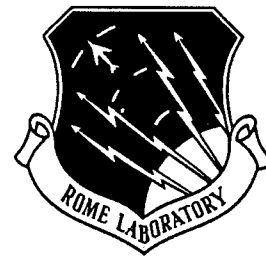


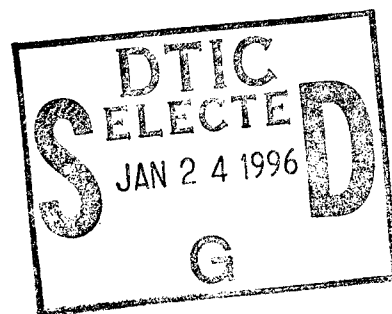
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PARALLEL SOFTWARE ENGINEERING TECHNOLOGY FORECAST, Blue Ribbon Panel Conclusions

RCI, Ltd.

Carl Murphy



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C³I Parallel Software Engineering Technology Forecast

Blue Ribbon Forecast Panel Conclusions

1. PREFACE

Rome Laboratory developed this technology forecast to identify the parallel software engineering technology required to meet Air Force mission-critical needs in High Performance Computing (HPC) environments over the next decade. The forecast concentrates on the quality and cost issues of the software development process for Command, Control and Communications applications (C³I) as well as performance. The "Parallel Software Technology Forecast" addresses three goals:

- 1) Anticipate technology directions of the parallel computer industry and forecast parallel software technology capabilities, ie, current trends in software technology related to emerging trends in HPC.
- 2) Identify key C³I factors in the Air Force mission and show what the implications of HPC are on the ability of the Air Force to develop C³I application software productively and efficiently.
- 3) Compare and contrast Air Force needs for parallel software technology to the commercial sector and identify opportunities effective bi-directional technology transfer.

The technology forecast involved five stages:

- 1) Rome Laboratory produced a summary version of its "Parallel Software Engineering Technology Assessment" report.
- 2) Rome Laboratory assembled a distinguished Blue Ribbon Panel consisting of technical experts from industry and academia. The Panel included: Dr Walter Beam (noted author on C³I and system engineering), Mr C. Gordon Bell, (Chairman, University Video Communications), Prof. Tom Cheatham (Harvard University), Dr George Lindamood (Director of Information Services for the State of Washington), and Dr Jeffrey Mohr (Chief Scientist, Information Technology Solutions).
- 3) Rome Laboratory announced a Technology Forecast Forum to solicit position papers. A broad range of *position makers* from academia, government and industry responded. Twenty positions were selected for review by the Blue Ribbon Panel as representative of the state of the art. In addition, Panel Members also provided position statements.
- 4) Rome Laboratory sponsored an invitation-only, Blue Ribbon Technology Forecast meeting at the Orlando Hyatt on January 23-26, 1995. Panel members and position makers interacted to produce the technology forecast. Presentations of each participant's view were followed by separate sessions on C³I, commercial off the shelf, and parallel technology impacts. The group then collaborated on notes that represent the combined trends, vision and strategy for C³I parallel software engineering.
- 5) After the interaction, this author set down the conclusions of the panel and distributed it for confirmation by the Panel Members. "Volume I: C³I Parallel Software Engineering Technology Forecast -- Conclusions" is the result. Volume II provides an assessment, analysis and confirmation of the Blue Ribbon Panel's conclusions. The title of Volume II is "C³I Parallel Software Engineering Technology Forecast -- Assessment, Trends, Vision and Strategy." The Volume II Appendices provide an assessment of the technology prepared by Rome Laboratory and brief summaries of the position maker's papers and presentations.

2. EXECUTIVE SUMMARY

Parallel software engineering can fulfill important roles in C³I systems. Using it, software engineers can overcome the time delay shortfalls of sequential computing. They can provide the C³I designs that assure delivery of required mission function in a timely fashion. In spite of few examples, the panel believes that parallel software engineers can solve the difficult and complex applications typical of C³I systems. A parallel capability allows designers to invent advanced warfighter information system applications. However, parallel software engineers need a better process and tool foundation to cost-effectively gain these capabilities. The panel members defined the trends, vision and strategy to define the process. (Note that the panel limited its discussion by excluding signal and image processing, believing that using parallel computers for such structured applications is a relatively well understood process.)

Throughout this report the following C³I Parallel Software Engineering terms apply:

Mission Function or *Tough Character Applications* -- these combine a mix of high complexity, unstructured (state and data dependent) paths, high dynamic resource fluctuation and frequent synchronization characteristics found in C³I environments. They are the most challenging computer projects.

Assured Delivery or *High-Integrity-Value* -- these factors are fault tolerance, availability, graceful degradation, security, reliability, survivability, repairability, usability, twenty-four-hour, seven-day operation time frame and the many other factors that are required for the mission in battle environments.

Mission Performance and *High-Time-Value* -- C³I applications operate where time responses are critical to mission success. Time is the essence of C³I systems. High-Time-Value can range from hard real-time to use of short time goals that might allow on-line plan changes during battle to increase mission effectiveness.

Parallel Software Engineering -- C³I systems must be engineered and are typically built by large groups. C³I parallel software engineering is the collection of processes and methods used to achieve predictable performance, programmability, portability, maintainability, adaptability and low life cycle costs.

2.1 PANEL CONCLUSIONS

The panel set some clear directions toward parallel software engineering processes and infrastructure. The issues of high-time-value, tough character applications and C³I mission factors express the challenges of parallel software engineering. All must be delivered at once, along with performance prediction at system definition, design and implementation layers.

The panel set the architectural target as a mix of high bandwidth capability distributed nodes and low latency multiprocessors. This means that parallel software engineering tools can separately address applications suitable for message passing, applications requiring low latency, and the tools needed to interface and control the interaction between them. Research should focus on performance prediction and effectiveness and use of parallel software engineering as a tool to achieve C³I mission factors while meeting mission time response needs.

The panel also laid out parallel software engineering goals that affect the way C³I systems would be engineered. The justification decision boundary between choices of commodity priced COTS, modular board level COTS, and military-unique approaches should be investigated and understood. Incremental building methods should allow incremental build and test methods. Probes and information gathering methods are indicated to take advantage of the "daily" exercised and evaluated C³I system. Engineering refinement layers are needed to facilitate change and new mission needs.

