advanced Development Model being assembled at BBN.

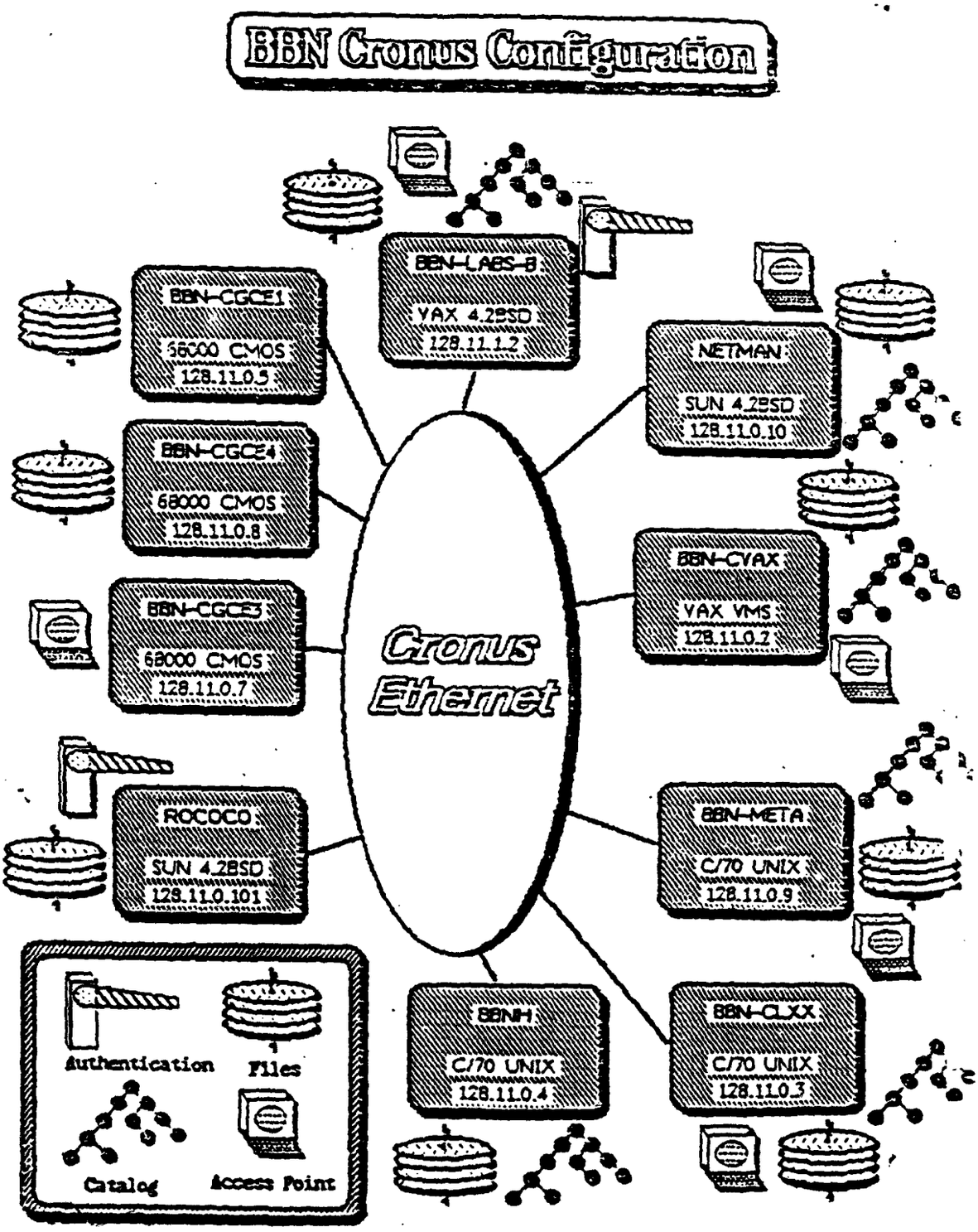


Figure 2 The Local Cluster Configuration

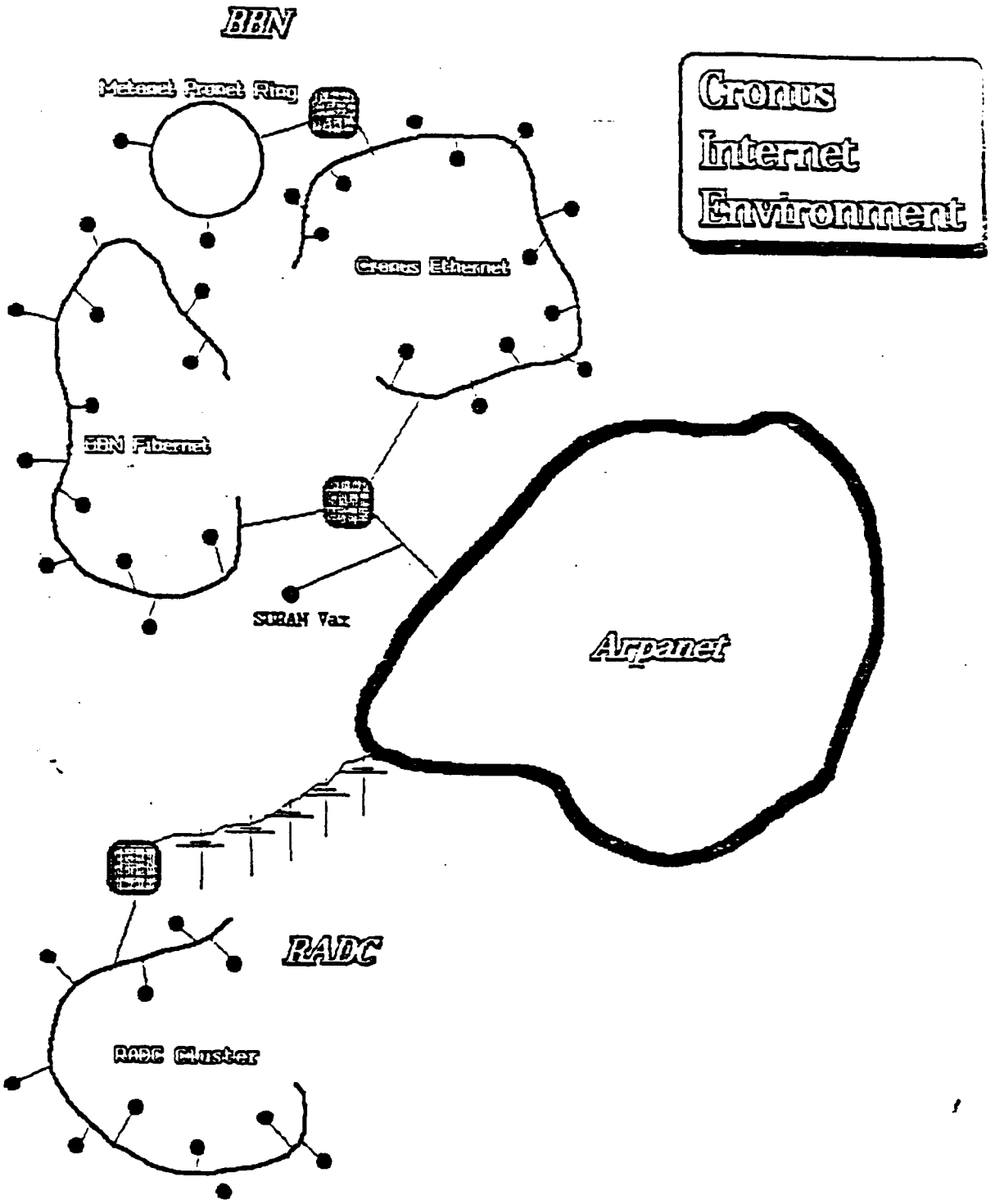


Figure 3 The InterCluster Environment

3 The DOS Functions and Underlying Concepts

3 1 Introduction

Expected usage of the DOS can be divided into five categories

1. Applications.
2. Application development and maintenance.
3. System administration.
4. System operation
5. System development and maintenance

