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RAPID ASSEMBLY AND USE OF ROBOTIC SYSTEMS: SAVING TIME AND MONEY IN NEW APPLICATIONS*

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Introduction

High costs and low productivity of manual operations in radiation, chemical, explosive and other hazardous environments have mandated the use of remote means to accomplish many tasks. However, traditional remote operations have proven to have very low productivity when compared with unencumbered humans. To improve the performance of these systems, computer models augmented by sensors, and modular computing environments are being utilized to automate many unstructured hazardous tasks. Establishment of a common structure for developments of modules such as the Generic Intelligent System Controller (GISC)¹, have allowed many independent groups to develop specialized components that can be rapidly integrated into purpose-built robotic systems.

The drawback in using this systems is that the equipment investments for such robotic systems can be substantial. In a resource-competitive environment, the ability to readily and reliably reconfigure and reuse assets operated by other industries, universities, research labs, government entities, etc., is proving to be a crucial advantage. Timely and efficient collaboration between entities has become increasingly important as monetary resources of government programs and entire industries expand or contract in response to rapid changes in production demand, dissolution of political barriers, and adoption of stringent environmental and commercial legislation. Sandia National Laboratories (SNL) has developed the System Composer, Virtual Collaborative Environment (VCE) and A^{primed} technologies described in this paper that demonstrate an environment for flexible and efficient integration, interaction, and information exchange between disparate entities.

System Composer

The diversity of robotic tasks within the United States Department of Energy requires different combinations of manipulators, tools, sensors, and operator interfaces. The requirements of these tasks are frequently best met with multi-organizational teams that integrate commercial equipment with advanced technologies developed in the laboratories. With the advent of GISC, a common structure was available for the development and integration of the diverse equipment and technology modules for specific needs, organizing and facilitating the efforts of many university, commercial and government participants. As more organizations begin to produce modular GISC agents, the need for an intuitive and rapid means of assembling the modules is ever more pressing. System Composer has been developed to fill this need.

System Composer is designed to be an object-oriented means of assembling, evaluating, deploying and operating robotic and manufacturing systems intuitively, rapidly, and efficiently from networked, distributed components. Formerly known as the Distributed

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Collaborative Workbench², it is a collection of both hardware and software tools which enable rapid integration of intelligent systems. There are nine categories of such resources addressed by System Composer: machining centers, assembly centers, robots, operator interfaces, communications, sensors, product requirements, process capabilities and controls (Figure 1). There are many benefits gained in using this approach. For example, the system designer need only consider the functional characteristics of the system modules. The internal details of module algorithms and processes are not required for the system designer's implementation planning. Likewise the developers of the individual modules need not consider application-specific details, only the internal workings of the module and its external interfaces. This development environment provides the means for continually expanding the tool kit library and their applications.