To meet these goals, parallel software engineering researchers will have to define new relationships with COTS computer vendors and integrators to determine the boundary of COTS suitability. We will also have to build relationships with COTS system vendors to establish testbed demonstrations. Also, different relationships are needed with operating C³I organizations to frequently communicate requirements, operations, test results and effectiveness. Meeting these new challenges requires merging parallel software engineering research to meet a wider range of commercial and military needs.

2.2 ASSESSMENT

C³I software engineering encounters the most difficult development problems known in computing. Mission constraints preclude use of over-specialized research computers and software methods.

Today's parallel technology performs well for well-structured, high-throughput applications. Those machines concentrate on throughput and structured applications, instead of general parallel computing, making system building and life-cycle support expensive and risky. This is because C³I applications are complex, dynamic, and closely coupled to other applications. They are also constrained by stringent time response and mission integrity factors. As a result, our parallel technology provides an inadequate foundation for software engineering of complex and dynamic portions of C³I systems.

Because of this specialization, applications do not scale. Hardware and operating software do not give the assured delivery (high-integrity-value) and fast time response (high-time-value) required in C³I missions. The C³I industry needs a more general purpose parallel capability that can be programmed for fast time response and assured delivery while executing complex and dynamic mission requirements.

Predictability of time response, integrity, and project management metrics are also necessary. Program managers expect that parallel software engineers deliver predictable time response in C³I systems. They expect these engineers to meet C³I mission factors for assured delivery in a well planned, organized development process. Parallel software engineer researchers should provide the process and tool foundation for C³I builders to do their job.

2.3 TRENDS

Demands on parallel software engineering for C³I systems will increase. This is due to a shift to joint task force theater operations and the need to put the warfighter in the loop. COTS capabilities will continue to grow by a factor of four every third year.

The panel reasonably expects increased demands for high-time-value, tough character applications and difficult C³I mission factors. Parallel software engineering should aid in providing time constrained solutions to C³I mission factors. These factors are the following: reliability, availability, security, fault tolerance and graceful degradation. C³I's high-time-value and tough character applications render the message passing techniques of scientific research parallel methods ineffective. Shorter time scales, dynamic reconfiguration, complex data interaction, visualization demands, and collaborative interaction will grow in importance. Interfaces and information interchange will become a critical use of parallel computers in C³I systems.

The panel projected a five year trend for commercial parallel computing systems. It includes the following:

- nodes with a 1 GMIPS Pentium-like microprocessor
- 256 to 512 MB memory
- a 20 GB disk drive
- Windows NT operating system
- Client programming model using "visual" programming language

- ATM-based distributed network
- data and multimedia access by SQL

The programming model is that a visual language with SQL extensions will deliver graphical user interfaces to obtain data from the network. Commercial systems might adopt object-based technology as its common data access means in order to access multimedia or complex data structures.

The vision includes only very high volume hardware, data base and operating system software and application package software. In this model the client desktop process views the network as a massive server. The system behind the network connection is featureless as far as the user programmer is concerned. Expected technical capability increases for single microprocessors, memory, disk units, and network bandwidth capacity allow the conjecture that almost all computation would be done by the client desktop workstation without any large scale application servers. A totally distributed peer-to-peer system results. (An exception would be interfaces to any pre-existent legacy systems.)

The resulting commercial distributed computing system would be suitable for many C³I application needs. Throughput applications would use ATM's high bandwidth (655 mbps). The distributed system would be effective for almost all of today's successful parallel applications -- transaction and decision support business applications, replicated engineering applications, and message passing scientific research.

However, fast time response and assured delivery of function require that some tightly coupled computing remain. Competitive forces for strategic decision making and concurrent engineering will create the need for the capability for high-time-value and high-integrity-value solutions. This yields an architectural separation with a distributed COTS foundation for some C³I parts and some high-time-value parallel computers for others. This dichotomy separates bandwidth-only throughput from low-latency fast time response demanding applications.

The client/server commercial programming model is good because it does not allow the application programmer any detailed knowledge of the system structure. Presently, SQL database management systems provide this model for data retrieval. However, the client/server model lacks a parallel application language, thus requiring that all processing past data retrieval be executed locally. There is no widely accepted client/server model for users to express execution on network or parallel application servers without explicit expression based on the system's structure.

2.4 VISION

C³I demands, budget constraints and COTS trends require improved parallel software engineering approaches. These demands mean that parallel software engineers must find better development cycle processes that incorporate high-end COTS and parallel machines. Understanding the justification line between uses of COTS, software engineered supplements and military-unique computing is a critical skill.

C³I systems have more stringent needs than do commercial systems. Their time cycle is also much shorter. In addition, due to battle engagement use, a computing error has greater potential for causing loss of human life. To meet these stringent demands, a C³I software design often must include the following:

- meeting time goals (high-time-value) coupled with C³I mission factors (high-integrity-value)
- diversity of applications
- distributed data repositories
- multiple access mechanisms
- dynamic resource allocation

- quick visual and imagery processing
- predictable performance and integrity
- tough character (complex, dynamic and closely coupled) applications

In the future, C³I software engineers would use tightly coupled parallel computers to meet those needs.

However, the panel expects that throughput and well-structured codes would, instead, use a COTS network of nodes with the client/server programming model. For C³I use, the network would use very high-end (speed and reliability) nodes and ATM switches. Such a foundation could meet network pathway bandwidth and single workstation application needs of many throughput and highly structured applications. However, it might not meet all C³I demands, especially where high time value and high integrity are necessary. Potential shortfalls of using an exact copy of the COTS are the following:

- anticipated ineffectiveness of SQL for diverse C³I data
- possibility of a short fall in ATM latency or bandwidth capacity for tight synchronization and data transfer respectively
- weakness of object-based methods for very large project design efficiency
- performance inadequacy of Windows NT to provide real time capability

The conclusion is that this "likely" COTS foundation needs a supplement of tightly-coupled, parallel computers with corresponding parallel software tools to help deal with the resulting complexity.