The system is intended primarily to support end application usage (1) However, to adequately support end applications it must also support the other categories of use Therefore, it should be possible for users working in each of these cases to perform their responsibilites by means of the DOS The goal of supporting these usage categories places requirements on the functions the DOS must implement, and on the tools it must be able to accommodate This section discusses the DOS functions

The DOS system provides functions in the following areas

- System access The objective is to support flexible, convenient access to the system from a variety of user access points, of varying cost, performance and levels of integration
- Object management. The notion of a "DOS object" is central to the user model for the DOS The DOS treats resources.

such as files, programs and devices as "objects" which it manages, and which users and application programs may access. The objective of the object management mechanism is to provide users and application programs uniform means for accessing DOS objects and provide an integrated model for expending the system into the application domain

- Process management. Like the object abstraction, the "process" abstraction is central to the user model of the DOS. In addition, it is useful as an organizing paradigm for the internal structure of the DOS. The objective of the DOS process management mechanisms is to implement the "process" notion in a way that enables processes to be used both to support the execution of application programs for users and internally to implement DOS functions

- Authentication, access control, protection, and security objective is to provide controlled access to DOS objects

- Symbolic naming. DOS users will generally reference objects and services symbolically. Symbolic access to DOS objects will be supported by means of a global symbolic name space for objects.

- Interprocess communication. The objective of the interprocess communication (IPC) facility is to support communication among processes internal to the DOS, and among user and application level processes

- User interface. The user interface functions provide human users with uniform, convenient access to the features and services supported by the DOS resources

- Input and Output. The objective here is to provide flexible and convenient means for users and programs that act on the behalf of users to make use of devices such as printers, tape drives, etc.

- Syster monitoring and control. The purpose of the system monitoring and control functions is to provide a uniform basis for operating and manually controlling the system

The principal goal for the DOS in each of these functional areas is to support features that are comparable to those found in modern, conventional, centralized operating systems, such as

Unix Multics. VMS. and TOPS-20.

. The rest of this section discusses the functional areas identified above in terms of our objectives in each area and sketches some of the concepts and principles that underlie our approaches for achieving the objectives

Each functional area is discussed in a separate section However. it will become clear from the discussion that these functions are not independent of one another These interrelationships occur across functional areas as well as within them. For example. objects and processes are intimately interrelated A process is a type of DOS object. and access to DOS objects is supported by interactions among processes. Furthermore. internally the system is structured to combine lower level functions and capabilities in one or more areas into higher level functions and capabilities For example. the relatively higher level notion of reliable (multiple copy) file objects is implemented by more basic (single copy) file objects

This internal "involuted" structure of the system is important If the structure and interrelationships are designed well. implementation can proceed in orderly and efficient stages from the lower levels to the higher ones. Furthermore. the resulting system implementation will exhibit internal order. making it easier to maintain and evolve in adapting to new

requirements

3.2 System Access

The objective in this area is to provide users with flexible, convenient access paths to the system.

The system will support a number of different types of access points including:

1. Terminal access computers (TACs). A TAC is a terminal multiplexer connected directly to the DOS local area network. It acts to interface a number of user terminals to the DOS. The software that runs on a TAC is entirely under the control of the DOS. User programs are not permitted to run on a TAC computer.

2. Dedicated workstation computers. A workstation is a computer that is, at any given time, dedicated to a single user. Workstations will be connected to the DOS local network. Workstation hosts have sufficient processing and storage resources to support non-trivial application programs, such as editors and compilers, and to operate autonomously for long periods of time. A workstation may serve as its user's access point to the DOS. User programs may run on a workstation.

3. The internetwork. The DOS local network is connected to the internetwork by means of a gateway computer which is a host on the DOS local area network. Users remote from the DOS cluster may access the DOS through the internetwork. Remote terminal access is accomplished by means of a standard terminal handling protocol (TELNET) which operates upon a lower level, reliable transport protocol (TCP).

Because of the distributed nature of the system, user interaction with the DOS is supported by software that runs on

one or more computers. This software includes two principal modules One module is responsible for handling the user's terminal Since this module will often run at or very "near" the user s access point. we shall call it as the "access point agent" The other principal user interface module interacts with the user at a higher level to provide access to DOS resources in response to various user commands We shall call this module the "user agent". It is useful to think of the access point agent and the user agent as processes These agent processes interact with other components of the DOS and with each other by means of well defined interfaces and protocols In addition. they play an important role in insuring the reliability of user sessions

The access point for a user session. in part. determines where the access point agent and user agent processes run. For a user whose access point is a TAC the access point agent runs on the TAC and the user agent runs on a shared host The access point agent for a user with a dedicated workstation runs on the user's workstation computer. and the user agent may run on the workstation or it may run on a shared host Users who access the DOS through the internetwork are allocated user agents that run on shared hosts. and their access point agents may run either on the (non-DOS) host used to access the DOS or on a host within the DOS cluster

Some DOS hosts may provide support for terminals directly connected to them It will be possible for users to access the DOS through such directly connected terminals These users will be treated much like users who access the DOS through the internetwork in the sense that the DOS will allocate user agents for them that run on shared hosts

The standard user interface software (for users accessing the DOS through TACs and the internetwork) will be written to operate with CRT terminals that have cursor positioning capabilities. In particular, this includes terminals that meet a subset of ANSI standards X3.41-1974 and X3.64-1977, providing cursor positioning and various other functions such as clear to end of line, delete line insert line, etc. More capable terminal devices (e.g., workstations with graphics displays) can emulate the standard terminal device to obtain a compatible user interface and certain programs may take advantage of these additional capabilities. In addition, a means will exist for users with other less capable terminal devices (e g , printing terminals) to access the system (e g , by using the TELNET Network Vitual Terminal or NVT as a lowest- common denominator terminal device).

3.3 Object Managememt

The DOS will support a wide-variety of objects. The objective of the DOS object management mechanisms is to provide access to DOS objects.

DOS object management will be based on the following principles

- Every DOS object has a unique identifier At the lowest level within the system, access to a DOS object can be accomplished by specifying its unique identifier and the desired access to an "object manager" process for the object.
- The DOS will support a collection of transaction-based object access protocols. These protocols will be type dependent in the sense that there will be different access protocols for different object types.
- Access to objects will be accomplished by engaging in the appropriate access protocol with an object manager process for the object. The interactions between the accessing agent and the object manager will be accomplished by means of interprocess communication (See Section 3.7).
- Input output devices will be treated as DOS objects Consequently, input/output devices will have object managers, and access to the devices will be accomplished by means of interprocess communication
- The DOS catalog (See Section 3.6) provides a means of binding symbolic names to DOS objects The catalog supports a lookup function (a symbolic name-to-unique id mapping) which enables objects to be accessed symbolically.
- The DOS will support a fixed set of basic object types (such as "primitive" file, "primitive" process, etc.). In addition, it will support more complex object types (such as "multiple copy" file, "migratable" file, etc.) which will be built upon the properties of the basic object types. Our design objective at this time is to develop the

framework for supporting more complex object types rather than to try to specify the semantics of those object types

Files are a particularly important type of DOS object The storage resources of dedicated DOS hosts as well as certain constituent hosts will be used to store DOS files Symbolic naming for DOS files will be implemented by the DOS catalog

Each host that provides storage for DOS primitive files will also support the object manager which implements the DOS access protocol for primitive files.

3.4 Process Management

As suggested above, the DOS will support the notion of a process Processes will be used both by the implementation of the DOS and to directly support user applications For example, there will be processes responsible for implementing the DOS object catalog and for implementing the DOS file system. In order to support user processing activity, there will be processes that execute standard tools, such as text editors and language processors, as well as specific command and control applications.

