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Simulation and Off-line Programming at Sandia's Intelligent Systems and Robotics Center[1]

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1. Introduction

One role of the Intelligent Robotics and System Center (ISRC) at Sandia National Laboratories is to address certain aspects of Sandia's mission:

- to design, manufacture, maintain, and dismantle nuclear weapon components.

Hazardous materials, devices, and environments are often involved. Because of shrinking resources, these tasks must be accomplished with a minimum of prototyping, while maintaining high reliability.

In this paper, we describe simulation, off-line programming/planning, and related tools which are in use, under development, and being researched to solve these problems at the ISRC.

1.1 Overview

The ISRC uses many commercial and in-house simulation tools to address system development needs in design, visualization, model-based control, and training. Where simulation is not feasible or requires further validation, the ISRC uses its prototyping facilities to provide experimental data to support development. Some ISRC in-house extensions to commercial simulation software have been driven by teleoperation needs. We also have brought practical automated assembly- and motion-planning systems on-line in the past few years. Other ongoing work seeks to bring design into the loop more tightly by combining automated planning with process-feasibility analysis and blending simulation technology with CAD.

Commercial simulation tools in daily use in the ISRC include:

- robot workcell-level simulators, such as Deneb's IGRIP and TELEGRIP, Silma's Cimstation, and Cimetrix's Cimulation;
- human/machine interaction simulations, such as Deneb's ERGO;
- discrete-event simulators, such as Deneb's Quest, for factory system simulation.

To address needs not met elsewhere, the ISRC has developed several modeling, simulation, visualization, operator interface, controls, and CAE tools. Some of these extend commercial products, while others are full in-house system development or integration environments. Tools and systems include:

- Sancho, a Graphical Programming system and Virtual Collaborative Environment;
- REMS, which adds radiation dosimetry to IGRIP simulations; and
- System Composer, an environment that assists in defining manufacturing system requirements and maps them to a component-level system definition.

We have also developed several other software packages that provide fundamental capabilities in simulation and automated programming and planning. This software includes:

- SMART, a modular control technology that is used both for haptic interface development and for piecewise refinement of control systems;

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- Archimedes, an automated assembly planner;
- SANDROS, a motion-planner whose performance smoothly bridges the gap between interactive and off-line motion-planning;
- Umbra, an object-oriented, extensible simulator kernel;
- the C-Space Toolkit, a library providing fast distance and interference computations; and
- Holdfast, which automatically designs fixtures for a given part, process, and modular fixture kit.

We are also attempting to advance simulation and automated planning/programming technologies in several areas:

- physical simulation with intermittent contact, and multi-level, variable-resolution simulation;
- combining life-cycle assembly-planning with ergonomically constrained motion-planning; and
- merging and extending CAD and simulation.

1.2 Roadmap to the Rest of this Paper

Section 2 describes the use of commercial simulation tools in the ISRC and important extensions that we have made for our needs. Section 3 describes advanced in-house automated programming and simulation technologies that are less coupled to commercial products. Finally, Section 4 describes directions for future work.

2. Commercial Simulation Tools as Used and Extended by the ISRC

In Section 2.1 we describe how the ISRC has been using simulation in the development of systems. In some cases, commercial products have been extended with Sandia technology to meet special needs. (See Section 2.2.) Integration and development environments built at the ISRC make use of both commercial products and in-house simulation and automated planning modules. (See Sections 2.3 and 2.4.) For many applications, simulation tied to model-based control is used in both operational and low-level control of key system functions.

2.1 Simulation at Work in the ISRC

The ISRC has been using simulation at the conceptual design phase to visualize and test workcell arrangements and quickly compare solution directions. For example, Deneb's IGRIP and Silma's Cimstation are used to visualize and evaluate robot and workcell size and layout requirements. The robotics layout-focused GUIs, extensive robot libraries and focused analytical tools allow rapid configuration and testing to shorten the engineering time needed for concept development.

For several systems where the ISRC was responsible for delivery of a production system, such simulation products were used for system conceptual design. Videotapes and images of the system in simulation aided the project engineers in communicating many characteristics of the system to the customers, who were unfamiliar with robotic operations. Accurate communication of characteristics, such as process flow, robot motions, station layouts, and overall system dimensions, helped immensely in negotiating to a common concept among the ISRC providers, their sponsors, and the system end users.