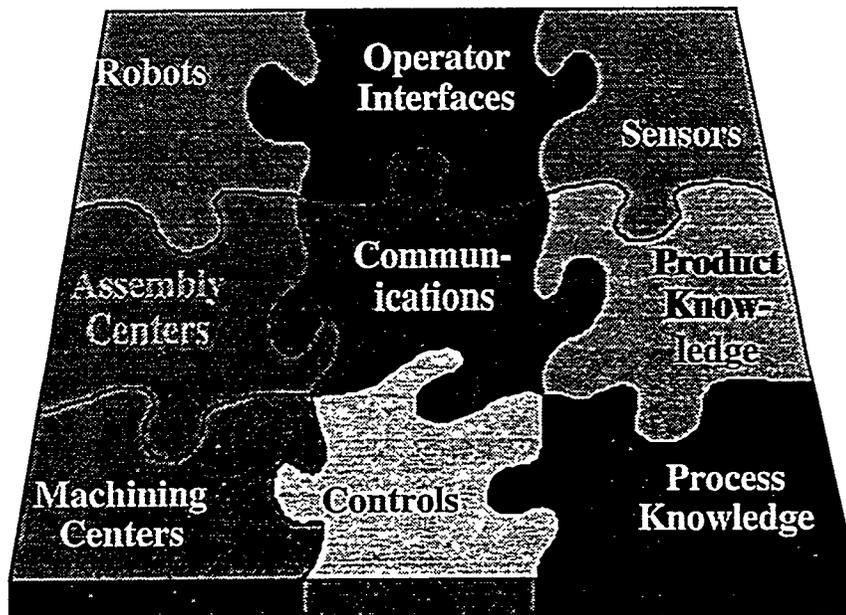


Figure 1. System elements that are assembled by System Composer

Using menus and graphical displays, System Composer prompts the operator to select integration parameters and system components. Integration parameters include rules, such as the communication types and grammar, which provide the framework for adding components. For example, if the system designer selects a GISC tool, then GISCKit software is called upon to provide communications between system components. In this case, the general command structure between supervisors and subsystems is defined by software called GENISAS. GENISAS commands sent from a supervisor are packaged and routed over networks by SNL-developed software known as ISOE (soon to be replaced by a commercially-supported product). Subsystems receive the packaged commands, "unwrap" and translate them into machine-specific actions using additional SNL-developed software called Robot Independent Programming Language (RIPL). All of this software is automatically configured and defined with the selection of the integration parameters.

System components appropriate for the task of interest are then selected from module libraries. Nine classes of components are currently available (see Figure 1). Mechanical systems include elements such as robots, machine tools, sensors, material handling hardware, assembly systems and various feed-back devices. Software modules include supervisory systems, task sequence generators, analytical software, decision software, and operator interfaces such as graphical user interfaces (GUIs) and graphical simulation

software. The physical operating environment can also be defined as a module. For example, a facility workcell or laboratory can be simulated and represented graphically for use in programming, testing and operation. Multiple variants of each of these categories and capabilities have been developed throughout the world, most of which, with the proper "wrapper," could be added to the libraries and made available through System Composer.

System Composer facilitates organization of system components during the selection process. Graphical icons appear on the screen for each module selected. The human operator can "drag and drop" the components into an intuitive organizational structure. Next, communication type and direction between components can be specified using a line and arrow representation. Supported functions are then automatically established for each component. Future work will include automatic recognition of class functions and determination of any variants (parent-child relationship) of a class with associated functional changes. Figure 2 illustrates the graphical organization of a supervisory module (Sancho), two robotic subsystems (Cincinnati-Millacron and Titan), and a pipe cutting system.