Software engineers would target their work toward a high performance COTS network. However, to meet well-defined mission time constraints, assured delivery and difficult "tough-character" applications, they must supplement it by adding tightly coupled parallel processors.

2.5 STRATEGY

There will be no silver bullet that solves these challenges to C³I parallel software engineering. However, the panel outlined a path toward gaining the necessary foundation and knowledge to do timely and responsive C³I engineering.

The system designer should base designs on an architecture similar to the COTS fabric and must justify any parallel supplement. The panel set the following goals for parallel software engineering research:

1) Generate C³I system level design tools that:

- model the COTS network and pockets of tightly coupled parallelism dichotomy,
- predict performance (time response) and integrity (assured delivery)
- establish system engineering metrics
- define the justification line between use of parallel and the COTS distributed fabric

2) Develop interface mechanisms for:

- connecting parallel with a COTS network foundation architecture into C³I systems
- achieving C³I mission factor capabilities
- testing and monitoring C³I exercises to capture mission factor and time value information

3) Reduce the cost and effort for development and life cycle support by:

- finding architectural independent design and programming models
- defining architectural independence as generational portability of today's solutions to tomorrow's computers

- insisting on refinement and performance prediction at each level (system, design and programming)
- adding the necessary coordination languages, effective protocols, and hardware interface drivers to demonstrate system level middleware functions

4) Find methods for:

- achieving dynamic reallocation of resources for meeting mission needs
- responding to collaborative interaction by multiple users
- inserting test or monitor probes for performance modeling and recursion testing
-

5) Experiment with COTS technology to enable continuous tracking of key commercial technologies, including:

- * operating systems
- * languages
- * SQL
- * object techniques
- * visual programming
- * ATM data transfer
- develop a demonstration testbed for emulating COTS architectures
- cooperate and communicate with the COTS industry to define and continuously revise the COTS network of nodes coupled with tightly coupled multiprocessors

3. BACKGROUND

C³I parallel software engineers should focus on the most difficult character applications coupled with the high-integrity and high-time value that define C³I computing. Parallel software engineers must understand COTS technology so they can use its rapid technology gains wherever appropriate.

The Blue Ribbon Forecast Panel for Parallel Software Engineering Technology Forecast convened to obtain the expert opinions and forecasts of leaders in C³I related parallel technology. The panel included C³I experts, commercial, government, and academic members. The panel organizers selected them due to their cognizance of architectures, applications, components and markets for parallel systems. In order to provide the panel with a diverse set of ideas on parallel software engineering, the organizers assembled position makers to obtain their ideas and projection of the future of parallel software engineering. Position makers represent a wide range of activities, among which were the following:

- industry level -- machine cost models, research center activities, industry health status and future industry viewpoints
- system level -- system engineering, engineering applications, C³I systems, and dynamic control
- programming models -- virtual machines and automated parallel programming
- programming tools -- visual, components, libraries, and debugging
- system effectiveness -- domain specific objects, libraries, and hardware architecture target development tools

The Blue Ribbon Forecast experts focused their attention on C³I system requirements for:

- high-time-value applications in C³I systems
- high-integrity-value C³I mission factors (fault tolerance, security, graceful degradation, physical constraints, etc.)
- difficult "tough-character" applications (dynamic resource demand, symbolic interaction, frequent synchronization, and extensive complexity)
- software engineering issues necessary for C³I-like projects: programmability, rapid development, and maintenance ease combined with effective performance and portability with predictable design and development performance allocation

4. SCOPE, DEFINITION & ASSUMPTIONS

The decision and information delivery system requirements of C³I systems are challenging. C³I Parallel software engineers should focus on warfighting planning, information generation and command decision making parts of the system. Budget constraints will require maximum use of COTS hardware, software and rapid development processes. Commercial information system COTS technology also poses a threat to our forces due to its widespread availability to others. It also raised expectations from commanders who demand rapid delivery of capabilities they might see in computer stores.

The panel set boundaries on the technology and forecast elements that it was to consider. The panel believed that the opportunities of parallel computing should derive from the mission needs, not from zealous enthusiasm over a particular technology. However, imposing this discipline should not inhibit the invention of new (or improvement of old) C³I applications and capability. The panel stressed the importance of the potential of parallel technology to meet high-time-value, high-integrity-value C³I component needs.

4.1 COMMERCIAL-OFF-THE-SHELF BOUNDARIES

The panel considered that one of its important roles was to determine the directions and condition of the commercial-off-the-shelf (COTS) parallel industry. The forces of change in commercial technology are the driving forces in computing. Also the economics of building military systems require maximizing use of commercial technology to reduce acquisition, development, and life time support costs. The reasonably expected state of commercial enterprise will support some C³I computing needs. However, its use will require aggressive study of the boundary between COTS, parallel machines, and existing C³I systems. Designers should use specialized military or parallel technology only when necessary to meet mission needs. Parallel software engineers need to define the right strategy for incorporating COTS for optimizing C³I capabilities. The reasons are that COTS components have rapid technology improvement cycles, broad acceptance and short learning curves.

4.1.1 Rising expectations from COTS technology

The performance and wide spread availability of COTS (workstations, networks, operating systems, data and object bases, languages, visualization, virtual reality, voice and pen interaction, and CD-ROM storage) will raise expectations on C³I systems. Parallel computing for business, engineering, and other government processes includes a variety of architectures. These typically include a number of small symmetric multiprocessors, some clusters of networked computing nodes and a few tightly coupled multiprocessors. Tightly coupled multiprocessors will be market viable only for high-time-value applications.

4.1.2 Potential threat from COTS technology

Third world countries might use COTS equipment to significantly increase their command and control and information warfare capability. Such a threat requires that our C³I builders fully understand the capabilities

of COTS equipment and its potential for command and control applications. Our challenge is to remain far ahead of the COTS capability through innovation and skillful application of parallel computers within a COTS-based C³I fabric.

4.1.3 C³I Boundaries

To concentrate on the right issues, the panel defined the boundaries of C³I systems as the following functions necessary to conduct Air Force warfare:

- data and information fusion
- information generation, display and visualization
- decision making
- human interaction with the process of command, control and intelligence
- action and reaction control
- warfare planning, direction, evaluation, and awareness
- managing the wide range of information that will converge on command centers

Therefore, C³I systems are planning, information and decision making elements of Air Force Warfare. The panel excluded certain subsystems, eg, sensor and image data sources for the C³I system and the external weapons and delivery systems that take commands to respond to a threat or meet mission goals. (We define these as effectors.)