The objective of the DOS process structure mechanisms is twofold.

1. To support the process concepts required to implement DOS functions, for example, object management

2. To provide a basis upon which to develop means for users to initiate and control processing activity within the DOS.

DOS process management will be based on the following principles.

- A basic type of process ("primitive" processes) will be implemented at a fairly low level. It will be bound to a particular host, and it will bear no special relationships or capabilities with respect to other primitive processes

- Primitive processes are DOS objects. As such, they have unique identifiers, and could be cataloged in the DOS catalog (See Section 3.6)

- More sophisticated process notions will be built upon the primitive process notion. For example, the notion of hierarchical process structures, where processes are related to one another according to the manner in which they were created, and where the relationship between processes determines the types of operations a process can perform on other processes, will be built upon the primitive process notion. Similarly, 'migratable' processes (processes that can move from one machine to another) will be built upon primitive processes

- The system will support the notion of "long lived" processes. A long lived process is one which the system will take steps to ensure exists over shut downs and restarts of the system and of individual hosts. Server processes will frequently be long lived

- Process I/O and interprocess communication will be handled in an integrated fashion. The notion of "primary" input and output streams for a process will be supported, and it will be possible to "link" processes together by connecting the input stream of one process to the output stream of another. Among other things, this will make it possible for one process to act as a filter or translator for the stream of data passing between two other processes.

3.5 Authentication, Access Control, and Security

The objective of the DOS in this area is to provide for controlled access to DOS objects. The purpose of the DOS access control mechanisms is

1. To prevent the unauthorized use of DOS objects. For example, it is important to ensure the privacy of sensitive data by preventing unauthorized users from accessing it.
2. To ensure the integrity of DOS objects. The objective here is to control the ways in which various objects may be used.

Convenient and flexible means should be available to users for specifying the types of access other users may have to their objects.

The access control mechanisms will be designed to be strong enough to protect the privacy and integrity of DOS objects against accidental disclosure or misuse, and against attacks by malicious, but inexpert users. It is extremely difficult to protect against attacks by dedicated expert users, and it is not a primary goal for the DOS to be invulnerable to such attacks.

There are two capabilities related to protection and security that are not goals for the DOS.

- Prevention of denial of service. Denial of service occurs when a user prevents or interferes with someone else's use of the system or parts of it. A simple example would be a user who seizes all the "job slots" on a timesharing system.

by logging in many times, thereby preventing others from accessing the system. Another example would be the situation that might occur if a user could run a program that floods the local area network with packets. This would prevent other users from using the network. Although the DOS will be able to prevent certain types of denial of service including those just described, it is very difficult, in general, to comprehensively prevent denial of service.

- Implementation of the military security model. The DOS will not implement multi-level security. The DOS would run in a "system high" mode if it were used to process classified data. The DOS access control mechanisms could be used, however, as a support for the Need-To-Know security model, just as access control in commercial single-host operating systems is used for this purpose.

Internally, the DOS will be organized so that much of its operation is accomplished by means of processes. Many of these internal DOS processes may be thought of as agents which act to carry out user requests. The principal DOS access control mechanism will be based on the identity of the agent attempting to access an object. An important part of access control procedures within the DOS will be to determine the identity of the accessing agent and the identity of the user on whose authority the agent is acting. Consequently, reliable authentication of users and processes will be an important element of the DOS access control mechanisms.

The DOS protection and security mechanisms will be based on the following principles.

- Each DOS user will have his own unique identity which is understood across the entire DOS system.

- Users of the DOS will be required to login once per user session In most cases access to DOS resources during a session will not require additional "logins" that involve explicit user participation

- User login will be accomplished in the conventional manner by supplying a valid user login name and password

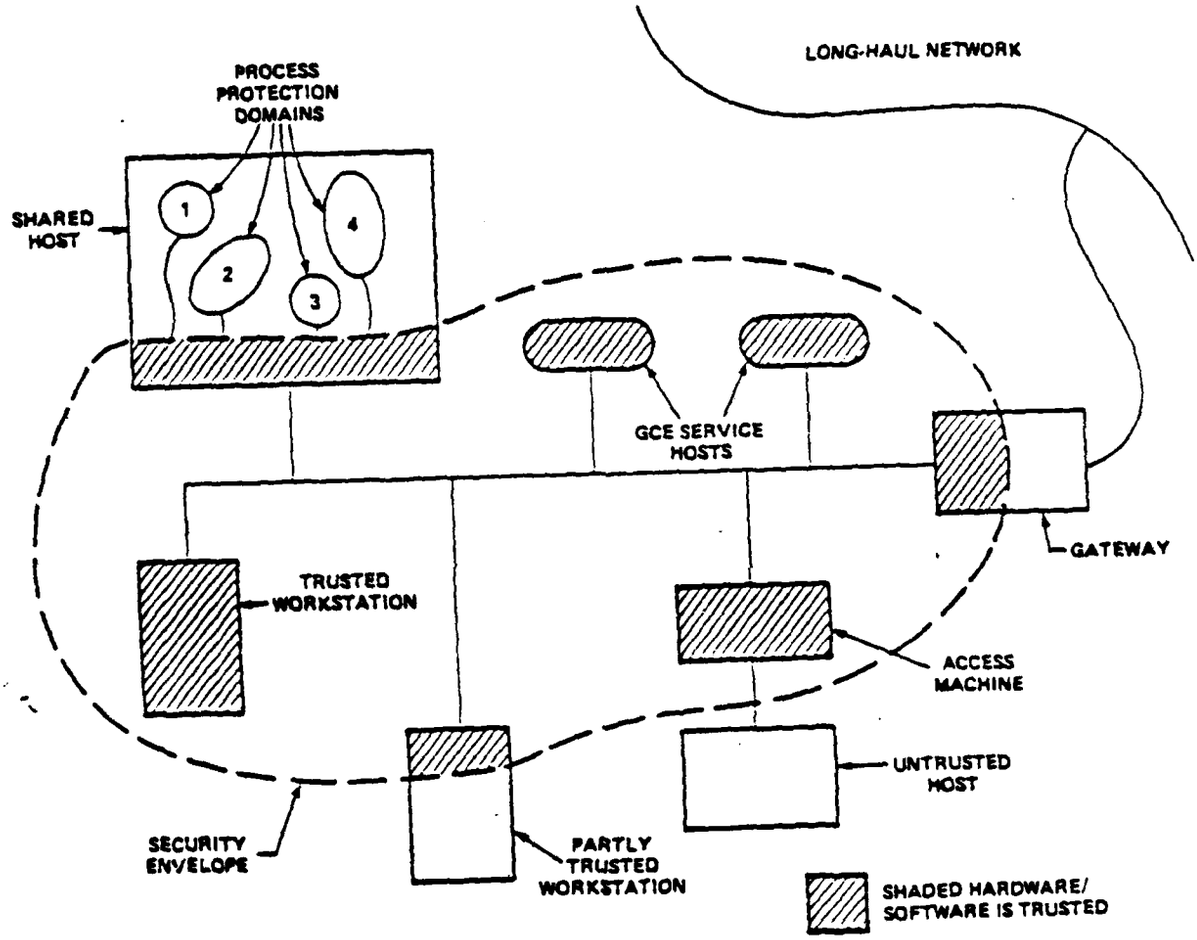
- User passwords that are stored within the system will be protected by means of a one-way (i.e., non-invertible) transformation A password check will be performed by first applying the transformation to the password supplied by a user and then comparing the result with the transformed password for the user that is stored by the system

- Attempts to access DOS resources will be subject to access control checks prior to access

- Attempts to access DOS objects will be treated by the system as being made on behalf of some registered system user. In order to enforce the appropriate access controls the object managers for DOS resources must be able to obtain the identity of the registered user from the accessing agent or to determine it from information supplied by the accessing agent.