In other situations, workcell simulations were only part of the overall simulation performed to create a conceptual design for an entire facility. In these cases, discrete event simulation tools such as Deneb's QUEST were used. In one case, the ISRC performed conceptual simulations of a civilian nuclear waste storage facility to prioritize development of robotic technologies in ways that best met the facilities long-term needs. Following up on simulation results, the ISRC used its prototyping capabilities to test and develop new special nuclear materials handling technologies for several operations within the facility. These demonstrations provided proof-of-concept to the facility planners, showing how robotics could be used where people could not go or where the radiation environment made operations difficult or slow for people to perform. Similar discrete event simulations and prototype demonstrations were also performed for a possible future plutonium storage facility. This project also included performing trade-off studies to determine optimal quantities of equipment (e.g., calorimeters) and facility features (e.g., truck ports) within the large facility.

The ISRC also has used simulation during detailed design to refine layouts, define mechanical component requirements, and develop initial software solutions. Both workcell and device-level simulators, and CAE tools are all used during this phase of design.

2.2 Integrated Radiological Environment Modeling

The Radiological Environment Modeling System (REMS) provides an example of how the ISRC extends commercial tools to address domain-specific needs. This system quantifies doses to humans working in radiological environments using Deneb's IGRIP and ERGO software. These products are augmented with custom C code to provide radiation exposure informa-

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tion to, and collect radiation dose information from, workcell simulations.

Through the use of a radiation transport code or measured data, a radiation exposure input database is formulated. User-specified IGRIP simulations utilize these databases to compute and accumulate dose to programmable human models operating around radiation sources. Timing, distances, shielding, and human activity may be modeled accurately in the simulations. The accumulated dose is recorded in output files, and the user is able to process and view this output. The entire REMS capability can be operated from a single graphical user interface [1].

REMS was developed because reduction in the radiation exposure limits may preclude or require changes in many of the manual operations currently being utilized in the nuclear weapons complex, nuclear power industry, radioactive waste disposal operations, and the field of nuclear medicine. REMS provides a graphical model of processes of interest, identifies equipment required, determines production rates, and quantifies the dose associated with the processes so that the benefits of automation versus manual operations can be identified and understood.

2.3 Graphical Programming, Virtual Collaborative Environments, and Sancho

The ISRC's efforts in Graphical Programming began with the need to preview and debug robot programs for handling hazardous materials in both structured and semi-structured high-consequence environments [2]. Graphical Programming uses 3D graphics models in an intuitive operator interface for programming and controlling complex robotic systems. It brings engineering simulation to the operator or programmer. Sandia's Graphical Programming systems allow operators to focus on high-level robotic tasks rather than the low-level details through features such as its model-based control architecture, "point-and-click" graphical user interfaces, and task and path planning software. Use of high-level task scripts minimizes the necessity of recompiling supervisory control system programs. Simulation enables users to preview the execution of the final robot control program and debug it if necessary.

Virtual Collaborative Environments (VCEs) combine shared, distributed virtual scenes with interaction over a network. The utility of VCEs is to allow distributed problem solving, sometimes through the use of specialized analytical tools. When used to extend Graphical Programming, VCE systems allow teams to collaboratively operate, evaluate, and maintain robots, machine tools, and other mechatronic systems. For example, robot control programs for individual subtasks can be developed by multiple engineering teams and coordinated to complete the overall task.

Sancho is Sandia's most advanced Graphical Programming supervisory software and is in use on several robot systems. It incorporates the advances described above and uses commercial software for robot kinematics, visualization, control, and operator interaction. Important components link kinematics and other high level model data to enable VR-based visualization and interaction over a network. Sancho can be rapidly reconfigured for new tasks and operations without modifying the supervisory code. Innovations, such as task-based interfaces, and event-based sequencing, have resulted in robot control methods that are easier and safer to use than teleoperation, off-line programming, or full automation. Sancho has also served as an integration point for various ISRC technologies. (See Figure 1.)

Sancho uses IGRIP and Telegrip for robot simulation, user-interaction, and control.