4.1.4 Parallel software engineering boundaries

The directions of parallel software engineering are dependent upon sequential software engineering. Other research technology developments may provide different supporting contributions for C³I systems. Therefore, the panel attempted to observe duplications of parallel software engineering to avoid overlap with other research programs. These boundaries are often difficult to establish. Several government programs already perform research and development in the following: operating systems, object design, scheduling, application programming interfaces, heterogeneous programming, application scheduling, scientific collaboration and distributed applications. Likewise commercial development continues for distributed objects, new operating systems, visualization, multimedia, virtual reality, data base access, protocols for Asynchronous Transfer Mode (ATM), and languages for more effective development of data and object manipulation. A research plan should avoid duplication. However, parallel software engineering researchers must establish a relationship with other research programs and C³I providers. Historically, other research programs have concentrated on highly structured scientific research applications that are not effective for C³I parallel software engineering. An interface to expose the C³I software engineering needs to other major research efforts is, therefore, necessary.

5. ASSESSMENT OF C³I REQUIREMENTS & DEMANDS

C³I systems will often need to use parallel processing to meet response time, physical constraints, and new mission functions. Because parallel computing improves response time, new mission capabilities are feasible. Designers use this approach to radically change mission requirements. They can radically improve a C³I system's war fighting capability by application of parallel technology.

The character of C³I applications is very different from scientific research, business transaction processing and other well-known parallel applications. Those character differences are a combination of complexity, interaction rate, and resource demand. Extensive (unstructured), frequent or symbolic (logical and decision) interaction, and dynamic resource demands are the most demanding. The panel referred to these as the

“tough” applications. The “standard” parallel applications typically have a structured, (large) message passing, infrequent interaction and static resource character. The greatest challenge to applying parallel computers to C³I systems is in dealing with tough applications with coupled high-time-value and high-integrity-value.

5.1 CONTINUED REQUIREMENTS FOR C³I MISSION NEEDS -- TOUGH CHARACTER APPLICATIONS, HIGH INTEGRITY AND TIME VALUE

5.1.1 Assessment of Parallel Technology and Software Engineering

Present COTS parallel computers have not provided an effective capability for delivering C³I mission factors such as reliability, availability, security, fault tolerance, and graceful degradation. C³I mission factors will continue to be important discriminators between C³I and COTS parallel systems. Software engineering tools that give better C³I factors would have a high value in commercial systems.

The panel viewpoint taken is that C³I system should have hardware components of commodity COTS, specialized (possibly parallel) COTS, and militarized components. These components would be workstations, networks, specialized processors, operating systems and runtime software for implementing C³I factors and meeting tough character applications. A future view of C³I systems is one based on a high level of available COTS computing machinery and software. The panel raised some concerns about over-enthusiastic COTS adoption. They also raised concern over potential long-range disadvantages of COTS. One example is the frequent and sudden obsolescence, common in commercial markets. The panel reasonably expects significant cost advantages through COTS. The panel recommends setting the goals of parallel software engineering by reflecting on the future of COTS components.

5.1.2 C³I component development

Until parallel software engineering environments are available that can simulate the entire C³I system, designers will use allocation of time and function to components. Software engineering is necessary due to the large scope and difficulty of building C³I systems. The necessity to use system and software engineering methods to build C³I systems is due to their size, high-time-value, high-integrity-value, and tough character. Since C³I design and development require many people, the visibility of the design and its implementation are very important.

Parallel computers exacerbate the situation because their performance (time to completion) varies widely when the design mismatches the architecture. Designers allocate function and performance to components when designing a C³I system. This is difficult even when the underlying capabilities of the computing resources are consistent and steady providers of computing capacity. Without the capability to predict the behavior of a parallel element in the system, the design risk becomes excessive.

Designers should not use parallel computers unless they identify clear advantages. In other words, they should not use technology for its own sake. However, when applications honestly require performance and integrity levels only obtainable through parallel computers, then system designers must be able to predictively use parallel technology. Parallel engineering researchers should create suitable metrics to aid designers in making these decisions.

Knowledge of dependable and predictable completion times for each component are required to conceptualize and develop architectures that deliver high value time. In addition, the extra computation required to deliver all required C³I mission factors must be predictable at design time, prior to detailed mapping steps to a specific architecture. Delivering reliable time of completion predictions on diverse character applications is a necessary design tool. Designers also need tools to help in delivering C³I mission factors and predicting the associated performance penalty. Tools that provide information about the

application's character are also necessary. It is also necessary to develop methods to incorporate C³I factors such as time guarantees, resiliency and integrity, and physical constraints imposed by operating in aircraft.

5.1.3 Complex data manipulation

The most compelling feature of C³I parallel software engineering is that applications are complex in all dimensions -- processing, data location and organization, interaction of components, response to changes, and necessity for integrity in combat situation. In addition, C³I data fusion techniques will increase in complexity. Additional complexity comes from added data sources, higher precision, and lower false detection rates. In addition, future systems require "information" fusion. This combines today's data fusion results into multiple information sets for use in different applications.

Commercial users will develop data mining techniques that use data content and histories to improve the capabilities of the run time system. Similar adaptive improvement of operational capability using data mining would improve the quality of C³I systems. These future uses require complicated data manipulation to such a degree that systems will require parallel computers to meet time goals. Single workstation technology advances alone are not adequate to meet these needs.

The multiple sets of applications that comprise a command and control system take widely divergent forms. Each form may have widely varying optimum data organizations. Relational data base managers are most prevalent in commercial systems. Their use in accessing multiple data arrangements is not as effective and is difficult to apply for highly diverse component access methods. An inefficiency in both access time and storage volume results. The C³I system has highly divergent applications with distributed data repositories that do not match a single "normalized" relational model which is tuned for high throughput transaction processing.

5.1.4 Shorter command time scales

Time is the essence of C³I systems. Predictable time response and assured delivery are the essence of C³I system design.

