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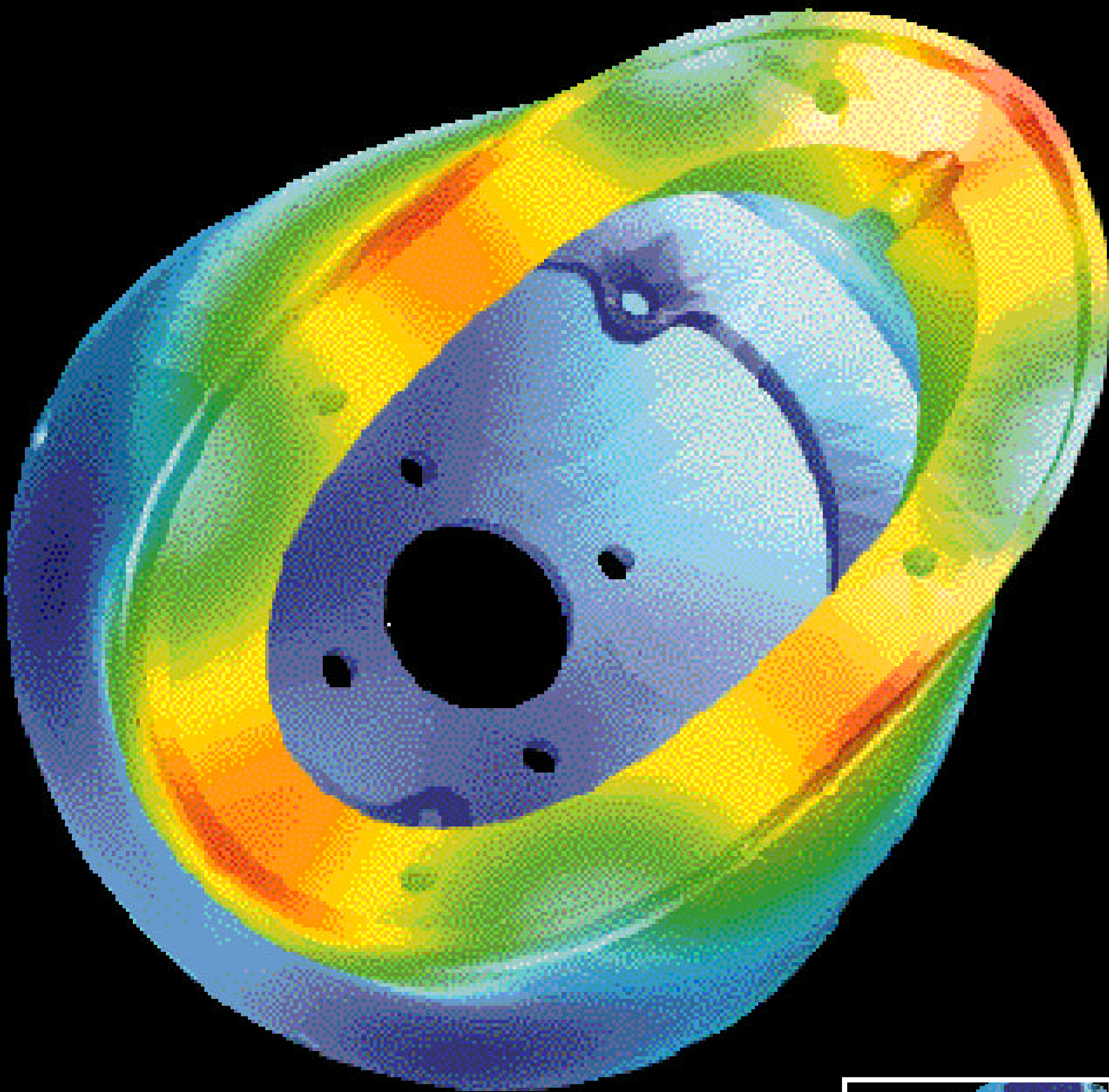
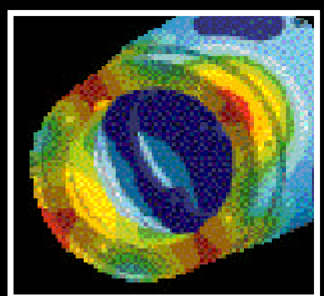
Solutions

Software Applications for Engineering Simulation and Processes





Analyzing Microminiature Devices

Multiphysics tools help develop tiny machines with parts measured in microns.