2.4 System Composer

System Composer is an integration environment that assists in the incremental definition of manufacturing-system requirements and in the mapping of those requirements onto the components of the manufacturing system. A graphical and hierarchical editor based on the VISIO commercial package is used to define the manufacturing process flow. System Composer manages the requirements and specifications development for a workcell or system and facilitates the use of advisors to decompose manufacturing processes into successive levels of detail. For example, at a low level, an interactive tool-and-operation editor has been developed to assist in the definition of tool algorithms and workpoints. Interfaces to other analysis and simulation products are being established. For example, an interface to obtain assembly planning information from Archimedes (see Section 3.5) has been created.

The system definition generated with System Composer is also used for simulating the desired manufacturing system. In this case, System Composer may use Umbra (see Section 3.2) with SGI's Performer for visualization of workcell operations. Thus, System Composer assists in the generation of the conceptual design and provides feedback to the design process as the manufacturing specifications are iterated to final design of both product and required manufacturing processes.

3. Advanced Simulation and Automated Programming Technologies

As resources for nuclear weapon maintenance and limited-life component production and design continue to decrease, it is becoming more important to predict how components will perform and how they will be manufactured, before they are produced. This, along with the difficulty of cleaning up hazardous waste environments, creates a need for software which moves from the realm of off-line programming to automated programming, including component assembly planning and robot motion planning, as well as more extensive simulation environments.

3.1 SMART

SMART (Sequential Modular Architecture for Robotics and Teleoperation) is a patented object-oriented system integration tool focusing on the rapid prototyping of "Telerobotic" systems, i.e., systems involving direct, continuous interaction between humans and mechanisms [3]. SMART allows the system developer to construct a complex system consisting of input devices (e.g., spaceball, teach pendants), sensors (e.g. capacitive proximity sensors, ultrasonic sensors, strain gauges), and robots (industrial gantry and pedestal robots, hydraulic manipulators) by connecting icons representing each sub-component. Once all the telerobotic behaviors have been generated, an autocode generator produces the source code needed to run the complete system, including run-time code, communications software and the operator interface. Because each module represents a passive sub-component of the system, stability for the connected system is guaranteed.

SMART has been applied to such diverse problems as cooperating robots, redundant robot control, force reflecting telerobotics, and kinesthetic virtual reality. To date, over 150 different modules have been developed. Because of the object-oriented nature of SMART, it is possible to move from a virtual equivalent of a robot running in a commercial robot visualization product such as IGRIP, to actual run-time operations with a robot, simply by replacing a single module in the system.

SMART has been fielded as part of a Navy robotic painting demonstration project. It is also being delivered to Hanford as part of a light-duty utility arm (LDUA) training and path generation environment.

3.2 Umbra

Umbra is a general simulator kernel that models systems as networks of modules that model system components. Modules operate within a single time-coordinated environment, and computation and data flow can be systolic or event-driven. A graphical user interface (GUI) with point-and-click interaction and 3D visualization enables the use of completed models as interactive applications. Umbra provides an interpreted interaction environment which allows the user to define, test, and optimize networks of compiled modules without re-compiling or re-linking the system. Umbra provides a class structure to allow engineers to develop and test modules with well-defined input-to-output transfer functions. Umbra is written in C++ and Tcl/Tk and uses SGI's Performer as its visualization interface.

Umbra has been used in three applications so far. First, Umbra has been used to develop training simulator and operator visualization tool on the Light Duty Utility Arm (LDUA), a teleoperated waste-remediation robot system. Second, Umbra has been used within System Composer to simulate the multi-robot Agile Manufacturing and Prototyping System (AMPS) to analyze potential manufacturing workcell configurations. Third, Umbra serves as the basis for a simulator used to develop mobile robot programs and evaluate design options for Small, Smart Machine (SSM) applications.

3.3 C-Space Toolkit

The Configuration Space Toolkit (C-Space Toolkit, or CSTk) is a software library that makes it easier to program motion planning, simulation, robotics, and virtual reality codes. Key functionality (a) enables the user to create special representations of movable and stationary rigid geometric objects, and (b) performs fast distance, interference (clash) detection, collision detection, closest-feature pairs, and contact queries in terms of object configuration. Not only can queries be computed at any given point, but they can be done exactly over linear-translational path segments and approximately for rotational path segments [4]. The Toolkit takes as raw model input collections of convex polygons that form the boundaries of the models.