Every time period in a C³I system grows shorter when the focus moves from monolithic central control to warfighter information delivery and decision making. Parallel computers most reasonably fit into high-time-value C³I components. One example is reduction in time for creating air battle command plans for a day's actions. The contribution of parallel performance could enable on-line plan changes-based on intelligence as it arrives during the day, allowing the plan to be adapted to meet immediate mission needs. Such an application would require collaborative action in setting up the daily plan and a rule-based system for safely changing parts of the daily mission during its progress. Users would base changes on the rule base and real time information gained during the day's operations.

Parallel computing is one method where the C³I systems can receive the steady stream of input, process event detections, make command and control decisions and meet a time response goal. The decision support actions take several streams of events from different sensor streams. It "fuses" them into higher a level set of event information and associates it with other information sources. A higher level of fusion might combine these with information-based on other data types, such as observations, satellite imagery or human input. The system evaluates these information events, often using empirical methods, to identify objects or activity, determine its value or threat and decide upon the proper response or attack. Detection of possible events and determination of a target must have high signal to noise and low false detection performance. In many cases, the system must perform this processing within a very short time frame, otherwise it is useless. Therefore, C³I mission success commonly depends upon meeting time response goals.

5.1.5 Dynamic reconfiguration

In aircraft space limits physically constrain C³I system facilities. Therefore, hardware serves multiple purposes. Collaboration among commanders will also become more common. Dynamic reconfiguration is also necessary to achieve graceful degradation and system integrity in combat and information warfare situations.

Parallel computers in C³I systems must have the capability for dynamic reconfiguration. In this case, components required in different time domains may use common resources. For example, a detected threat might cause redirection of processing. In dynamic reconfiguration, the system determines which of the components to run at any given time. By using the resources to best advantage, designers can have the maximum capability for the minimum hardware costs. Often computer resource demands come from new events or from computed information. This requires that the system to respond and use its machinery differently. This dynamic change capability is not typical in today's common parallel architectures. Often an event identification perturbs processing control. Also a human can interact unexpectedly, basing their decision on displays and visual processing. When this happens, the mission may change. The system must switch all its resources to the highest priority and may require that the computation change significantly to perform a new function.

Parallel computation to accomplish these fixed time response computations must have the same capability. Dynamic resource allocation is a necessity for meeting C³I mission needs. Of growing importance is the capability for multiple users to interact with a computation as it progresses. Collaborative techniques will eventually contribute to concurrent engineering or other industrial design and information decision making. This technology might also impact the designer's expectations of a C³I system. Collaborative interaction will be an important factor in increasing demands for more rapid refinement of decisions through multiple scenarios. Parallel computers can solve these problem types.

5.1.6 Visual and Imagery impact

Humans have limited capacity to absorb information. However, their ability to analyze a multidimensional situation picture is far beyond computer capability. Getting that picture and supporting information to decision makers is now feasible. This places a new demand on the C³I system to create and present the right information and pictures for full situation awareness without overload. The C³I system of the future will move away from simple displays of alphanumeric and line graphics with text overlays for information display. C³I system requirements will follow commercial systems and provide significantly higher information content screens. These include scene images, high resolution vectors, symbolic icons, tables, charts, etc. Providing this extra information may reasonably require video storage, added bandwidth communication, and selection mechanisms for human interaction. In addition, designers will include new forms of image analysis and comparison, possibly directed by human controls. This added capability demonstrates significantly increased expectations of access to information and requires high performance processing. A higher demand on computing capability results.

Visual displays, with much higher information and data content, will drive designer's expectations in future C³I systems. This may change the organization of processing, transfer and storage of symbolic and real imagery significantly. Both parallel computers and high performance networks may be necessary to perform scene analysis, compression, storage, transmission, etc. Three-dimensional scenes, as that possibly provided in new displays like virtual reality, require ray tracing. C³I applications will have similar imagery for radar scenes, human observations, events, and tracking. The system designer must provide image processing and symbolic decision processing in collaboration with information fusion and human interaction. This is a type of image processing that falls within the C³I system, at the information generation and its intelligent use for decision making involvement with the user.

5.1.7 Global interfaces and information interchange

Change, flexibility, less-structured and distribution requires exercising the system for validation and testing. Parallel software engineers must provide interfaces to allow for constant refinement of the system through information collection and operational testing. There is a need for a more closely coupled parallel tool set with actual C³I system operations. Understanding the application's character, the costs and methods of delivering C³I mission factors, and the necessity for time guarantees requires information collection and knowledge building that many research parallel tool developers presently lack. The parallel software engineering program needs ways of transferring information on fundamentals about the character, factors and high-time-value of C³I systems. Software engineering for parallel systems needs to be in-the-loop to enable its progress to bring the full value to C³I systems. These demands on C³I system change the importance of interfaces to other systems, typically causing an increased input/output rate.

Parallel computers play an important role as information and data storage and buffering mechanisms for input and output and for transfer of information between C³I system components. Additionally, the parallel computer may be necessary to transform data so that each C³I component capability meets its time goals. In addition, the parallel computer makes it feasible for software researchers to create the capability to meet C³I factors, or for the execution of applications with a tough C³I mission character.

Advanced methods of decision making incorporate intelligent and adaptive methods. They must constantly improve themselves by rule changes or by training. To accomplish this improvement it is necessary that the system have feedback or information gathering capability to achieve its full potential. In-the-loop system probes and data collection are important components for the development of future C³I systems. An information-gathering probe would be a valuable tool, especially if it were a part of the development process during architectural concept, design, testing, exercises, and life cycle support. Much of the value is the feedback of information on the adaptation and evolution of the system to achieve improved results over time.

C³I systems operate within an environment where existing "legacy" equipment already operates, and where external system interfaces play an important role. Just as business systems have the necessity to deal with legacy systems, so do C³I system components. Due to the long life time of C³I systems, designers must consider that each parallel component will become a legacy of its own. Designs should be extensible to accommodate mission and technology obsolescence. The model is that parallel computers go into the fabric of existing and future C³I systems only where designers prove them necessary. The panel reasonably expects this for high-time-value and tough character application needs. Therefore, an important component will be the interface mechanisms between parallel and COTS systems. Common sense dictates that system interfaces need a balance of bandwidth capacity and low latency to match the interfaces for high-time-value cases. Simulation and analysis of the C³I system can give some insurance for achieving the time goals necessary in high-time-value applications. The panel does not expect that scientific research center methods will be significant aids in solving this issue because they are throughput rather than high-time-value oriented.