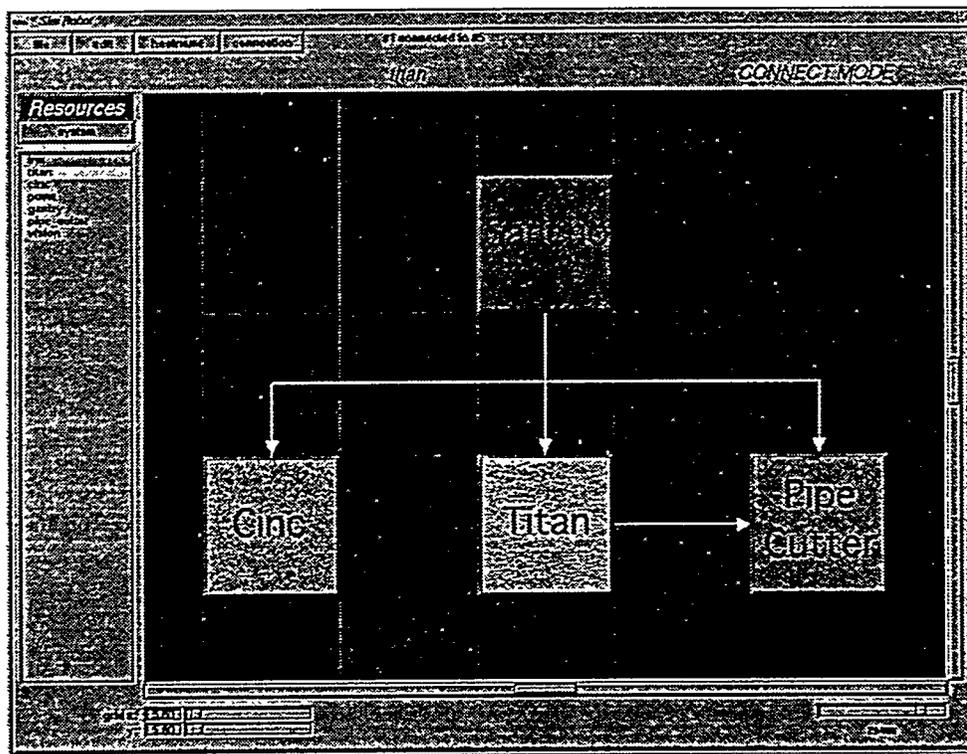


Figure 2. System Composer graphical screen for organizing subsystem components

Subsystem components themselves may be assembled from other components. The Titan subsystem in Figure 2 was assembled by System Composer using the components shown in Figure 3, including a force-torque arm and six degree-of-freedom space ball input/feed-back devices, as well as a path planning module, simulation software and a Titan II robot with controller. These components are themselves modules created for assembly with the Sequential Modular Architecture for Robotics and Teleoperation (SMART)^{3,4}.

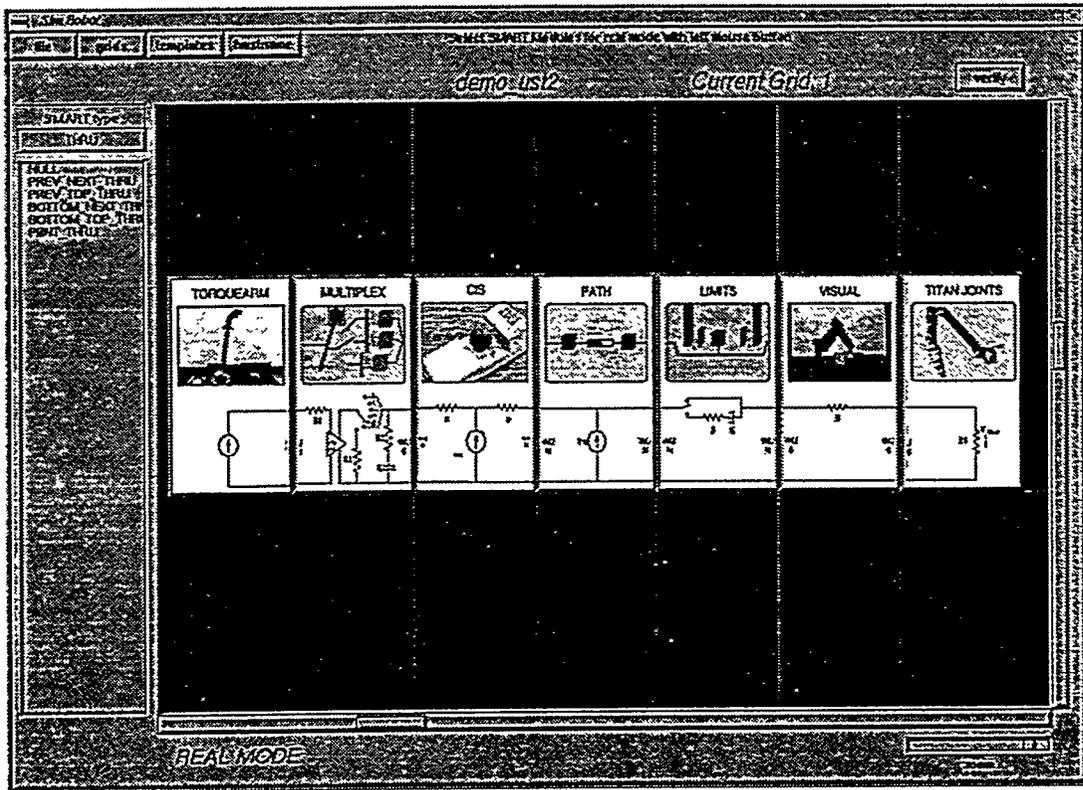


Figure 3. Robotic subsystem assembled from SMART modules in the System Composer Environment.

Once the organizational structure is established graphically, System Composer has been designed to validate the assembled system according to the selected integration parameters. Generally this involves determination that each module with specified communication needs can in fact communicate with other appropriate modules. An example of this might be a robotic subsystem which can only operate properly under certain conditions; these conditions are determined by an independent sensor unit. Both the robot subsystem and sensor unit require connection to a supervisor and must have sufficient intelligence to receive commands from and report back to the supervisory unit. Though not yet demonstrated, this function of System Composer will automatically verify that these conditions are met.