Configurations are given in terms of homogeneous transforms. A simple system for displaying and animating the geometric objects is included in the implementation. The C-Space Toolkit currently serves as the geometry engine for the SANDROS motion-planning system described below. Current plans will integrate the CSTk with Umbra to add the CSTk's geometric capabilities to the general simulation kernel. The CSTk is also being used in the Dynamical Simulation and Immersive CAD projects described in Sections 4.1 and 4.2.

3.4 Motion planning

Over the past decade, motion planning has been an active area of research in the ISRC. Collision-avoiding motion planners have been developed for point-to-point, visit-point, trace-curve, and cover-surface problems for manipulators. These problems cover a variety of practical problems, from simply moving the end-effector to spot-welding to surface-painting.

The best-known of these algorithms is the SANDROS (for *Selective and Non-uniformly Delayed Refinement Of Subgoals*) point-to-point planner [5]. The current implementation is fast enough to be used interactively for everyday point-to-point motion planning problems, and it uses Telegrip for a front-end. SANDROS's planning time varies with the difficulty of the problem. Specifically, SANDROS runs as fast as a collision checker when a simple jointspace-interpolated point-to-point motion suffices for collision free motion, and planning takes progressively more time as necessary detours become more difficult. On problems up to medium-size (10K polygons) and difficulty, planning takes less than a minute on a modern workstation, and often much less time.

SANDROS can be used for producing collision-free motion given either an interference-free start and goal or a sequence of interference-free tagpoints that might cause collisions under joint interpolation. A post-processing module smoothes the final path output. We have already found it useful in automated off-line programming, and we look forward to using it as an interactive motion-synthesizing tool in building simulations.

3.5 Archimedes Assembly Planner

A major component in the ISRC's automated planning toolset is Archimedes [6]. Input to Archimedes consists of a complete CAD model in ACIS format, plus an assembly description file. The basic output is an assembly plan, but current project emphasis is in the direction of cost analysis, cost optimization, and multimedia output. The final chosen plan can be exported in a variety of text forms, as video, as a Web-browsable HTML plan, or even (soon) as a VRML2 animation. (See Figure 2.)

Archimedes' processing can be viewed as four progressive stages. First, after Archimedes has loaded the model, it checks for geometric validity by assuring that each contacting pair of parts is separable along at least one insertion direction. Problem situations due to modeling limitations can be "overridden" by the user, who tells Archimedes what to do in incorrectly modeled situations. Next, Archimedes derives an initial, geometrically valid assembly plan. Assistance from the user is rarely needed, and a z-buffer-based motion-feasibility-checking makes this step surprisingly fast. Assembly plans for up to a few dozen parts are produced in seconds, while assemblies of roughly 500 parts have taken about 20 minutes. Third, the user incrementally imposes additional constraints and Archimedes re-plans until a practical plan is produced. Re-planning is an order of magnitude faster than the initial planning, due to cached assembly information. Finally, the user can choose a cost function and ask Archimedes to find a plan which is geometrically correct, satisfies all given non-geometric constraints, implements the user's specific instructions where the model was deficient, and for optimizes the chosen cost function.

3.6 Automated Gripper and Fixture Design

Another ISRC automated planning tool is Holdfast, which creates plans for part fixtures [7]. Holdfast takes geometric data about a component to be fixtured as input and produces appropriate fixture geometry to securely hold the part for machining or assembly processes. The fixture geometry is based on modular fixture kits. It is composed of vertical posts, which either constrain the horizontal movement of the part or support it from below, and clamps, which further restrict part motion once the part has been loaded into the fixture. Holdfast also takes input about the expected forces during the machining/assembly process and uses that to determine the optimal placement for the posts and clamps. In addition, Holdfast can incorporate process-related constraints on the placement of clamps and posts into the fixture plan.

For a given problem, Holdfast generates an initial fixture plan quickly and then proceeds to calculate plans that optimize the fixture for the expected forces. Geometry for modular parallel jaw grippers can be automatically generated by Holdfast similarly. When these grippers are closed, they hold a part using the sides of posts that are mounted on each jaw of the gripper. (See Figure 3.) The Holdfast software has also recently been extended to evaluate existing fixtures when a component to be fixtured has had an incremental design change.