6. VISION OF COTS PARALLEL TECHNOLOGY AND SOFTWARE ENGINEERING

Parallel software engineers will adopt high end COTS technology to a greater extent. One vision is for a dominance of desktop computers interconnected by high performance ATM networks. In this view, all application processes have local views of data or images accessed from the network. In this model, the only parallel application necessary is the SQL access of data. The reasonable expectation is that these general COTS architectural directions will many solve C³I throughput requirements. However, the need for mission factors, solutions to tough character applications and high-time-value of C³I systems requires additional

pockets of tightly coupled parallel computers to solve these special cases. These may also be COTS supplied, but may require special parallel software engineering methods to achieve the necessary mission. Military-unique problems would also be present within this framework.

6.1 NETWORK OF HIGH PERFORMANCE PERSONAL-COMPUTER NODES

A broad vision of the future COTS parallel industry agrees with Gordon Bell's vision of COTS industry based on his Scalable Networks and Platforms (SNAP) architecture. SNAP has the following components:

- nodes based on the highest performance but largest volume microprocessor (likely to be an Intel-based computer with 1 GMIPS, 128 MB memory and 20 GB disk drive by the year 2000)
- some nodes would have a four-processor commodity level symmetric multiprocessor (The Compaq ProLiant is a present day example.)
- a single, standard, commodity-priced operating system with network and multi-user capability (Windows NT is the top contender -- Unix might become outmoded due to high support costs of its many variants.)
- Asynchronous Transfer Mode (ATM) would be the local, wide area, and global network connection
- all data access would be by SQL queries into the network or disk unit
- multiple applications could operate at each node
- computing would be peer-to-peer instead of client server (the entire fabric of nodes and ATM switches would be a virtual server whose architecture is hidden by the data base manager)
- no shared memory is provided by this model -- to give scalability of the nodes and network
- metrics of the SNAP network are message delay (latency and overhead) and bandwidth limit delay (gap)

The continued processing capability increase by a factor of four every third year, economy of scale and better learning curves are the primary driving factors. The result is that commodity pricing lets almost all applications use the ubiquitous SNAP network of nodes. This architectural model represents the expected trend target of commercial throughput computing.

6.1.1 Pockets of tightly coupled nodes

The bulk of the market would tend toward the commodity market represented by the SNAP network. However, there remains a commercial market for decision support machines for high-time-value and high-integrity-value applications. There will be a growing number of large complex applications that require higher performance. Two routes are open to the designer: distributed message passing and tightly coupled multiprocessor servers. For both routes the SNAP network provides the basic fabric. The SNAP architectural model did not include coordination languages to run concurrent systems over the network, all applications were to be single client-based. Coordination languages let designers set up pipelines or concurrent replicas in a SNAP-like network. Middleware control software is necessary.

The panel also expects that today's message passing applications will fit well on the SNAP architecture. The distributed computing route requires a coordination language for distributing large grain applications across the network. Coordination languages let designers set up pipelines or concurrent operations in a network. This middleware control software is necessary for fitting today's message passing applications on the SNAP architecture. The projected SNAP architectural model does not include a coordination language to run concurrent applications over the network. In the SNAP model, all applications run in a single client node and get data from calls into the network. However, organizations often find significant competitive advantage by using high-time-value applications. Many organizations will continue to seek solutions that

give them competitive advantage. This favors multiprocessor servers. Hardware vendors, with a base of commodity sales to the SNAP-like COTS requirements, would find their highest value added and profit from these servers in pockets of high-time-value or high-integrity-value.

6.2 COTS NETWORK OF NODES -- A FABRIC FOR C³I SYSTEMS?

The reasonably expected vision of a C³I system is one that incorporated a maximum amount of COTS elements. However, C³I designers must provide for high-time-value cases, high integrity C³I mission factors, and tough character C³I applications. Commercial client desktops probably would not deliver the combined high-time-value and high-reliability-value required in C³I systems. However, commercial vendors already have fault tolerant and high performance servers. Substitution of these high-end COTS servers may provide a COTS foundation for meeting high integrity C³I mission factors and tough character applications. An important tool will let engineers design and build a C³I system out of a high-end COTS fabric combined with COTS parallel components.

6.2.1 Anticipated Shortfall of COTS Capabilities for C³I

C³I systems have shorter time scales, attach more importance to integrity, serve for a twenty-four hour day and are constantly on-line. They should gracefully fail, delivering reduced capability even when components are lost. This capability brings added costs. As a result, the goals and requirements of the COTS-SNAP architecture and those for C³I systems diverge. A key question is determining if COTS technology is adequate for the C³I mission. Parallel software engineers will need in-depth and complete knowledge of COTS technology to arrive at the right answer. Engineers must gain the experience necessary by continually developing information collection at these interfaces.

Today's COTS parallel computers are highly capable within very specific markets. These are: scientific research, multi-user replicated engineering, fault-tolerant transaction processing, and batch decision query applications. Projected designs for multimedia, communications switches, and replicated engineering systems suffer a similar narrow specialization. C³I applications require general purpose parallel computing to meet the needs of unexpected results of data fusion, information fusion, decision making, and control, planning -- all within high-time-value and high-integrity-value constraints. Most of today's COTS examples are useful only for multi-user throughput. In addition, there is a difference in the depth of concern for the high-integrity-value C³I mission factors such as the following:

- reliability and fault tolerance
- rapid software development, easy maintenance and enhancements
- security
- graceful degradation
- dynamic reallocation
- physical constraints

Some commercial systems provide high availability and fault tolerance, for example, systems for transaction processing. These represent a high-integrity-value COTS market but are specialized to high throughput transaction rates instead of high-time-value decision making.