By Steve Groothuis
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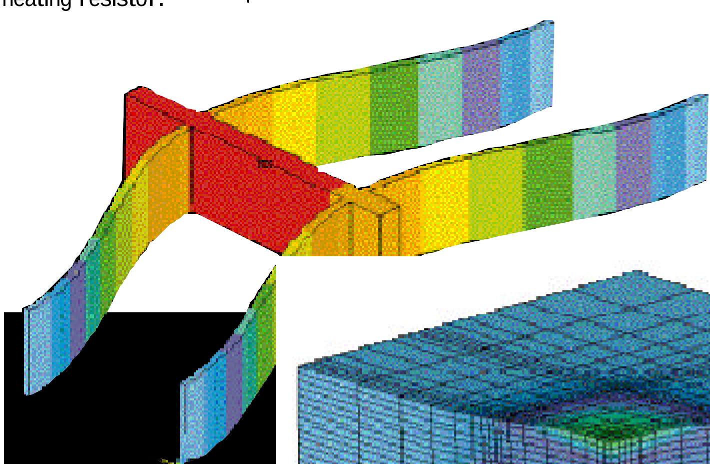
One of the most rapidly growing technology specializations is MicroElectroMechanical Systems (MEMS). Made using semiconductor fabrication techniques, these devices have tiny parts measured in micrometers (millionths of a meter or microns), and are frequently combined with integrated circuits on a single chip to provide built-in intelligence and signal processing.

These small, intricate devices must perform accurately and reliably, often in the hostile environments of vehicles and industrial machines. As a result, engineers developing MEMS must rely on finite element analysis (FEA) software to study these microstructures in determining stress, deformation, frequency response, temperature distribution, electromagnetic interference, and electrical properties.



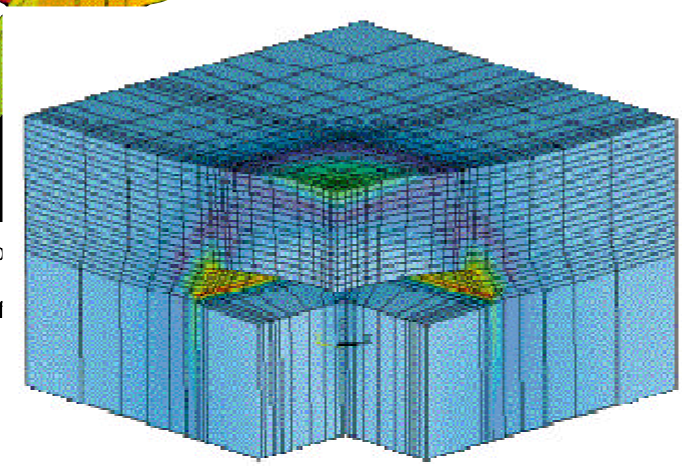
In this Lucas NovaSensor lateral thermal actuator, thermal/electric coupled-field analysis determined the displacement of the part as a result of feeding current through a heating resistor.

Rapidly Growing Market

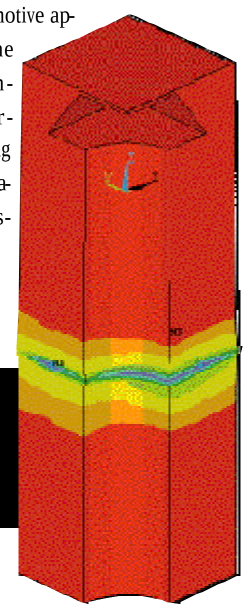
According to the market research firm Frost & Sullivan, MEMS is one of a handful of new technologies that could revolutionize the 21st century. They estimate that the total MEMS market, now at $1.4 billion, will increase at a compound annual growth rate averaging 17 percent through the year 2004, when the market is expected to exceed $3 billion.