4. Technologies for the Future

The expected needs for small-lot production of nuclear weapon components early in the next century include new abilities to simulate and visualize parts of the design to production process, as well as extensions of technologies discussed in the last section. We now outline several simulation- and automated-programming-related research areas at the ISRC: dynamical, multi-level, and variable-resolution simulation; the marriage of assembly planning and motion planning with ergonomic constraints; and a more flexible CAD/simulation capability.

4.1 Improving Simulation

The ISRC's interest in physical simulation results from the need to produce new designs with highly maintainable reliability in the face of limited testing resources. In particular, we wish to predict the statistical robustness of certain mechanisms and the assembly, disassembly, and maintenance procedures that contribute to their life-cycle costs. Physical simulation also is important to future directions in automated planning and design.

We are developing an efficient dynamic simulator to accurately predict probabilistic distributions of motions for arbitrary numbers of bodies experiencing multiple applied forces and intermittent contacts [8]. Currently available simulators frequently cannot handle complex time-varying contacts. Our approach utilizes a compliant surface model to account for the fact that macroscopically-rigid bodies are not absolutely rigid at contacts [9]. The model is much less computationally intensive than full finite element methods. Our primary product will be two stand-alone modules: one that provides fast collision detection and multi-contact dynamics, and another for statistical analysis. We intend to validate our simulation methods through physical experiments.

Since technology already largely exists for simulation at resolutions above and below that of (nearly) rigid-body mechanics, a natural direction for exploration is to integrate simulation at multiple levels into one environment. This means that the resolution of a simulation would not have to be sacrificed for breadth of scope when there are adequate computational resources and time. In many cases it might be possible to simulate a few components of a simulation in detail while driving the rest of the simulation with previously obtained distributions. We see this is as a solution for the problem of checking whether seemingly small changes to designs or processes will affect the overall operation of a system. Our interest in the area of multi-level, variable-resolution simulation arises from our design and life-cycle process needs and from a project that investigates the design, programming, and use of relatively large numbers of Small Smart Machines for achieving a complex task.

4.2 Ergonomics and Motion Planning in Life Cycle Assembly Tasks

With the current Archimedes assembly planner as a base, extensions are now being developed to allow inclusion of broader classes of operations in assembly planning during product design. One aspect of this effort is to include more phases of the entire product life cycle: not only initial assembly of a mechanism, but disassembly and re-assembly operations necessary for maintenance or repair, part upgrades, and recycling in product disposal. Attempts to plan these operations would highlight product design features that make maintenance difficult.

Current capabilities include tool clearances in the assembly plan. Human-body-part motions to perform assembly operations are being integrated into our software. The integrated motion planning software should also be able to assess the reachability or ergonomic practicality for a human or robot performing the assembly operations [10]. For example, use of a screwdriver alone might be possible in a remove-and-replace maintenance operation; however, when a hand is placed on the tool, the hand or the arm to which it is attached might unavoidably interfere with assembly components except in an awkward posture. Thus, ergonomic and reachability analyses would identify unfeasible maintenance operations early in the product design cycle, rather than after prototype production and integration into a larger assembly when modifications are much more costly.

4.3 CAD Meets Simulation

Tightening the design-analysis loop implies closer links between the technologies of CAD and simulation. By bringing simulation-like capabilities to CAD, we hope to improve visualization, interaction, and thereby, intuitive analysis. At the same time, achieving appropriate global and local fidelity of CAD models is necessary to maximize the return on simulation effort.

Ongoing work at the ISRC seeks to improve the use of CAD models in simulation and engineering analysis. Problems include: surface degeneracies and closure problems in solid model data, data translation problems, differences in level of detail between design and analysis models, and lack of fundamental algorithms for producing certain kinds of analysis models from 3D geometry. These discrepancies can result in complete failure to produce an analysis, or increase the time required for analysis by orders of magnitude. We hope for results that lead to seamless, automatic transitions between design and analysis activities.

We are currently developing a capability for performing solid modeling operations, including topology-changing editing, in an Immersive CAD environment. A central technology being developed is the ability to perform shape-changing operations in real time, while preserving design intent, without the long regeneration times present in current CAD systems. Providing geometry editing through an immersive (virtual reality) interface will make solid model editing much easier than traditional CAD, simplifying the task of creating models for simulation. Additionally, the immersive environment is capable of rendering simulation results directly. One environment is used for both problem definition and viewing analysis results [11].