The necessary component upgrades for using the COTS-SNAP architecture in a C³I design are critical to understand. C³I systems would not use commercial communications networks. However, other aspects of the system would be similar. This means that independent vendor applications, software tools and languages, training, and other market infrastructure capabilities would transfer into the C³I system. Significant cost savings accrue even though hardware components are upgrades from the least expensive commercial equipment. The conclusion is that the COTS fabric provides a model for the C³I one.

The greatest future challenge may be to solve the toughest of applications needed in C³I systems. Designers would use pockets of tightly coupled parallel computers for meeting high-time-value, C³I factors, and tough character missions. A frequent exposure at the interface between the projected SNAP fabric and multiprocessors is necessary to understand that boundary. This mixed COTS fabric with pockets of high-time-value machines is the reasonably anticipated network design. It should be the starting point for military and C³I applications.

6.2.2 Data and network access

The complexity of C³I information location and organization may be significantly higher than in commercial systems. Parallel software engineers will have to be aware of and correct COTS weaknesses.

A C³I system must organize and communicate C³I mission data and information for rapid access by multiple applications. In addition, the times allowed to access information is much shorter than in commercial systems. There are several areas of concern:

- high-time-value access during dynamic reallocation and changes in application due to threats, plan changes, and defensive responses
- multiple organization of data for different C³I components within the same system
- access to information must be highly secure, yet available to the applications that require it
- network protocols must provide for guaranteed communications, assurance of resources, and process adaptation to the demand of widely varying event information
- the correctness of the system has human life consequences not found in business systems that will dominate the directions taken by the COTS architectures
- suitability of SQL as an effective data access method in multiple application accesses and within high-time-value constraints
- suitability of ATM latency in high-time-value systems
- reusable methods to efficiently implement C³I factors and develop software for tough character applications

7. VISION FOR C³I PARALLEL SOFTWARE ENGINEERING

Use no technology for its own sake.

Software engineers must take total procurement cost conscientiousness, including software development and life cycle considerations. The panel recommended a strategy to maximize the use of a COTS fabric as a foundation. However, parallel software engineers should also use COTS parallel and military-unique computers where they are necessary to meet high-time-value goals, C³I mission factors and character. Total procurement cost conscientiousness is the metric, not hardware cost alone. This strategy requires programmability combined with performance and portability. It also requires that the underlying system concept have a close relationship to COTS where it applies. An important requirement is to know how to determine the relationship between COTS-SNAP and parallel computers. That interface is one of the challenges a parallel software engineering research program.

7.1 C³I PARALLEL SOFTWARE ENGINEERING

Parallel software engineers need system engineering tools that allow behavioral simulation and mission performance evaluation during design, development and coding.

A suitable computer aided system design tool is necessary to design the interfaces in C³I systems. These tools are necessary to allocate function and performance to components, and predicting their performance

and C³I mission factor capability. A designer typically iterates their design until they meet all mission needs. One result of the panel's vision is the identification of a tool to determine the interface between the SNAP-like architecture COTS and the parallel machine part of the system. As the designer attempts to allocate functions the design tool would predict performance on the SNAP-like COTS architecture. When the designer cannot meet high value time limits the tools should allow introduction of a series of sizes of parallel architectures to meet the high-time-value goal. Thus, the tool lets the designer find the decision surface between SNAP-like COTS fabric and COTS modular parallel or military unique components.

A system design tool provides for an overall system allocation of components. In addition, programmers need application development tools for design and programming of applications. Engineers need methods of application development that include performance prediction and specification execution. Refinement methods, object-oriented methods, specialized components and virtual computing models should be considered and placed intimately into the loop of C³I exercises, testbeds, and applications.

The panel found that the Bulk Synchronous Parallel (BSP) model eased discussions of architectures and applications. BSP uses super step barriers. It has well-defined terms for communication-to-computation ratio and barrier delay costs. A useful tool is one that would let C³I system engineers emulate SNAP-like architectures on present day parallel computers. To do this, its developers would have to normalize for projected bandwidth, processing, and storage capability. The BSP super step barriers could be useful in that normalization. If engineering tools could match the architecture to a cost model it could be easier to develop virtual machines as targets for programming tools. Experiments in emulation of predicted COTS systems provide a test bed to allow quantitative performance engineering that attains C³I mission factors. In addition, designers could explore techniques for testing of tough character applications.

7.2 OBJECT-ORIENTED DESIGN, DEVELOPMENT, AND PROGRAMMING

Object-oriented is the label often used to mean portable, reusable, rapidly developed, and easily maintained programs. However, object-oriented methods are not a silver bullet that makes all progress easy. These methods are often hard to build for effective operation and new designs often require changes to meet all goals. However, if they establish the right foundation, they can build better methods for solving the complex problems posed by C³I parallel software engineering.

Object-oriented design and development methods have made a significant impact on display screen programming, data exchange between independent applications, and organization of access to data objects. Commercial system and application programmers have accepted these methods. Small programming groups are making significant productivity gains through object reuse, easier software maintenance and efficient enhancements. There are questions about how to overcome performance loss in C++ when compared to compiler optimized C, how to best use C++ in large projects, and how to provide better design visibility. There is also doubt about using object-oriented methods as a cure-all. Others were more optimistic but recognize that a solid foundation is necessary to gain the advantages of object technology. Object-oriented methods are playing an increasing role in commercial systems. This technology has solved the productivity problems for creation of displays. It has reduced the screen building and human interaction programming task significantly. Likewise the language typically chosen by commercial support staff is also becoming object-oriented. System design techniques are also following this path. However, these are not yet mature.

Some of the panel members believed that SQL was not adequate for the commercial systems of the future. They found that programmers would most likely program using a combination of visual object-oriented languages. Examples are Visual Basic or Smalltalk for screen and SQL calls and C++ for higher level system programming.

8. STRATEGY FOR C³I PARALLEL SOFTWARE ENGINEERING

The vision of the forecast panel for parallel software engineering concentrates on how to make parallel computing effective for C³I systems development. The panel expressed the importance of getting parallel software tool builders involved directly in C³I testbeds and demonstrations. These should concentrate on dynamic reaction, interfaces to insert COTS fabric and COTS parallel, parallel software engineering tools and architectural independent software engineering methods.