According to Frost & Sullivan, automotive applications, such as inertial air bag sensors, comprise one-third of the total market, the largest proportion of any industry using MEMS. The medical market is another large market segment, using bioMEMS in disposable blood pressure sensors and other applications. MEMS technology also is used for ink-jet printer nozzles, display devices, and other electronic equipment applications.

Analysts at the market research firm System Planning Corp. believe pressure sensors have an especially large potential, particularly in automotive applications. According to the firm, ten or more MEMS sensors could be used in tomorrow's new cars, for measuring values like fuel level, tire inflation, hydraulic and oil pressures, and airflow.



Displacement and stress produced by fluid pressure are represented on this model of a micromachined silicon diaphragm made by Lucas NovaSensor.



Stress caused by differences in thermal coefficients of expansion for silicon, Pyrex, solder, and Kovar were determined from this analysis of a Lucas NovaSensor pressure sensor.

System Planning Corp. foresees great potential for MEMS inertial sensors, with applications such as accelerometers in air bag deployment systems, as well as vehicle suspension systems and antilock braking systems. Other promising applications include smart munitions that can alter their paths after firing, pacemakers that monitor patient activity, vibration sensors in industrial machines, and motion control applications such as robotic “grippers” and disk drive arms.

Economy and Simplicity

The MEMS advantages for these applications include the low cost and overall simplicity of the devices. Produced through the same semiconductor fabrication methods as integrated circuits (ICs), thousands of MEMS can be mass-produced on a single silicon wafer. The devices can be easily manufactured using older IC fabrication equipment that otherwise would have to be retired, since the dimensions of MEMS devices are greater than those of state-of-the-art semiconductors.

MEMS can be produced and sold for a fraction of the cost of conventional sensing devices. Conventional blood pressure transducers costing $600, for example, can be replaced by MEMS intravenous sensors selling for about $10. MEMS devices not only cost less, but their one-piece construction also is more reliable than larger electromechanical systems with multiple parts. A single-point MEMS accelerometer, for example, can replace an array of electromechanical crash sensors mounted around the front of a car and connected to a microcomputer with a complicated wiring harness.

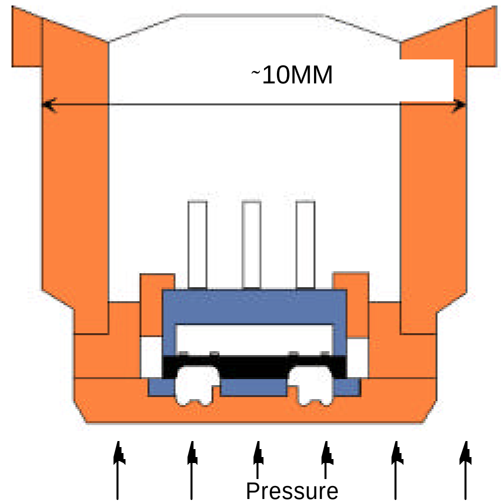
Design Challenges

One of the most formidable tasks in the development of MEMS devices is designing these miniscule parts (some thinner than a human hair) and determining how to optimize performance. These devices often perform in a machinery environment that is less than hospitable.

Developing the internal components for these devices, as well as associated packaging so that MEMS operate flawlessly for years in these demanding applications, is the challenge. They must endure damaging internal heat buildup while withstanding a variety of structural loads and ambient temperature swings. Parts also must survive severe shock and vibration, and be compatible with the media, e.g., corrosive gases.

A MEMS sensor that measures gas pressures in the range of 0.15 psig by detecting a few-micrometer deflection of a microdiaphragm, for example, often must undergo shock and vibration as it is knocked, jarred, and shaken on a piece of factory-floor equipment. “Imagine trying to detect a sneeze in the middle of an earthquake,” says one MEMS designer at Lucas NovaSensor. “That’s the scale of the task for MEMS.”