- We assume the existence of a "security envelope" which surrounds the DOS local area network and some of the key DOS components (see Figure 4) DOS components which are within the security envelope may trust each other, and processes outside of the security envelope are not able to masquerade as trusted processes.

Figure 4 shows a possible relationships between hosts and the security envelope A shared host (typically a multiple access application host) will participate in the DOS access control mechanisms by means of augmentation to its trusted "monitor" or "supervisor" processes. Generic Computing Elements, which supply DOS essential services will be wholly contained within the security envelope, i.e., untrusted applications are



The DOS Security Envelope
Figure 4

not permitted to directly alter the programs resident in system GCE s Gateways attached to the cluster must "protrude" through the security envelope. because they connect the trusted local network to the untrusted internet. at a minimum. gateways could explicitly mark all traffic entering the cluster as "foreign". in a trustworthy manner Access machines may be used to connect completely untrusted hosts to the cluster. In this case the access machine would validate all interactions between the untrusted host and the DOS components inside the security envelope. Workstations attached to the DOS may either be fully trusted. and hence inside the boundary of the security envelope. or partially trusted. A partially trusted workstation is presumed to contain some tamper-proof hardware and software components that protect the DOS from anti-social behavior on the part of the workstation.

3 6 Symbolic Naming

Naming is an important unifying concept for the DOS The means provided for naming objects is one of the most important factors determining how easy and convenient a system is to use

The DOS will implement a global symbolic name space for DOS objects. This name space will have the following properties.

- The symbolic name for an object will be independent of the object's location within the DOS
- The symbolic name used to refer to an object will be the same regardless of the location within the DOS that the name is used
- Common syntactic conventions will apply to symbolic names for different types of objects (including files, devices, server processes, etc.)

The symbolic name space will be implemented by means of a DOS catalog data base (or simply "catalog"). The catalog will implement a symbolic name-to-object mapping for the DOS objects it catalogs. The catalog will not usually store the objects themselves, but rather will store information about the objects. Information about an object will be stored in a catalog entry for the object. This information will be sufficient to allow access to the object. In particular, the catalog will store the global unique identifier for each object it catalogs along with any additional information required to locate the object within the DOS. In addition, it may also maintain certain attributes of objects it catalogs.

While in some sense the catalog can be thought of as a logically centralized data base, it will be implemented in a distributed fashion. In particular, the catalog will be dispersed among a number of DOS hosts and some parts of it may be replicated. It will be dispersed to ensure that the system is scalable and that the catalog is reliable. While all of the

information in the catalog. even for very large configurations. might fit on a single DOS host. it seems unwise to store it on a single host In large configurations the load placed on that host would likely represent a performance bottleneck Furthermore. the cataloging functions would be vulnerable to a failure of that single host Parts of the catalog will be replicated to ensure high availability of critical catalog data

The symbolic name space and its supporting catalog will be based on the following principles

- The name space will be hierarchical The name space hierarchy can be thought of as a tree with labeled branches
  - o The leaves (terminal nodes) of the tree represent cataloged objects.
  - o The symbolic name for an object is the name of the path from the root node of the tree to the node that represents the object
  - o Non-terminal nodes of the tree represent collections of catalog entries and are called "directories"
  - o Directories are DOS objects. and they have names The name of a directory is the name of the path from the root to the node that represents the directory Thus the non-terminal nodes of the tree also represent cataloged (directory) objects
- A set of general operations for manipulating the catalog. directories and catalog entries. independent of the types of objects. will be provided
- The catalog can be used to obtain information about an object However. issues associated with accessing the object. such as access protocols and object representation. are separate from the naming issues that are addressed by

the catalog.

- The catalog data base will be organized to efficiently implement two types of lookup operations symbolic name-to-catalog entry, and unique id-to catalog entry. The symbolic name lookup operation is supported for human users "Wildcard" designators will be supported. The unique id lookup operation is supported for programs.

- Operations which modify the catalog will be implemented as atomic transactions in order to maintain the integrity of the catalog in the presence of concurrent activity and possible failures of system components.

- The catalog will have the ability to maintain "linkages" to other name spaces This is supported to permit name spaces of constituent hosts to be (weakly) integrated into the DOS symbolic name space This will be accomplished by an "external name space" object which can be cataloged like any other object. For example, it will be possible to catalog the directory /usr/rjones/memos on some Unix DOS host as a DOS external name space object Coupled with appropriate file access software on the Unix system, this would permit a user to refer directly to files in the cataloged directory from the DOS name space

- The catalog can be thought of as a (complex) DOS object. As mentioned above, directories within the catalog are DOS objects Therefore, access to the catalog can be controlled by the same mechanisms that control access to other DOS objects. This access control will help ensure the privacy and integrity of information in the catalog. Access to the objects themselves are, of course, also subject to access controls.

The catalog is an important component of the DOS. It will be used not only to support the cataloging requirements of DOS users, but also to support the implementation of parts of the DOS. For example, as noted above in Section 3.3 the symbolic naming requirements of the DOS file system will be supported by the DOS catalog.

Not all DOS objects will be cataloged in the catalog It will be possible to access uncataloged objects directly by means of their unique ids

3 7 Interprocess Communication

The objective of the DOS interprocess communication (IPC) facility is to support the communication requirements of the DOS Requirements can be identified at two levels

1. The system implementation level. The collection of software modules that implement the DOS execute as processes on various DOS hosts. These processes must interact to implement the DOS. These interactions are supported by the interprocess communication facility
2. The user application level Some of the application programs that execute in the DOS environment may be structured as distributed programs A distributed program is one whose components may run as cooperating processes on different hosts The components of such a distributed application program will need to communicate

The IPC facilities that are available at the application level will be built upon the system level IPC facility.

The DOS interprocess communication facility will be based on the following principles

- The IPC mechanism will support a variety of communication modes including datagrams and connections (i.e., reliable sequenced, flow controlled data streams)
- It will be built upon the standard DoD IP (internet), and

TCP (transmission control) protocols This assumes that the implementations of the DoD protocols that are used will provide adequate performance (low delay, high throughput) If they do not, it may be necessary to build the IPC directly on the local network (Ethernet) protocol

- Interhost and intrahost communication will be treated in a uniform fashion at the interface to the IPC facility That is, the same IPC operations used for communicating with processes on different hosts will be used for communicating with ones on the same host Of course, to achieve the efficiencies that are possible for local communication the IPC implementation will treat interhost communication differently from local communication

- The IPC facility provides addressing by means of unique id Processes, having UID s are directly addressable through the IPC

- The IPC facility will support "generic" addressing This will permit processes to specify interactions with other processes in functional terms

- The IPC mechanism will provide means to directly utilize some of the capabilities of the local network For example, the Ethernet supports efficient broadcast and multicast The IPC will provide relatively direct access to these capabilities by supporting broadcast and multicast addressing To achieve the design goal of component substitution it is important for the DOS system to be as independent as possible of the specific characteristics of the particular local network chosen for the ADM Therefore, care must be taken to avoid building dependencies on the particular ADM network technology into lower level DOS mechanisms, such as the IPC In our opinion, this is not an issue in the case of the broadcast and multicast facilities, since many state-of-the-art local network technologies support similar capabilities

3.8 User Interface

The purpose of a user interface to the DOS is to provide human users with uniform, convenient access to the functions and

services performed by the DOS resources.

The user interface is software that acts to accept input from a human user which it interprets as commands to perform various tasks and to direct output to the user which the user interprets as the results of commands previously requested or as unsolicited information from the system (or possibly other users). As discussed in Section 3.2, it is sometimes useful to think of the user interface functions as being provided by access point agent and user agent processes.