Two other efforts seek to improve the models used in simulation. First, work is beginning on automatically converting scanned range data to CAD models in an effort we call "Cloud-to-CAD" [12]. This project addresses the need to quickly obtain accurate models of objects for which CAD data is unavailable or that deviate from the original design data because of modification, damage, natural wear, or manufacturing variation. Algorithms are being developed to recognize fundamental surfaces from scanned data and create closed solid models, in the presence of noise, and accounting for incomplete data from individual scans. A complementary project on Rapid World Modeling has been seeking to fuse range data and image data to quickly provide 3D models that are highly accurate in appearance and geometrically accurate enough for conceptual and gross-motion analyses [13].

5. Conclusion

A range of simulation and off-line programming activities are taking place at Sandia National Laboratories in the Intelligent Systems and Robotics Center. The ISRC uses off-the-shelf commercial simulation tools to help make decisions about workcell and facility layouts and process flows. Commercial tools with substantial extensions are used to predict radiation doses to workers, enhance the programming environment by using Graphical Programming techniques, or to integrate system configuration, requirements and operations in System Composer.

A variety of advanced programming technologies have been developed at Sandia to allow solutions to nuclear weapons complex problems. These include environments that bridge virtual and real worlds, like SMART and Umbra, as well as enabling technologies, such as the C-Space Toolkit, motion planning and assembly planning, to answer questions during planning of system operations or product design.

Finally, several new technology areas were described which reach completely beyond capabilities of today's commercial tools. Highlighted were the simulation of intermittent contact dynamics of objects, multi-level variable-resolution simulations, the combination of ergonomics and assembly planning, and new capabilities that combine the best of CAD and of simulation environments.

These capabilities show the breadth of operations typical of the work ongoing in the ISRC, either in simulation or with production hardware, in research into new computational capabilities or in the integration of commercial components with sensory systems. These capabilities are being developed primarily to solve nuclear weapons complex problems; however, cooperative projects with industry and universities also move these capabilities forward. Solutions to both nuclear weapons and industrial problems in the next few years will undoubtedly continue to provide avenues for extensions and new creations in the area of simulation and automated programming.

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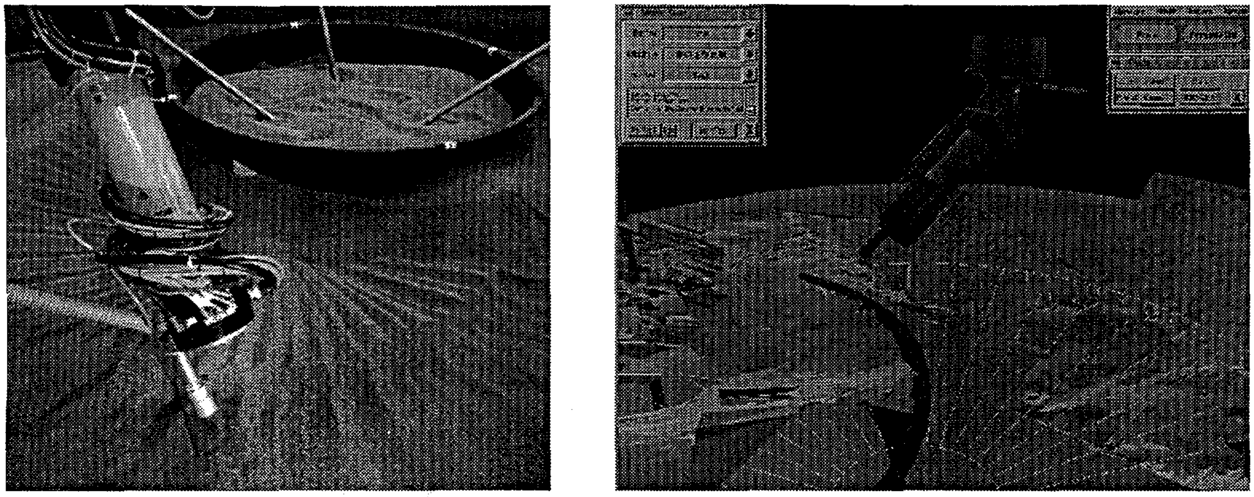


Figure 1. Sancho has been an integration point for many ISRC technologies, such as motion planning and rapid world modeling.