Another complication in MEMS design is that many physical phenomena interact to affect the operation of the devices, including mechanical driving forces as well as resonant behaviors, thermal levels, piezoelectric effects, and electromagnetic interference. The way in which MEMS are packaged also can affect the operation, reliability, and accuracy of the units, compounding the difficulty of MEMS design. Because many of these effects are interdependent, predicting output and performance of a MEMS device is a complex problem that defies the intuitive approaches often used in the development of larger assemblies.



The Technical University of Berlin used ANSYS software to develop a MEMS sensor for measuring cylinder pressure in combustion engines. Above is a schematic of the sensor with the package membrane-based piezoresistive sensor chip.

Developers of MEMS also have obstacles to overcome in prototype testing. While physical mock-ups of conventional electromechanical devices may undergo several test and redesign cycles, the initial semiconductor fabrication setup for MEMS is very costly and so time-intensive that prototype testing is almost always performed to validate the design rather than to identify design flaws.

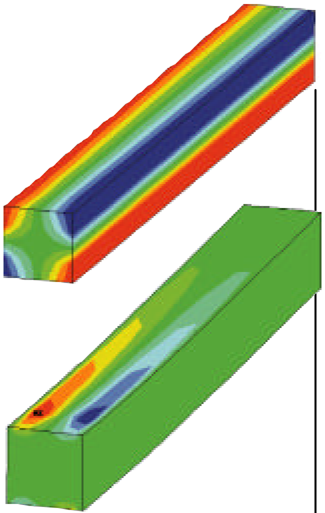
“The device has to work right the first time,” explains Steve Lewis, design engineering manager at Analog Devices. “The design has to be verified and refined up-front in development so the unit operates as intended when we validate with a single round of physical testing.”

The Analysis Solution

To meet these challenges, MEMS engineers rely almost universally on engineering simulation in designing the devices. One leading package particularly well-suited to MEMS development is ANSYS/Multiphysics from ANSYS, Inc. The package is ideal because of its capabilities such as electromagnetic, coupledfield, mechanical, CFD, and design optimization.

Multiphysics analyses simulate many different physical effects for different element types, each with its unique attributes such as material properties, boundary conditions, analysis options, loads, couplings, constraints, and solver requirements.

Structural analyses determine parameters such as stress, strain, displacement, and natural frequency vibrations in mechanical parts as a result of applied loads. Available computational fluid dynamics capabilities handle problems ranging from laminar, turbulent, and compressible flow to the simulation of pressure drops, velocities, and thermal distributions. Heat transfer problems involving both solids and fluids are common in MEMS, since heat buildup is so destructive to electronic circuits. Electromagnetic analyses are used in cases of devices with electrically or magnetically generated forces to calculate force, torque, inductance, impedance, Joule losses, field leakage, and field saturation.



Analysis by Colibri Pro Development AB shows voltage distribution in a MEMS gyroscope piezoelectric beam in resonant vibration. The top image is for maximum applied harmonic voltage. Results for voltage passing through zero are shown in the lower figure.

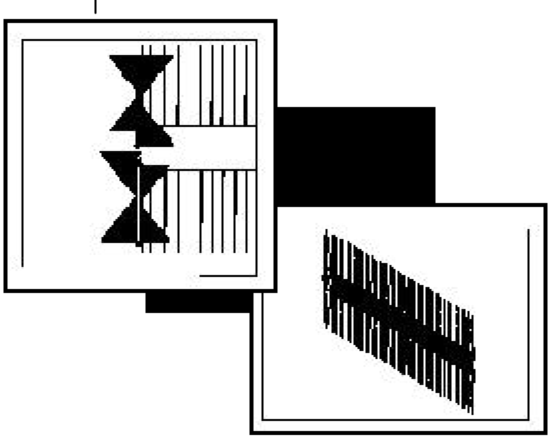
Coupled-field analysis allows users to determine the combined effects of interacting variables and is particularly helpful in MEMS design. For many of these variables, multifield elements are available in ANSYS software to directly solve coupled-field interaction. For example, thermal and electrical effects can be combined to study Joule heating, the effect of an electrical current passing through a resistive part which produces a temperature increase in the part. In MEMS, piezoelectric direct coupling of electrical and mechanical elements also is useful in determining both the amount of part deformation resulting from a given current flow, and vice versa. In ANSYS software, acoustical and structural elements also may be coupled to account for fluid vibrations and the way they are transferred to physical parts, an important consideration in MEMS pressure transducers and fluid flow devices.