8.1 INSERTION INTO THE C³I ENGINEERING PROCESS

Engineers need tools at a system level scope when engineering parallel software systems. This includes the following:

- design modeling of parallel computer hardware and software in a hierarchically staged process -- focused on the tough applications that C³I systems require
- tools for programmability-with- performance on high-time-value applications
- tools to integrate high-time-value applications with both existing C³I applications and the future fabric described by the SNAP model
- tools to reduce the risk of achieving good results on tough character C³I applications, focusing on the toughest types tools that predict performance and factors on any mission character

8.1.1 Integration with other subsystems

Parallel software engineering would be most valuable if more closely associated with exercises and demonstrations of C³I systems. The recommendations were to attain tools and processes for the following:

- on-line monitoring of C³I environment for capturing high integrity and time value
- on-line monitoring of C³I environment for determining capabilities and resources required
- create processes for designing and implementing effective interfaces from parallel to other C³I system components -- especially clusters of nodes that represent the reasonably expected SNAP-like COTS architectures

8.1.2 Support for dynamic adaptation

A critical capability was one that let the system rapidly and effectively change directions of processing. The system makes these rapid changes to respond to human interaction, mission change, and new phases of operation. The system can change mission activity to respond to better information. This may be one of the valuable assets of parallel computing when resources switch to meet any newly demanded processing. Dynamic adaptation based on decisions made by the C³I system would require parallel computing for artificial intelligence and knowledge-based decision making. In addition, the parallelism and dynamic adaptation allow the system to provide fault tolerance and resiliency by determining its state and responding with a reconfiguration that meets mission needs to the best of its capability.

8.1.3 Architectural independent software representations

The industry needs an architectural independent programming model. Defining such a model has many difficulties because of the diversity of application character and architectural capability. The panel and position makers described several approaches that build on a hierarchy of layers of design, architectural selection then machine selection. In addition, automatic parallel program generators for these layers are the subject of research of several position makers. However, none had applied these methods to the tough application character type problems that are similar to C³I ones. Air traffic control was the only difficult example given by the researchers. A problem seems to be that the architectural targets have been parallel

computers and tools built primarily for scientific research. Due to the significant difference in character and requirements, a simple transfer of this technology from scientific research might not be effective. This does not lessen the need for the hierarchical tools.

8.1.4 C³I Parallel Tool Requirements

The panel suggested the following tool requirements:

- coupling of C³I parallel software with application modeling
- integration analysis tools to provide interfaces with other systems & drivers
- coordination languages for design, applications and integration
- tools to find and identify the optimum boundary between COTS SNAP-like clusters and more tightly coupled parallel computers
- tools to allow the maturity of the SNAP-like COTS fabric to be evaluated to determine when to apply software enhancements to gain the C³I factors
- methods to gain involvement in C³I exercises, operations, activities to gain better software operational level knowledge
- cost models and prediction methods for time constrained applications, tough application character and addition of C³I mission factors to parallel applications

The panel recommended that designers include the following testing and verification mechanisms in their designs:

- probes that allow testing parallel computers in the mix of subsystems and specialized architectures in C³I systems
- regression testing tools for parallel executable codes during system verification

8.2 PLANNED RESEARCH FOCUS

The goal of parallel software engineering is to create development processes and architectures to meet both high-time-value goals and high-integrity-value goals within the parallel HPC environment. Applications of any character should be feasible with performance, programmability, and portability. In order to accomplish this daunting task, parallel software engineering must concentrate on the most difficult character applications. These are the ones that have extensive complexity, dynamic resource demands, symbolic interaction and frequent interaction, ie, the toughest problem types. However, parallel software engineering must recognize the need to integrate those results with existing C³I systems and the vision of commodity SNAP-like architectures.

8.2.1 Strategic Research Areas

The general areas of research recommended are the following:

- system supervisor and control -- create the necessary additions to commodity COTS for control of the SNAP-like architecture and interfaces to high-time-value nodes
- architectural independence -- C³I must apply to latest processor and architecture capabilities, therefore the need to continually port to new architectures is critical to maintaining military advantage
- non intrusive entry and coordination with C³I systems to solve latest needs -- varied operational modes and demands require that information be collected to better design and refine the use of parallel computing in C³I systems

- interface and cooperation with industry for obtaining an effective COTS a common fabric - - requires advanced emulation, including methods of obtaining C³I system factors like reliability, fault tolerance, security, graceful degradation, and dynamic resource change
- track commercial advances in distributed processing, coordination, operating system, data or object base and language software
- adopt new technology into the C³I system model as long as there is a benefit -- this is reasonably expected to be the least expensive manner to do a majority of the mission needs
- develop standardized methods to meet the C³I mission factors and the tough problem needs, yet providing rapid software development and easy maintenance and enhancements

8.2.2 Short Term Research

There are several short term limitations whose study would resolve major issues. If solved they would also be effective in the commercial-decision-support system industry. Some of these study areas and limitations are the following:

- determine a suitable organization of C³I data -- in place of SQL relational organization -- experiments were suggested by the panel to determine the limitations and advantages
- generate an application framework for creating dynamic resource changes in parallel systems -- study the capabilities required to respond
- create monitoring and testing tools to reduce uncertainty of correctness, performance, and mission factors
- evaluate operating system, interconnect access protocols, and network protocols that limit parallel performance, reaching C³I factors, portability, reuse and performance prediction
- determine the programming models and matching parallel architectures that can resolve the time uncertainty problems of parallel computers
- find methods of achieving high-time-value performance and gaining high-integrity-value using code reuse technology
- continue to support system engineering tools that can provide the applications allocation to SNAP-like COTS systems combined with HPC multiprocessors
- develop a hierarchy of executable specification tools for high-time-value design and development layering

The executable specification tools should include the following ones:

- provide for engineering of C³I mission factors, performance, and multiple application character needs
- create performance prediction tools -- relate to a hierarchy of design stages that would be useful to the system designer
- relate the performance prediction tools to cost models
- define the hierarchy to allow the removal of the uncertainty of availability of specific processor architectures
- provide tools that give design visibility at each level in the hierarchy
- provide reverse engineering capability for understanding of designs

These issues need focus so they can gain the proper priority, feasibility, time sequencing dependencies and budgets.

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