After the new system has been designed, communications established and the organization validated, System Composer will search the appropriate computer networks, find the specified hardware and software, launch the system components and initiate the actual communication between them. At this point, the system is operational, and System Composer resources may become part of the operator interface for task execution.

During system assembly and operational testing, subsystem parameters may be modified and evaluated. One demonstrated example of this is the ability to switch rapidly between real and virtual devices. System operations are first halted, then by a button push, devices such as robots, sensors and tooling can be disconnected from the control loop and replaced by simulated devices in the graphical interface (and vice versa). These devices receive commands, simulate operations and report information in exactly the same manner as the real device, and are thus the key to accurate system simulations. With subsystem tests, the

simulation can be "tuned", multiple cycle tests run to validate complex system operations, and tasks pre-programmed without actual hardware movement.

System Composer has been demonstrated in several applications using machines, software and computing resources at distant locations. One of the first demonstrations was a system comprising a Schilling Titan II robot and controller, a capacitive Whole Arm Protection (WHAP) sensor, SANCHO supervisory software, IGRIP* graphical simulation software, and a force-torque arm for operator feed-back. These were defined, assembled, and operated in both virtual and real modes. The robot, controller and WHAP sensor were located approximately 1.5 kilometers from the computing systems operating System Composer, the supervisor, graphical simulation and the force-torque feedback arm. All of the components were connected only by standard networks. The entire process, from initiating the System Composer (Figure 2) to actual system operation, was completed by one person in approximately five minutes. This compares to an estimated custom integration time of two to four months

A second System Composer demonstration is associated with a project called "Agile Manufacturing Production System" (AMPS). This flexible, modular factory's first trial product is a delicate switch tube assembly, which calls for the integration of an assembly subsystem, a transport subsystem, and a task sequence control unit. The assembly subsystems in this case are Adept SCARA robots, augmented by a vision system for location of the part trays fed by a Bosch conveyor subsystem. The production script for the system is automatically derived from a CAD file analyzed by the Archimedes system (see A^{primed} below for further description). Parts are retrieved, aligned, and stacked in proper order in a fixture, then transported to a sintering furnace. The task sequence control unit will coordinate the assembly resources, balancing loads between assembly stations in real time. System Composer integrated the production components and operated the system in virtual mode, in 10-20 percent of the estimated manual time required. At this writing, one Adept workcell has been assembled and demonstrated using the system thus integrated, and the entire production facility is being assembled. By accurately simulating the entire production line, system sequences will be debugged before the actual hardware is operational.

A third example of System Composer use is in the demonstration of how a long-reach manipulator (LRM) would be used in underground storage tank remediation (Figure 4). In this case, the final design of the LRM system is not yet complete. By assuming approximate geometries and a commercial controller, System Composer was used to assemble and operate most of the control components, including prototype sensors, in a simulation demonstration. Input devices included a 6 degree-of-freedom space ball and a force-torque arm, as well as a graphical interface. Whole-arm protection (WHAP) sensors were integrated into the control loop, and activated by hand during the demonstration. As a result of the System Composer integration, much of the LRM control system and some of the prototype hardware has been demonstrated years prior to the full system implementation. This provides ample opportunity to find and address software and hardware issues in the overall control system and existing equipment, and prepare for final integration of the longer lead time equipment. The integrated system and time gained in this way may also be utilized for operator training purposes, allowing the operators to train on actual equipment while cutting training time from the critical path.

* IGRIP is a registered trademark of Deneb Robotics, Inc., Auburn Hills, Michigan, USA.