"Uniform" and "convenient" are subjective characteristics which are hard to quantify. However, we can say in general terms what we mean by these characteristics in the context of a DOS user interface. By uniform, we mean that the manner in which a user requests access to various functions and resources should be similar regardless of the particular DOS components that implement them. For example, the way a user instructs the DOS to run a program should be the same (except for the name of the program) regardless of where within the DOS parts of the program will execute. By convenient, we mean that a user should not have to pay undue attention to the details of the mechanics of establishing access to DOS functions and resources. For example, in order to run an interactive program, a user should not have to explicitly establish a communication path with the host that will

run the program. Similarly, to delete a file a user should not have to explicitly establish communication with a file manager on the host that stores the file and instruct it to delete the file.

To be uniform and convenient does not mean that a user interface must make the network or the distribution of the system invisible to users. In many situations users may want the distribution to be transparent, and the user interface should operate in a way that provides transparency. However, there will be situations where it will be important for the distribution to be visible to users, and for users to be able to exert control over how the system deals with aspects of the distribution. For example, to use the system to do their jobs, system operators and maintainers will need to deal relatively directly with the system's distributed nature. Furthermore, "normal" users, from time to time, may want to control where programs run or files are stored.

One of the ways the DOS will differ from most conventional single host operating systems is that truly parallel execution of user tasks will be possible. It will be important that a user interface for the DOS provide means to initiate, monitor and control multiple concurrent tasks.

The development of DOS user interface functions will be based on the following principles, many of which are particularly

well suited to interactive command and control environments

- Since many user requests cannot be performed directly by the user interface, the user interface acts on the user's behalf to initiate activity by other DOS modules. The nature of the interactions with other DOS modules is governed by internal DOS "protocols" and interface conventions, and is accomplished by means of interprocess communication.

- An important type of activity a user can initiate is the execution of a program. In this case, the user interface acts to initiate execution of the program and to establish a communication path between the user and the program. In addition, means are provided to permit a user to switch his attention back and forth between the executing program and the user interface.

- The user interface will enable a user to initiate and control multiple simultaneous tasks. In particular, a user may have several application programs executing concurrently.

- Although the user interface bears a unique relationship to the rest of the DOS system, the underlying DOS system will be organized so that much, if not all, of the user interface functions can be written as application level software.

- There will be a variety of user interfaces available over the lifetime of the DOS. The earliest ones will be modified versions of existing COS user interfaces, with the later ones custom designed for the DOS and or its particular applications.

3.9 Input / Output

The term "input/output" is used here in a rather limited sense to mean the process of getting data into and out of the DOS cluster. The objective of the DOS in this area is to provide

flexible and convenient means for users and application programs to make use of devices such as printers, tape drives, etc

To support i/o adequately in its distributed environment the DOS should provide

1. The ability to refer to devices symbolically. For example, users should be able to obtain listings of files by means of "print" or "list" commands which explicitly or implicitly refer to a printer symbolically. Similarly, programs should be able to direct output to a printer by referring to it symbolically

2. The ability to distinguish among and to refer to physical devices. In moderate and large configurations there will be more than one printer (or tape drive, etc) These devices are likely to be located in different areas. It is critically important that the tape drive from which a program reads is the one that holds the right tape. Similarly, when a user requests a listing it is important for him to be able to control which printer will print it so that the output is near his office rather than 1/2 mile away. Thus, one user's "printer" will not necessarily be the same as another's. Furthermore, when a user accesses the DOS from a different location then normal, he should be able to rebind his "printer" to one of the printers that are near him

The object paradigm developed above, which involves objects, object managers, and object access protocols, is almost sufficient to support DOS device i/o. In addition, the system will provide means for a user to "bind" a particular symbolic device name to a particular physical device.

In summary, DOS support for i/o will be built upon the following principles

- Input/output devices will be treated as DOS objects As such, they will have unique ids and may have symbolic names

- Access to devices will be supported in the same way access to other DOS objects is supported Access will be accomplished by interacting with an object (device) manager in accordance with an appropriate object (device) access protocols The interactions will be supported by means of interprocess communication.

- The notion of device binding will be supported by means of the DOS catalog This will permit users to bind symbolic names to particular physical devices

- Some types of i o operations when suitably abstracted are meaningful for files and for devices Sequential i o is a good example File-like interfaces for device i o have been shown to be useful in a number of systems The DOS will support file-like interfaces for certain i o devices.

3 10 System Monitoring and Control

The purpose of the DOS system monitoring and control functions is to provide a basis for system operations personnel to operate and control the system.

The system monitoring and control functions will be built upon the following notions.

- Two types of information will be gathered system status information, and information about the occurrence of exceptional events. Status information will be collected on a periodic basis as a normal part of system operation Information about exceptional events will be collected as the events are detected.

- Status information and information about exceptional events will be routed to an on-line display which system

operations personnel can monitor

- The detection of certain exceptional events will trigger an "alerting" mechanism to call the events to the attention of operations personnel

- It will be possible to (selectively) log the occurrence of exceptional events in a event log data base

- The DOS will support a system control protocol which will make it possible for operations personnel to control the system operation from a single point (e.g., operator's console) as a DOS user. This protocol will provide means to reinitialize the system ("warm" restart), to halt the system, and to set parameters within various DOS components which control aspects of the DOS operation

- The status gathering facilities will be flexible and comprehensive enough to support performance monitoring experiments

- The monitoring and control system will be easily extensible to new resources added to the system over its lifetime

4 System Integrity and Survivability

Users of modern day computing facilities have come to expect the integrity of their computing system and the data it stores and manipulates for them despite occasional system component failures The command and control environment in particular requires the continuous availability of key applications despite these failures To the extent that applications and access to applications come to depend on DOS system functions to achieve goals of system uniformity those functions must be reliable and continuously available Further, the role of the DOS as the common software base extending throughout the cluster makes it a convenient and cost-effective place (from a programming standpoint) to support generalized, system wide mechanisms for building survivable applications

By availability we mean the fraction of scheduled up-time during which a system is in fact able to deliver normal services to its users Continuous availability then refers to the ability of the system to supply services without pause over some relatively long period of time The period is sufficiently long to present a significant chance of component failure Thus a system design which achieves continuous availability must employ some elements of fault-tolerant system design By integrity we mean the operation of the system in accordance with

its specifications while it is available, despite failures from time to time which may render the system temporarily unavailable. Maintaining system integrity is basically a matter of maintaining the consistency of system and user state information ("stored data") The term survivability is virtually synonymous with "continuous availability", although the emphasis is perhaps different. "survivability" suggesting the possibility of violent failure modes

A goal of high (but not continuous) availability implies attention to mechanisms for orderly system restarts, that will preserve system integrity across system outages The restart process may be partially manual, and may involve relatively lengthy integrity checks and system reconfiguration procedures (e.g., replacing a disk pack, restoring files from backup tapes). Continuous availability, in our terminology, refers to the ability of the system to automatically reconfigure itself or to retry failed operations, in order to maintain the normal semantics of a given function in spite of failures In a continuously available (i.e., survivable) system, a failure manifests itself only as a tolerable performance degradation and/or insignificant loss of data or function

Our distinction between high and continuous availability can be illustrated by the following examples Operator invoked

reversal to a backup copy of a damaged file would constitute a recovery measure suitable for a goal of high availability. In contrast, designing a function (e g authentication service) so that the system can automatically detect a host failure and subsequently route requests to an alternate source of the function would be a mechanism for continuous availability. In either case, the integrity of the system must be maintained whenever system services are available.

At a minimum, key system functions and applications must be highly available, and in many cases also continuously available. Ideally, all system services would be continuously available in the command and control environment. However, cost and performance criteria may dictate that high availability is acceptable for some functions, especially if the expected failure rate is low. Functions such as authentication, initiation of user sessions, and access control must be continuously available for the system to operate at all. Other functions (e.g., access to selected application data) may satisfactorily be provided on a highly available basis, whereas still other functions (e g., data collection for experimentation) need not be provided at all unless all system resources are operating normally.