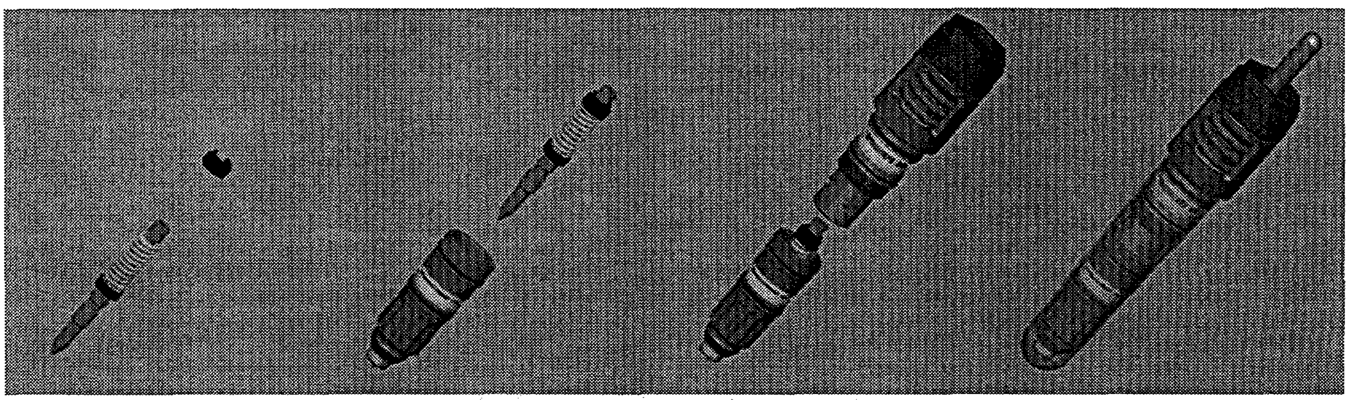
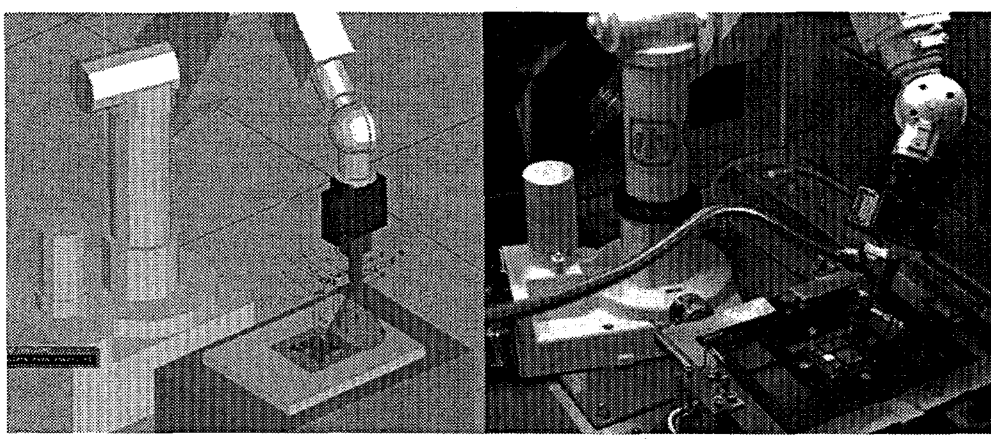


Figure 2. Shown are four steps in an assembly plan produced with Archimedes (from collaborative work with Cummins Engine Company).



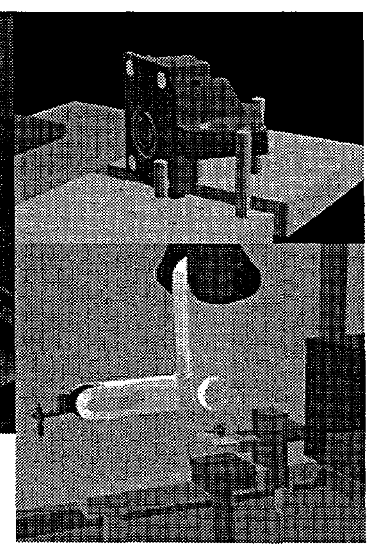


Figure 3. Sandia's Automated Component Cleaning system utilizes graphical programming and simulation, motion-planning, and automated modular gripper design.