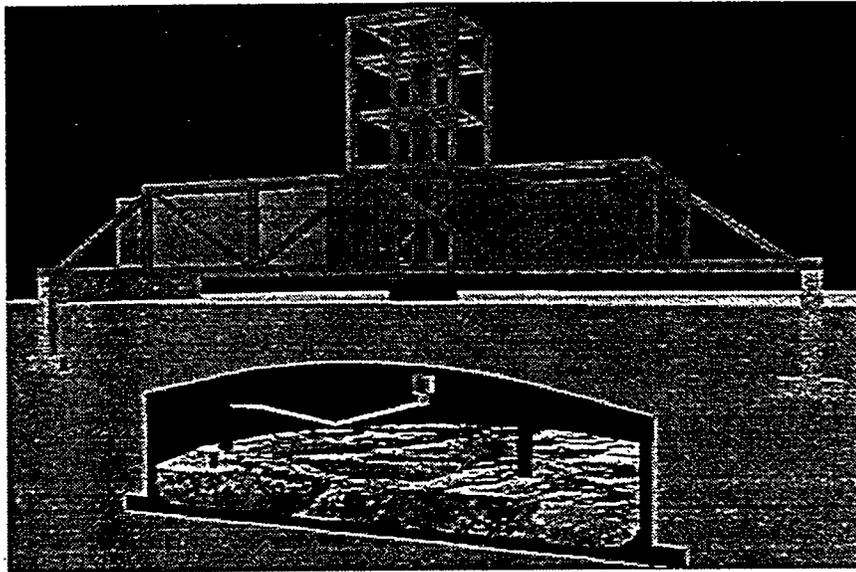


Figure 4. Long-Reach Manipulator (LRM) simulated deployment for underground waste storage tank remediation, as viewed from System Composer.

The progressive improvement in system integration is illustrated by a sequence of projects involving multiple robots, sensors, processors and controllers. In a demonstration of robotic technology for underground storage tank remediation in 1991, approximately 75 person-months were required to integrate multiple robots, processors, tools, sensors and simulation software into a working system. In an unrelated demonstration in 1993, a system with similar components was integrated in approximately 15 person-months. These improvements were due, in significant measure, to the use of the GISC approach. Similar systems today, with components developed in the GISC format, could be assembled and reassembled in a matter of days. By making use of modular, reusable code, and by simulating system behavior in parallel with system development, System Composer is reducing cycle times, simplifying the processes, and improving efficiencies of system integration efforts.

Virtual Collaborative Environment

Virtual Collaborative Environments (VCEs) are information architectures that make it possible to share electromechanical resources including robots, machine tools, sensors, or other machine systems and software resources across great distances⁵. VCE technology is a powerful tool particularly for robotics and remote technology development.

These software resources can be controlled from computer workstations connected to the proposed National Information Infrastructure (NII). As illustrated by Figure 5, a researcher or operator at one of those stations can explore the possible utility of software that has been developed at a different laboratory or university. They can then test its effectiveness on robotic hardware that is installed at a third site.

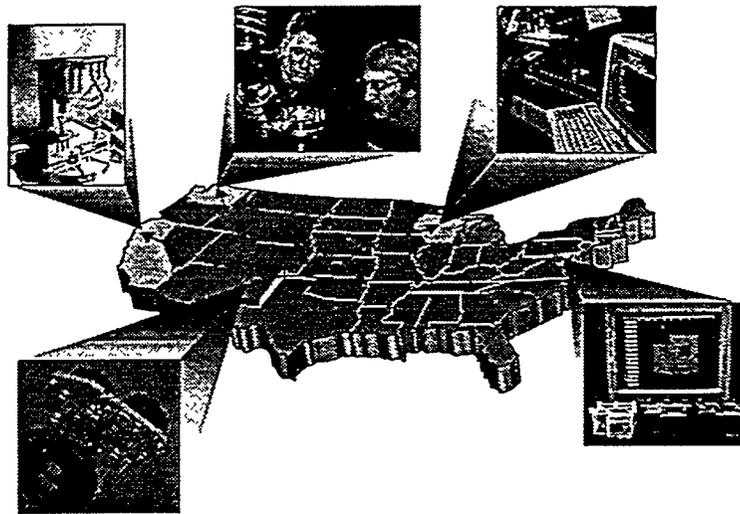


Figure 5. Virtual Collaborative Environments link widely-dispersed resources in a virtual laboratory or manufacturing mode.