All three aspects, integrity, high availability, and continuous availability, play important roles in the overall

effectiveness of the system for command and control environments, and will be collectively referred to as system reliability.

4.1 Reliability Objectives

The reliability objective of an automated command and control cluster is to provide reliable command and control applications. The role of the 'system' with respect to the reliability of these applications is threefold:

- Ensure the 'correct' operation of the system in the presence of expected patterns of component failure and subsequent restorations of service. Included in this is that the system does not, under a broad range of failures, lose or corrupt data that is essential to either its own 'correct' behavior or to the 'correct' behavior of its supported applications.
- Provide key DOS system functions and access to those functions in a manner which can survive a limited set of system failures, and which is designed to support high availability.
- Provide DOS based mechanisms accessible at the user programming interface which are useful for constructing reliable applications.

4.2 General Approach

Failure handling in the DOS is based on first identifying the set of failure modes over which the system is expected to maintain integrity and be continuously available. Our approach

to system survivability is through making each of the system components themselves survivable The idea is that a collection of survivable subsystems will lead to survivable systems with the decomposition making the problem more manageable and promoting tailored solutions in different parts of the system The definition of each major DOS system function includes the integrity and survivability characteristics to be supported should the expected failures occur Based on the reliability properties of the specific system functions other functions using them can then be built which are immune to the outages handled by the abstract function

The integrity and consistency of system functions are derived from the careful ordering and synchronization of the parts of the individual and parallel operations and the grouping of related parts into atomic operations that have coordinated outcomes DOS functional survivability always derives from redundancy of one form or another either in processing elements and executable programs or in data or in time (operation retries) Making the data accepted for storage by the system resilient to component and storage media failures in the sense that data is not lost despite these failures is one special case of the general redundancy concept

The DOS architecture calls for hardware redundancy to

support all survivable functions The approach is to at minimum provide a homogeneous processing base for any particular survivable function, as a means of simplifying the issues of fidelity and coordination between the redundant elements In many cases, by building software which is portable across a variety of host architectures and systems, we can even use a heterogeneous processing base to achieve needed redundancy The role of the DOS software is to support the replication of critical code and data, to control the detection of failures and to induce recovery procedures In some cases multiple redundant servers will be supported to share the processing load in the absence of failures, as well as to provide continued service during failures In other cases restart from a prior consistent checkpointed state represents a powerful base on which to build

4 3 Specific Approach

We expect the key functions of the the DOS to be able to recover from the following types of failures

- Single host outage at arbitrary time without loss of non-volatile memory This comes in two forms transient, in which the host is restarted within minutes, and long term (hours at minimum) during which the host is effectively no longer available Transient failures of this sort are expected frequently (a few times per day for large configurations) while long term failure is relatively infrequent (a few times per month)

- Single host outage at arbitrary time with additional loss of long term non-volatile memory (e g disk crash) These failures are always long term and occur infrequently (a few times per year)

- Operator controlled forced host shutdown with ample warning for proper shutdown preparation (e.g. down for emergency or preventive maintenance) This occurs relatively frequently (a few times per week)

- Transient pair wise communication failures This is predominantly a temporary failure with the expectation that subsequent retries over a sufficiently long interval will succeed This condition frequently occurs due to temporary congestion random noise hardware and software interfaces not designed for worst case timing conditions etc

- Single host temporarily loses communication with the rest of the system but continues to operate This is the long term version of the pair wise transient communication failure pattern across all pairs for this host It occurs relatively infrequently and can be the result of a malfunctioning network interface This single host isolation represents the most likely pattern of network partitioning which is anticipated using a single local communication bus architecture As we expand the communication architecture to include multiple local networks and inter-cluster activity we expand and make more complex the likely failure patterns

- Any failures that can be made to look like one of the above

In general, handling failures involves techniques for failure detection, reconstitution of remaining components into a working system, and subsequent reintegration of temporarily failed components back into the operational system after they are repaired The techniques selected to detect and recover from these failures will vary depending on the expected duration and relative frequency of the failure Mechanisms selected to handle

infrequent events can usually be of limited performance and include manual procedures Mechanisms for frequently occurring events must also take into account the performance characteristics of the solutions adopted

The following techniques have been well studied and are suitable for supporting various aspects of system reliability in the DOS <1>

- Redundancy of program file and processing elements as sources of alternate site service
- Atomic operations and isolation of partial results to ensure the consistency of function and data
- Stable storage and guaranteed permanence of effect to ensure that data and decisions once accepted by the system will not be lost
- Checkpoint and restart to support backward error recovery
- Timeouts to recognize failure conditions and initiate recovery activities
- Status probes and status reporting to ensure current operability

In addition, the GCE concept of interchangeable parts is viewed as a manual approach toward easily reconfiguring components for continued support of important system functions by using parts from less important functions utilizing a common hardware base It also serves to reduce the inventory of spare parts necessary

<1> "Distributed Operating System Design Study Final Report" BBN Report No 4671, May 1981

to achieve a satisfactory level of backup reliability

The following problems are not being addressed during the current effort except as a secondary consideration.

- Complete, extended communication outage within cluster
- Arbitrary and general partitioning within the local cluster.
- Loss of global (internetwork) communication services

Handling these problems may be important to the command and control environment. However, we believe that addressing their solution remains for future consideration.

5 Scalability

The objective in this area is a system architecture and design that is cost-effectively scalable over user population sizes ranging from small configurations (e.g., tens of users) to large configurations (e.g., hundreds of users). The aim is to attain uniform functional and performance characteristics over reasonably scaled versions of the system by adding additional hardware and software capacity without introducing excessive escalation of per user cost and performance or requiring redesign of the system structure.

5.1 General Approach

The scalability of a computer system is dependent on many capacity and performance factors ranging from hardware component interconnect structures to high level software resources fabricated through systems programming. Due to the off-the-shelf nature of many of the primitive system components being used and the generalized nature of the eventual applications, efforts to achieve system scalability must necessarily be focussed on the scalability of the system functions supported by the DOS.

In general, system scalability and support for system growth can be somewhat different things. Scalability is often

achievable by procuring "larger" units for larger configurations, whereas growth is often associated with "additional" units over a period of time. Clearly, addressing the growth issues can, in many ways, subsume the scalability issues. One of the major attractions of a distributed architecture is that it can potentially support growth beyond the limits of conventional systems and hence can attack large scale system scalability from a growth standpoint. Additionally we believe it is operationally and logistically more attractive to support scalability needs from an incremental growth viewpoint in order to limit the number of distinct parts and limit the effects of losing a single unit.

Our system concept for meeting scalability objectives relies on five main points supporting system growth:

1. Adoption of an inexpensive communication architecture which makes it simple to include additional processing elements.

2. Selection of modular, inexpensive DOS hardware so that DOS processing elements can be added in small increments as needed without grossly impacting total cost of the system.

3. Careful attention to the potential size estimates for a maximum configuration to ensure that software structures can be made large enough (e.g., address fields) and that, where appropriate, their implementation is partitionable across multiple instances of the function which share the processing and data load.

4. Avoidance of so-called N squared solutions which require each element to interact with every other element. While these approaches are usually acceptable for smaller configurations, they often break down for larger ones.