Submodeling features allow users to apply an analysis output from an entire structure to a selected portion of the model, which is remeshed and analyzed in greater detail. In MEMS, this scaling capability is particularly useful in rendering details of parts measured in micrometers in a comparatively large macroassembly where dimensions often are measured in millimeters. In ANSYS software, users only specify the required region and the software automatically superimposes the correct boundary conditions. This allows engineers to obtain more accurate information about the tiny components of a MEMS device without representing the entire structure with a fine mesh.

Optimization routines determine the optimal design to meet all requirements while minimizing or maximizing specified factors such as shape, weight, temperature, deflection, etc. Users define a range of values for selected parameters and the software iterates through multiple analyses, feeding results from each into the next simulation until converging on a satisfactory result.

Simulation in Action

At consulting firm Colibri Pro Development AB, Dr. Jan Soderkvist uses ANSYS software extensively in the development of MEMS gyroscopes for high-end automotive applications such as suspension controls, rollover sensors, and navigation systems. Currently, the hottest application for the gyro is in electronic stabilization systems for cars. In these units, orientation is sensed by measuring the vibration amplitude of a tiny tuning fork.



Analysis of an accelerometer from Analog Devices shows displacement of the sensor mass.

"The vibration amplitude we are sensing in these devices is only one-tenth of an atomic radius," says Soderkvist. "With such a sensitive system, every possible physical effect must be considered, so we use coupled-field analysis and multiphysics capabilities extensively. The piezoelectric effect changes with the frequency. Thermal and electromagnetic fields interact with the tines. Therefore, the entire system has to be tuned to optimize resonance and minimize error sources from outside shock and vibration."

At Analog Devices Inc., analyst Don Carow uses ANSYS software to help him design the company's line of MEMS accelerometers. His company designs crash sensors for air bag deployment, two-axis units for front/side impacts, and a new low-G sensitivity model used recently for sensing head movement in virtual-reality headsets. The accelerometers are only nine millimeters square, with all parts made of micromachined silicon. A small central mass (800 micrometers square and 2 microns thick) is suspended by an array of spring-like tethers only 2 microns wide, spread around its perimeter. As the unit accelerates, the mass moves and forces the tethers closer to a stationary set of fingers. The resulting change in capacitance between the tethers and fingers is proportional to acceleration and is measured by built-in signal-conditioning circuitry that provides the unit's electrical output.

Carow says submodeling is essential in representing the small tethers in the context of the rest of the structure. Also, modal analysis capabilities predict mode shapes and resonant frequencies, so designs can be tuned to vibrations most often encountered in automobile crashes, for example.

According to Carow, multiphysics analysis involving different effects was particularly useful in solving a production problem with silicon wafers curling excessively during deposition and etching, due to differences in thermal coefficients of expansion between layers. "By coupling a thermal analysis with mechanical stress, we were quickly able to determine the resulting deformation and curvature using a single ANSYS model," explains Carow. "Otherwise, manual calculations and trial-and-error changes would have held up production."

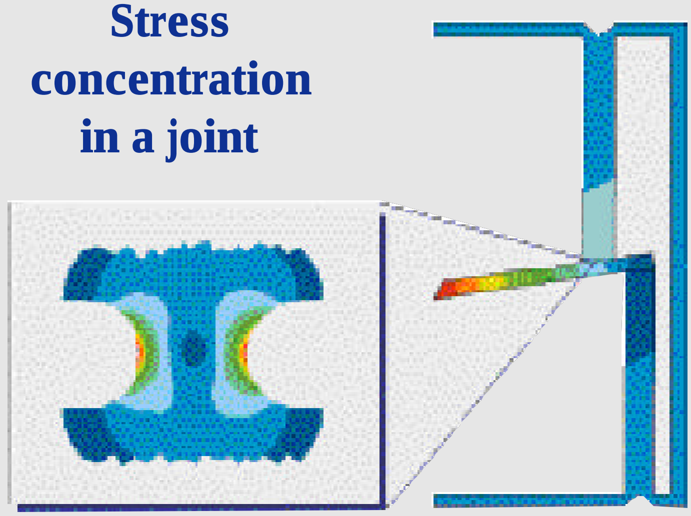
ANSYS tools also are used to handle a wide range of MEMS applications in many disciplines at Lucas NovaSensor. Their main product line consists of pressure sensors, in which a tiny silicon diaphragm deflects under pressure to change the device's resistance and produce an electrical signal.