To test this concept, SNL has collaborated with the U.S. Department of Commerce's National Institute of Standards and Technology (NIST) to operate robotic workcells at SNL in Albuquerque. Researchers at NIST used graphical programming techniques to generate paths and robot functions, then downloaded the commands to the SNL system across a 1.5 Megabits/second network connection. During the execution phase, live video and equipment position updates were returned to the remote site for viewing. This entire remote programming and viewing process required only seconds. SNL robotic workcells in New Mexico have been controlled in a similar manner from the states of Washington, California, Oregon.

The VCE derives much of its integration and execution capability from the System Composer. When a remote resource is to be connected into a local system, System Composer can be used to establish the appropriate communication links and inform other system components of any new hierarchy. Virtually all of the System Composer capabilities can be utilized where a VCE is desired.

When operating remotely, however, additional issues must be addressed. Long distances and large amounts of data transmitted over computer networks can result in communication delays or latencies that hinder real-time control of remote devices. Safety and security are also a concern. Control of the resources within networked systems must be maintained, excluding outside influences from the control loop. The proprietary nature of the resources and activities must also be considered and interests protected. To address control and safety issues, the current mode of operation, as demonstrated with NIST, is to locally review and approve commands generated remotely prior to permitting execution of operations. Secure network communication and encoding methods are currently being explored to address security and proprietary issues.

The value of the VCE lies in its ability to rapidly bring together widely dispersed resources into a "virtual laboratory". In programs sponsored by the U.S. Department of Energy's Office of Environmental Management, more than 20 widely-dispersed National Laboratories and universities, as well as numerous commercial enterprises are developing robotic technologies for the retrieval, handling, packaging and safe disposal of hazardous waste. Similar cooperative efforts exist elsewhere in the world, such as the European

Commission's TELEMAN Programme, which coordinates a multi-national team addressing Telerobotics in the Nuclear Environment. Producing a coherent product from such diverse resources is a coordination and logistical challenge. By providing a virtual presence, colleagues can instantly share data and control of resources regardless of location.

Rapid VCE connections can increase productive communications between organizations. With proper equipment and network access, resources can be linked in a matter of minutes. The convenience of establishing effective connections for system development and testing purposes could promote more frequent or even constant high-density communications between collaborators. In the case of the SNL - NIST connection, constant audio, visual and data communications were maintained for hours and even days during development of the remote robotic demonstrations. This communication promoted a synergism between the organizations that increased effectiveness of the collaborating teams.

Established VCE connections can also facilitate scheduling of resources. Research organizations often have resources such as robots scheduled for multiple programs. For some potential collaborators, particularly universities, prime user time occurs during the summers and semester breaks, which become scheduling bottlenecks. VCEs would permit use of the resources by the universities without the need to leave campus, allowing in-session testing, thus adding flexibility to scheduling while at the same time saving travel costs.

Commercial enterprises may also benefit from establishment of VCEs. For example, testing of a new machine or set of machines for both function and compatibility with an existing system might be accomplished while the machines are still at the fabricator. Communication and control difficulties could be identified and resolved prior to delivery, resulting in shorter installation and "burn-in" periods. Demonstrations of operation and compatibility using actual equipment at different locations may benefit both client and vendor, facilitating decisions regarding future capital equipment investment, as well as providing a useful marketing tool.

Increased applications of Virtual Collaborative Environments will thus enable government, university and industrial groups to test concepts and demonstrate systems with a regularity, flexibility of schedule and minimization of logistical cost never before available.

A^{primed}: Agile Product Realization of Innovative Electromechanical Devices

The concept of bringing together a broad spectrum of minds and resources to rapidly create and test a new product family is exemplified in the manufacturing arena by a project at SNL known as A^{primed}. The A^{primed} project integrates many of the key components of "agile manufacturing"⁶ into a complete, step-by-step, design-to-production process, with the goal of minimizing new product-to-market cycle time. Among the elements of A^{primed} are communication and information flow, human factors and statistics, component design, process characterization and fabrication technologies including robotics.

To demonstrate how designing for a family of products (rather than a single product) could reduce time to market for custom devices, a low-production-volume nuclear safety device called a Pin-in-Maze Discriminator (patent pending) was chosen for product design (Figure 6). A Discriminator is much like a combination lock, designed to prevent unintentional activation of a system. A pin follows a maze unique to each Discriminator, changing direction according to a received signal. A ratchet prevents backward movement. If a

sequence of signals is not precisely correct, the pin will become trapped and the Discriminator will seize, preventing any further advance toward activation.