5 Select application systems for inclusion in the demonstration configuration which themselves scale through a range of sizes

5.2 Specific Approach

The selection of a bus communication architecture and Ethernet in particular is in large measure based on providing a simple underlying basis for system scalability The bus architecture provides a simplified means for supporting a hardware base in which every processing unit can a priori communicate equally well with every other processing unit without regard for routing processor placement and other such issues In addition Ethernet can physically support large numbers of processing units which can be added regularly or removed and can also inexpensively support small configurations An important non-goal at this stage of the project is the scalability of the network communication medium itself Future work in this area could be based on adding an additional Ethernet link to each processing element (also a reliability measure) or on complete network substitution

Low cost incremental expansion also motivates the selection of the M68000-based GCE, which will be used as a building block for many DOS functions As with other multiprogrammed hosts, a GCE can multiplex a number of DOS functional elements when used

in small configurations, and make use of dedicated function units optimized and configured for the specific function in larger or higher performance configurations The ability to scale up or down also played a role in selecting application hosts for the initial demonstration environment Both the UNIX and VMS subsystems are supported on a range of hardware bases both larger and smaller than those for the current configuration The current testbed configuration includes a number of different UNIX systems of varying size and capacity

Supporting system software scalability implies ensuring adequate or adequately expandable address fields table sizes etc to meet anticipated needs of target configuration sizes It also implies including growth as a factor during the design of the implementation of DOS system functions There are two distinct aspects of a distributed implementation of a given function One aspect is concerned with redundancy as described in the previous section The other is concerned with partitioning and load sharing of responsibility for a function to provide support for a larger client base It is generally easier to build a self-contained implementation of a function than it is to develop a partitioned implementation since there are fewer error recovery considerations and fewer resource management considerations However to meet our scalability objectives, some functions may require a partitioned design for supporting

large configurations, although they may also be run unpartitioned during initial development and for small configurations. The analysis of the need for a partitioned implementation will be done over the system lifetime as functions are designed, on a function by function basis. In many areas we expect the functional units to be self-reconfiguring, automatically using whatever resources are currently available. However, some forms of system expansion will occur infrequently enough to allow inclusion of off-line manual approaches to some scalability problems.

6 Global Resource Management

In many computing environments and most especially a command and control environment the administering organization needs some degree of control over the ways in which system resources are allocated to tasks to meet their processing demands This control is frequently provided by the ability to designate some tasks as more important than other competing tasks and in the ability to effect automated resource management decisions in an attempt to improve some measure of system performance These functions are often referred to as 'priority service' and 'performance tuning' respectively Most computer systems provide some facilities in these areas and many provide rather elaborate facilities which more than adequately address command and control needs within a single processing node The goal in this area is to provide support for sustaining these elements of system control in areas that transcend a single processing node

6.1 Objective

The objective in the area of global resource management is to augment the resource management facilities already present on individual systems with simple additional mechanisms for supporting various policies of administrative control of

automated distributed resource management decisions The emphasis is on methods for ensuring the prompt completion of important processing tasks and on the distribution of processing load across redundant resources

6.2 General Approach

Global resource management in a communications oriented environment is an area where the system wide ramifications of employing such techniques are not completely known The focus of our effort is on those aspects of global system control directly related to the distributed nature of the processing environment In particular, the DOS will focus on the coordination of the priority handling of all parts of any single distributed computation and on the selection procedures for choosing among replicated redundant resources present in the DOS cluster DOS global resource management control will be applied initially on large grain decisions (e g initiation of a session opening a file initiating a program) in an effort to simplify the system and limit the communication and processing overhead that would be required for finer-grained global decision making We do not anticipate the necessity for reevaluating these resource

management decisions at finer grains as a potential source of further optimization. The system concept is that adequate administrative control will be achievable by controlling the set of tasks which may be competing for resources (load limitation), and by controlling the pattern of use of specific instances of the resource which they will be competing for. This is to be accomplished by providing means for administratively limiting the offered load and influencing both the resource selection procedures (where a selection is possible) and the sequencing of the use of the resource after selection using priority. The insertion of DOS control points for limiting load, effecting global binding decisions, and controlling order of service are a sufficient set to carry out administrative policy.

6.3 Specific Approach

The DOS system model is based on active user agents (processes) which access a wide variety of abstract resource types, some of which are directly associated with physical resources (e.g., a VAX processor), and others of which may have distributed implementations built out of composite non-distributed objects. All of the resource types have some form of type dependent resource management software associated with them. The following three points are important to our global resource

management concepts.

1. Every resource request has a "priority" attribute associated with it which is derived from the initiating agent. Although the resource management discipline will be different for different types of objects, the intent of the priority attribute is to provide an object type dependent form of preferential access relative to the use of the resource. Users could have a range of administratively set priorities available for their use. The current priority of a request initiator will determine how the task competes with other active tasks. Low priority tasks could be suspended or prevented from generating any additional resource requests if the offered load on system resources rises too high.

2. Automated DOS global resource management decisions will be made predominantly when an agent accesses an object which has multiple instances (e.g., multiple processors able to execute the same code, multiple instances of a file, etc.). The algorithms for making the selection will be controllable by the manager of the object. System operators will be able to set policy parameters which control the mechanisms which managers use to distribute their processing load. Algorithms for load distribution could make use of object attributes, recent load conditions, previous selection, first to respond to broadcast, etc.

3. We are assuming adequate network transmission capacity when smoothed over reasonably short time frames (i.e., no continual network overload). This assumption, which seems to be substantiated by early available local network operational experience (albeit not in a command and control environment) makes resource management of the network bandwidth generally unnecessary at this time. If scaled load projections indicate potential long term overload situations, our approach for the Ethernet will be to attempt to develop techniques for detecting and limiting the effects of this situation. While to date it has been unnecessary to develop such techniques, a promising approach might be to attempt to establish a dynamic network transmission priority level, forcing temporary deferral of data transfers below this priority level, and providing a means for raising the current level until the overload subsides.

Using these mechanisms, controlling the processing activities of the DOS cluster becomes a policy issue of selecting appropriate priorities and parameters to maximize the ability of the system to meet specific information processing objectives

7 Substitutability of System Components

Over the course of time and especially when deployed in non-laboratory operating environments, we anticipate the need to substitute alternative hardware and operating system components which are more appropriate for their environment than those selected for the initial ADM configuration. It is desirable to be able to alter components in order to match the system characteristics to the needs of operational environments and also to reflect system evolution, including changing availability and cost-effectiveness of components. The ability to perform appropriate substitutions of components in the DOS system is expected to expand the applicability of the DOS system and to lengthen its useful lifetime.

7.1 Objective

The objective in this area is to design the system so as to maximize the potential for component substitution in the system architecture at a later time. System components which are candidates for substitution are the local area network, the GCE configurations, the application hosts and operating systems, and the gateway. In addition, major software components (e.g., standard network protocol implementations like TCP) must be

easily replaceable without altering the overall system structure should they prove deficient or if better protocols evolve Easily replaceable system components is a goal that is carried up all the way to the eventual application which populate the DOS

7 2 Approach Use of Abstract Interfaces

The intent of component substitution is to replace a functioning unit with another one capable of performing basically similar operations but with other properties which make it more attractive or appropriate than the original For example substituting a fiber optic communication network for a coaxial cable network might make sense for a command and control environment concerned with portability or electromagnetic radiation While the basic communication properties of the two systems are equivalent as far as the DOS is concerned environmental considerations might motivate the substitution Similarly most computer systems can be made to perform a wide range of tasks However some are judged better than others for certain applications and hence would motivate the selection of different application hosts to suit the needs of particular command and control applications In the software area particular algorithms or approaches selected during system design

are likely to prove deficient and will need replacement, based on actual use with a minimum disruption

Our approach for supporting component substitutability is to define and use appropriate abstractions of the substitutable components as the entity incorporated into the DOS. The abstract interfaces are based on common properties of a class of interchangeable components not on specific capabilities of a single component Except under special circumstances, unique properties and peculiarities of the hardware selected for the ADM will be avoided in the definition of abstract interfaces and where used will be isolated in the code supporting the abstraction to facilitate emulations within other components