Gertjan van Sprakelaar, senior design engineer, explains that fluid flow features are used often in their work. Also, multiphysics analyses are indispensable tools in studying thermal-actuated MEMS devices, in which an electrical current passing through a resistive structure heats the part to deform it and close a tiny electrical circuit. “In these studies, a direct coupled analysis with one solution accounts for electrical, thermal, and mechanical effects,” says Van Sprakelaar.

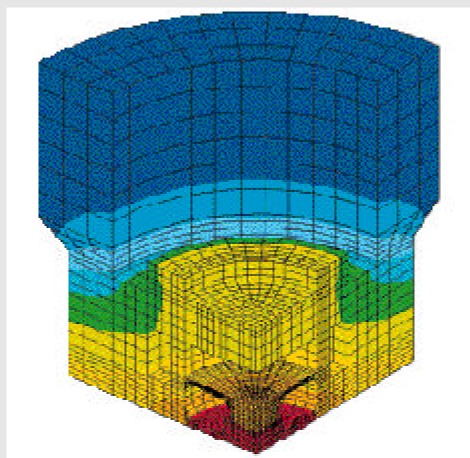
ANSYS multiphysics capabilities also are useful in packaging studies. “In devices with parts so small, sensitive packaging can significantly alter measurement accuracy,” explains Van Sprakelaar. “The problem is far too complex for manual calculations, and trial-and-error prototype testing would take too long.”

Like most of the organizations developing MEMS, Lucas views multiphysics simulation as a critical tool in the product-development process, not only for its specialized analysis capabilities, but for its power in communicating design ideas and facilitating cooperation among members of the development team. According to Van Sprakelaar, analysis software helps connect mechanical engineers, circuit designers, packaging engineers, and chip fabrication personnel to better collaborate in solving multidisciplinary problems and to develop optimal designs.

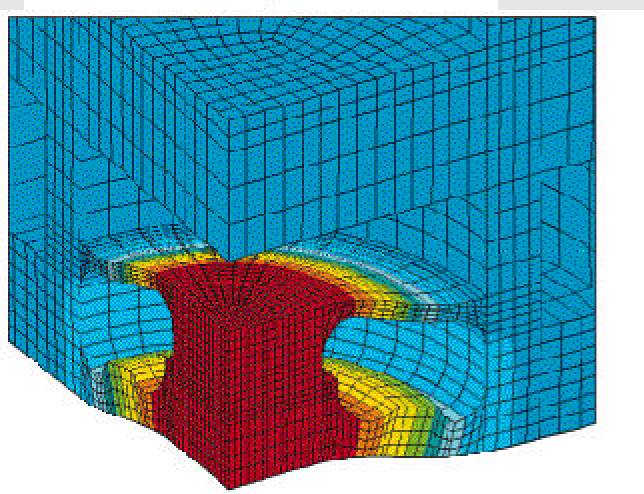
Stress concentration in a joint



Analysts at Colibri Pro Development AB used ANSYS submodeling to study stress concentrations in a 4-micron-wide joint of a MEMS test structure used for evaluating the quality of a 10-micron-thick polysilicon film. Design of the joint was optimized to be sufficiently flexible yet withstand buckling and fracture forces.



Automotive MAP sensors work on principles of piezoresistivity while sensing the pressure in the manifold. The sensitivity of the device is measured with ANSYS software.



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