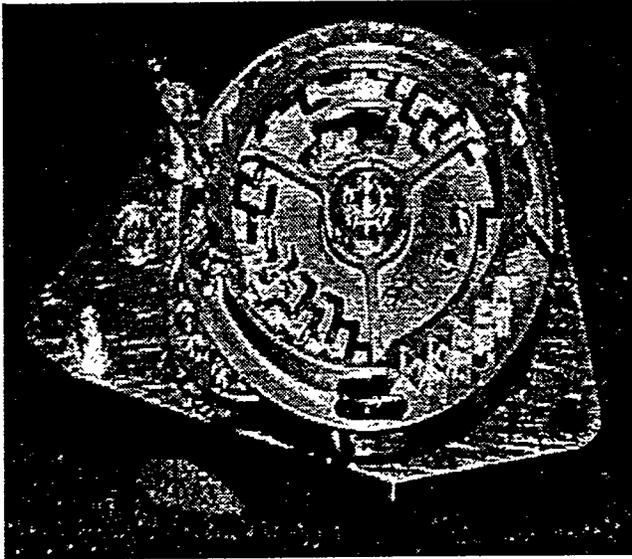


Figure 6. Assembled Discriminator safety device

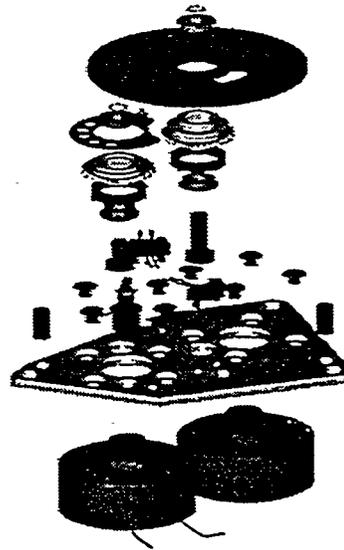


Figure 7. Discriminator assembly simulation

A typical Discriminator has approximately 40 component parts with a variety of sizes and shapes. Alignment tolerances are very tight, and the angular alignments critical. Clearances are extremely small, ranging down to 15 μm . Approximate manual assembly time is 4 hours for some critical components.

For effective quality production of unique product, a Parent/ChildTM design concept⁷, testing and/or analysis were applied in all stages of the design process. Discriminators with some common components and some parametrically configurable components can meet very different customer requirements for speed and robustness. The variations are represented by a parameter design space from the "Parent"⁸, from which a "Child" design can be created, hence the name Parent/ChildTM design concept. Components common to all units such as motors, bearings, gears, mounting plates and controllers can be tested once to cover all design variations. Each mazewheel could be different, however, requiring unique parametric path generation. To prevent unwanted seizure of the Discriminator due to warpage, testing and/or finite element analysis of each mazewheel could be required.

To speed the initial Discriminator design and the subsequent maze wheel analyses, A^{primed} promotes concurrent engineering communications using Interactive Collaborative Environments (ICE) for X applications sharing⁹. ICE is a method which permits distributed engineering staff to share visual and computing resources on-line in real time. Rapid and seamless information exchange between members of a project team is facilitated in ICE by streamlining communications and information flow. A central Product Data Management system configured to support Parent/ChildTM design is also used to reference current design, manufacturing and test information¹⁰.

Machine and process characterization - the need to know what machines, tools, and machine settings (feeds and speeds) are capable of producing the required parts - is also a part of A^{primed}. Milling settings and inherent variability of processes were characterized to

ascertain capability of producing required parts. A force-controlled robotic deburring and edge finishing operation was also available for complex components requiring such operations.

Reliable, repeatable processes are essential for quality production of unique products. Therefore, technologies for robotic assembly were also developed and/or integrated into the A^{primed} effort. SNL software called the Archimedes System accepts assembly models from Pro/Engineer or ACIS, determines whether the design can be assembled, produces valid assembly sequences, then automatically translates the sequences into robot code for an Adept robot-based simulation using Cimstation[†]. Simulation immediately illustrates the assembly process with parts interactions, and generates assembly documentation. Task planning software and plan translation software can automatically prepare a detailed device-specific robot program that can drive a workcell. Simulation immediately illustrates the assembly process with parts interactions, and generates assembly documentation.