Two additional implications fall out of this policy We must expect to lose some efficiency of implementation, since we may need to avoid features that have been built into some components explicitly to solve problems which we may encounter We expect this effect to be small The second side effect of the abstract interface should be increased productivity during the development of the DOS, since an abstract interface is easier to understand and work with This is in effect, the argument used for higher-level programming languages and standards of all kinds The adoption of standards of various kinds, as mentioned earlier, also enhances component substitutability by providing

abstractions which are already incorporated into many product interfaces

The attractiveness of using abstract interfaces extends to the design and decomposition of both the DOS and its applications The Cronus system concept is oriented toward convenient replacement and evolution of the components managing the abstract objects which the system maintains

7 3 Approach Specific Interface Plans

This section presents a number of standard interfaces which we plan to employ While this list is not exhaustive we believe it captures the major interfaces on which the success of hardware substitutability will most depend

The initial version of the DOS is using the Ethernet standard as a communication subsystem We expect to be able to switch between optical fiber and coaxial cable implementations of the Ethernet as may prove desirable based on a cost and availability basis More importantly our abstract network interface will avoid using features of the Ethernet protocol which are not common to local network technology We expect to use only packet transfer, broadcast, and possibly multicast in developing the network abstraction In addition, we expect to

use IP datagram service as the lowest level IPC abstraction This enhances our independence of the underlying network, and makes it easier to later substitute alternate communication subsystems which can support the abstraction such as the Flexible Intraconnect There has been recent validation of this aspect of substitutability when Cronus was easily transported to a pronet ring local area network system

The GCE s represent the implementation base for a number of important DOS functions It is therefore critical that we address the issue of substitutability for the GCE s GCE substitution has two aspects one is the ability to substitute another machine for the present GCE the second is the ability to substitute for parts of the GCE

We plan to address the first problem the ability to switch GCE s at some future date by programming in common high level languages to the greatest extent possible We are focussing on two languages C and Ada C is a language developed as part of the UNIX system with the goal of being portable to a variety of machines It has largely met that goal although it requires careful attention to coding style to assure the portability of programs written in C <1> However there is the possibility of

<1> The choice of C was dictated by its immediate availability and the software support already available for C on the GCE processor, a Motorola 68000 The portability goal has been amply demonstrated during the initial phases of system construction in

a better choice. Ada. being available in the future Since Ada is a DOD standard language its availability on a variety of processors relevant to command and control environments is assured To date there has been no development using Ada. since support for this language has been slow to migrate into operational environments

Substitutability within the GCE is also a matter of concern and attention We are building the GCE strictly out of off-the-shelf components using published and emerging standards to minimize our commitment to any particular part of the GCE For instance. the GCE uses a Multibus bus and backplane. which is supplied by a variety of vendors in a wide range of capacities The processor board is currently a design developed by Stanford and licensed to at least four manufacturers who are producing compatible boards Revisions of this board form the basis for the SUN Workstation product line With only software changes the type of processor board can easily be changed since there are probably more different processor boards available for the Multibus than for any other computer bus The use of the Multibus also assures easy substitution of memory. Ethernet Controller. device interface components etc and increases the

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having a single source copy of most Cronus system components which can be compiled and run for any of the VAX (UNIX or VMS). M68000 (UNIX. GCE. SUN Workstation). or C/70 (UNIX) architectures

likelihood of meeting as yet unidentified needs for hardware interfacing with off-the-shelf components, due to the popularity of the bus

Our ability to do general substitutions for application hosts is based on our attempts to use portable languages, a network (Ethernet) which will soon have interfaces available for a wide range of computer systems, and the concept of a DOS access machine. Use of portable languages in the DOS means that we will be able to move software from one DOS host to another. The use of an access machine as a means of connecting an application host to the DOS is intended specifically to minimize the effort of host substitution by maximizing the retained software in the access machine GCE. Precisely which DOS functions can be handled within the access machine GCE without incurring a similarly complex interaction with the host is yet to be determined.

Finally, a most likely substitution to be made during the course of our effort is a substitute for the ARPANET gateway. We have adopted the use of an LSI-11 as the gateway to be able to use standard, off-the-shelf ARPA internet gateways. A successor to the LSI-11 gateway is being developed as part of another BBN project. One aspect of our attempt to keep in step with Internet community activities is an anticipated changeover to a new gateway when it becomes appropriate to do so.

8 Operation and Maintenance

It is desirable for the design of any computer system to facilitate the operation and maintenance of the system In our opinion this is one of the areas that has not yet received adequate attention predominately because few extensively distributed systems have reached operational status Distributed systems and especially systems incorporating many heterogeneous parts are far more complex than their centralized homogeneous counterparts Routine chores such as adding new components to the configuration coordinating new releases of system software detecting malfunctions and measuring current system performances become much more complex in a distributed system environment The natural tendency to handle each component separately has shortcomings in the effort required and the sophistication needed to correctly complete simple monitoring and maintenance activities The reason for citing operation and maintenance as a goal is our belief that the success of the distributed system concept in Air Force command and control environments will to some extent be dependent on the management of the routine housekeeping and tuning chores associated with any computer system

The objective in this area is to simplify the operation and maintenance procedures for the system so that these tasks are

manageable by personnel other than system programmers Simplified procedures do not necessarily mean automated procedures (although many such functions, including those mentioned earlier while discussing system control and monitoring will be automated), nor will they necessarily be as simple as in current computer systems (the environment is quite a bit more complex)

At this time our approach to operations and maintenance issues includes the following elements

- The monitoring and control functions designated as part of the system coherence objective address a number of automated operations issues and serve as a base of operations support
- The DOS will provide a number of other mechanisms (e g distributed file system software tools) which can serve as a useful foundation for developing simplified maintenance and operations procedures throughout the system
- As part of the test and evaluation phase, we will operate and maintain the system and are ourselves self-motivated toward simplified operating procedures

9 Test and Evaluation

One of the important aspects of introducing new system concepts or approaches is the need to answer the question of how successful they have been in meeting their objectives The test and evaluation aspects of our project are intended to provide these answers Test and evaluation needs to be more than an after-the-fact activity and can be a positive factor in driving the design and the implementation Our general approach to system test and evaluation is to use system components and the system as parts of the implementation become available Parts of the system architecture are hierarchial (especially the communication aspects) and we are using (and evaluating) these parts immediately in the implementation of high levels Much of the system design is formulated by employing a basic system model to various functions the system provides This provides both immediate validation of the concepts involved and actual use of the software supporting those concepts on multiple machine architectures We have experienced and expect the continued need for reimplementation of selected components which prove to be either functionally or performance limited based on early use Our approach of intermixing design and implementation allow these components to be more easily pinpointed and corrected earlier in the development cycle.

We are also focusing initial end user emphasis on the system developers using the system in the normal course of their work. In this way, the feedback path from user to developer is minimized. Design decisions which cause great difficulties will be rapidly exposed and revised. The system developers are also likely to be more tolerant than other users of small "rough edges" which means that they can begin to use the system earlier, before it is completely finished. A consequence of this is that the initial services integrated and developed for the system are oriented toward the needs of the system developers. In many cases (e.g., program maintenance) these services have utility in other environments. In those cases where utility is limited to system developers, they do form the foundation of supporting the enhancement of the DOS system through it own facilities.

The system developers are further testing the system design through the implementation of some system services, such as file archiving and other commands as client level programs. The implementation of these services tests the ability of the DOS to support such system functions without further modifications of the software within the DOS.

The experiences of the system developers, however, are no substitute for those of application programmers. Application

programmers can be expected to make demands upon the completeness and accuracy of the documentation, for example, and to exercise the system in ways that were not anticipated, or not often used, by the developers. Because application programmers will lack in-depth knowledge of the DOS implementation strategies, their reactions will be an important test of the user-level conceptual models defined in the user manuals. Due to limited time and effort, only small-scale examples can be constructed exclusively for system evaluation purposes.

SUPPLEMENTARY

INFORMATION

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