A robotic workcell to assemble the family of pin-and-maze discriminators is shown in Figure 8. It consists of a single controller for both an Adept SCARA assembly robot and a cartesian robot that delivered a tack-welding laser beam, integrated machine vision, three grippers to accommodate 1 mm to 51 mm grasping widths on various shapes, robotic adhesive dispensing tools, a parts tray, 4 assembly fixtures and application software to integrate the system. The robotic workcell has shown the potential to reduce overall assembly time by up to a factor of 40, with about 2/3 of the operations demonstrated to-date.

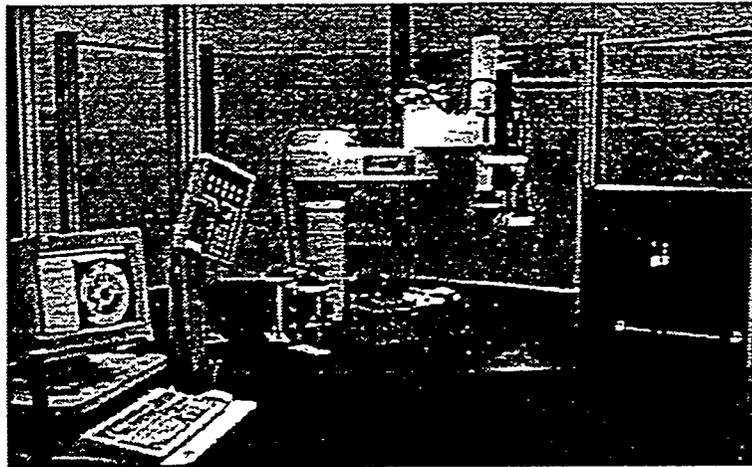


Figure 8. A^{primed} Pin-in-maze Discriminator assembly workcell

A^{primed} has demonstrated significant reduction of design-to-production cycle times for precision electromechanical devices. For two separate product realization efforts, each geared to a different set of requirements, A^{primed} demonstrated complete design to product realization of a custom device in less than a month¹⁰. This reduction was achieved through the Parent/Child[™] design concept, which requires a number of re-useable technology advances. Advances include automating some parametric designs, automating previously time-consuming portions of analytical processes, automating generation of assembly sequencing, and automating generation of control code for a flexible assembly workcell. Similar to other integration efforts at SNL, elements of the A^{primed} project are all

[†] Cimstation is a trademark of SILMA, Inc., Cupertino, California, USA

linked together using computer networks for high-speed communications and efficient, tailored interactions.

Summary

In a capital and resource-competitive environment, increased cooperation and resource sharing among organizations has become increasingly desirable. Three technologies developed at Sandia National Laboratories have been presented that enhance the abilities of research and commercial organizations to collaborate more effectively.

System Composer is a menu-based application to integrate large robotic systems from diverse hardware and software components. It allows the system integrator to choose an available rules package, (such as GISC), communication protocols, system supervisory software, hardware subsystems, and analytical and decision software subsystems. The modules chosen can then be arranged graphically by "drag and drop." The configuration is then validated automatically and launched by System Composer.

Virtual Collaborative Environments (VCEs) are information architectures that make it possible to share electromechanical resources including robots, machine tools, sensors, or other machine systems and software resources across great distances using electronic networks. Based on System Composer capabilities, the VCE is enabling government, university and industrial groups to test concepts and demonstrate systems with a regularity, flexibility of schedule and minimization of logistical cost never before available.

The A^{primed} project integrates many of the key components of "agile manufacturing" into a complete, step-by-step, design to production process. A^{primed} demonstrated product realization of a custom device in less than a month, using a process that is readily adaptable to other electromechanical devices. The process includes qualifying a design parameter space for a family of products, using extensive virtual and physical testing, as well as all facets of requirements development, analysis and testing, design, parts fabrication, and automated assembly planning and execution. The intensive collaboration between the disciplines is enabled with an electronic infrastructure including product data management and virtual co-location communications.

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