Visualizing Body Motion

WHEN you think about it, lots of people could use the knowledge obtained from capturing, re-creating, and analyzing body motion in 3-D (three-dimensional) form. One group might be specialists: orthopedic surgeons, to plan surgery or physical therapy; athletes, to maximize their training and performance; robotic engineers, to “teach” robots how to interpret motion; and animators and video game designers, to make their animations more realistic. Another group might be the folks who want to understand their own common ailments, such as repetitive motion problems or tendonitis.

Studying body motion is not a new activity, but the data-gathering techniques for these studies have changed over the years. Currently, one common way of collecting motion data is by attaching reflective markers on a human actor at strategic points—on shoulders, elbows, hips, knees, ankles—and then videotaping the actor in motion. The video images are digitized for computer extraction and calculation of the 3-D locations of the markers. The calculated results are presented in graphical form, which may be plots or stick figures. While useful, these graphics are only coarse approximations of actual human movement. If used for animation purposes, for example, they would require a great deal of rendering before they could be considered finished. For studying biomechanics, their accuracy and level of detail are limited by the relatively small number of data points from which their information has been extrapolated.

Recently, Lawrence Livermore engineers Shin-Yee Lu and Robert K. Johnson demonstrated the next step in motion imaging systems. Dispensing with reflective markers, Lu and Johnson devised a system that detects data points on a grid of parallel, closely spaced vertical lines that have been projected onto a moving object (see figure above), which is then captured at video speed. Motion information collected in this way is dense, continuous, and uniform. It can be used to produce a real-time, complex visualization of movement that is realistic enough to be pasted directly into an animation. Lu and Johnson call this system CyberSight.

(a) (b)

(a) A vertical line grid projected onto the face of Livermore engineer Robert Johnson to capture information from closely spaced points along the lines results in (b) this CyberSight visualization.

How to Get CyberSight

The line grid projected onto a moving subject comes from a glass slide precisely etched with parallel black lines; such slides are commonly used for calibrating instrumentation optics. Other than this slide and the projector, the CyberSight system components are similar to those of other motion imaging systems. Two charge-coupled device (CCD) cameras, which are semiconductor image sensors, produce the video signals. To sense the data points, the cameras are firmly positioned a small distance apart from each other to take “snapshots” from two perspectives. Operated from 1 to 10 feet away, the cameras take the snapshots at the standard video rate of 30 frames per second. The CCD images are digitized by an image frame grabber and stored in memory boards. From there, they are transferred to a host computer for calculation and reconstruction into 3-D computer representations that can be presented as rendered images.

The sample images of a facial expression sequence in the figure on the next page are taken from CyberSight data that were reconstructed into several perspectives. Unlike a conventional photograph, the images are generated from a computer model of true dimensionality that can be manipulated, analyzed, and visualized. This feature makes CyberSight useful for biomechanical analyses. The complex information will allow computer models to calculate body surfaces and volumes, determine relationships between bones and muscles, and estimate velocity and force of movements.

Calculating Three-Dimensional Space

By solving the problem of collecting complete, voluminous motion data, CyberSight has uncovered another problem. As

collected, the data are of two-dimensional image planes that must still be transformed into 3-D moving images. This is hardly a simple task, given that each image frame from each camera may contain as many as 250,000 data points. Thus, it is no surprise that the key component of CyberSight is its complex image-processing code.

The code transforms 2-D objects into 3-D objects by mimicking human stereo vision. When we look at an object, each eye receives a slightly different image because it sees from a slightly different angle. This angular difference provides us with depth perception. The geometric expression of depth perception has been adapted by the computer code to calculate depth, using the two views of each data point sensed by the stereo cameras. The computer calculation is based on the principle of triangulation, a measurement technique that uses two known points to derive a third value. The triangulation uses the known, left–right views of an image point, the geometry of the camera arrangement, baseline distance, and converging optical angles to establish the position of that image point in space. The figure on the next page simplifies the basis of triangulation.

Camera geometry is determined by means of a calibration process. During calibration, images are taken of reference target points with known spatial positions, and these are used to back-calculate the camera geometry and lens parameters to be used for actual videotaping.

Matching the Left and Right “Eyes”

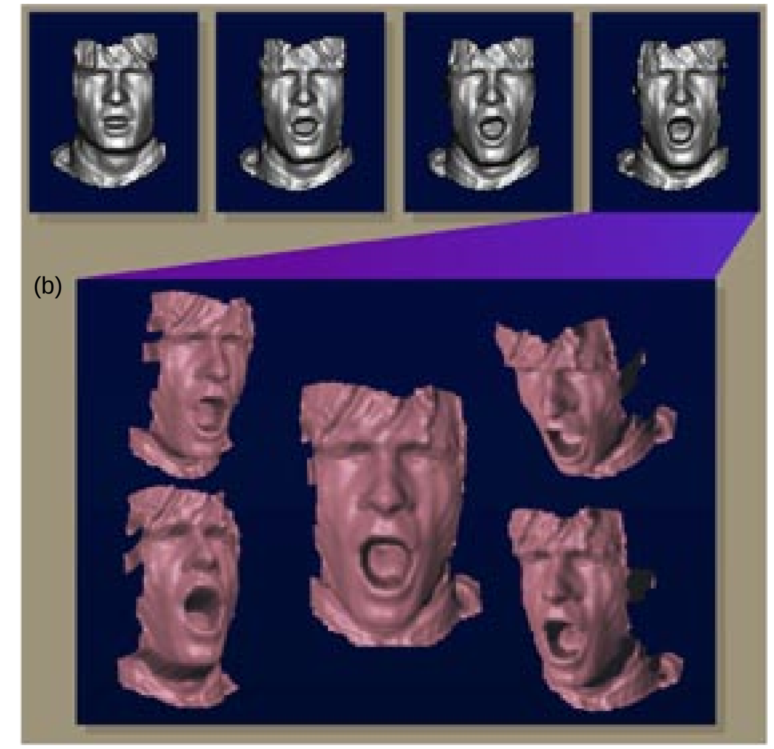
Before the calculations for depth can be made, the left and right views of the data points must be accurately matched. This difficult, time-consuming task requires a very high degree of computational complexity. The matching involves associating the correct left and right views of the same data point, associating them from the same image frame, and then tracking them from frame to frame so that movement reconstruction is logical. Additional complications come from changes in perspective, such as curvatures and orientation, caused by the moving object. Yet another type of problem intrudes when, on occasion, one view of a data point is eclipsed from the common view of both cameras, so not every data view has a stereo counterpart.

The computational techniques for left–right matching, like the 3-D transformation technique that imitates stereo vision, use principles based on the relationship between physical and mental processes, i.e., how stimuli lead to sensation. The computations imitate the human eye’s ability to pick up intensity changes, make use of high-contrast features in an image (such as edges and intersections), and filter or “smooth” received data. They also use dynamic programming, in which small subproblems are solved. Those solutions are used to solve larger and larger subproblems until eventually the problem itself is solved. The techniques result in a code with some ability to interpret “context” in performing the left–right matches and to fill in some missing details, such as the eclipsed data views.

Building on Past Work

The work on CyberSight follows earlier robotic motion studies that Lu and Johnson performed for LLNL’s in-house Laboratory Directed Research and Development project. The purpose of that work was to program robotic “hands” to handle hazardous waste. The work captured the interest of pediatric hospitals that are seeking better ways to design treatment for cerebral palsy. Their need gave Lu and Johnson

(a) (b)



The reconstruction of a facial sequence displayed as (a) a normal surface display at one-thirtieth of a second and (b) a rendered image from different perspectives

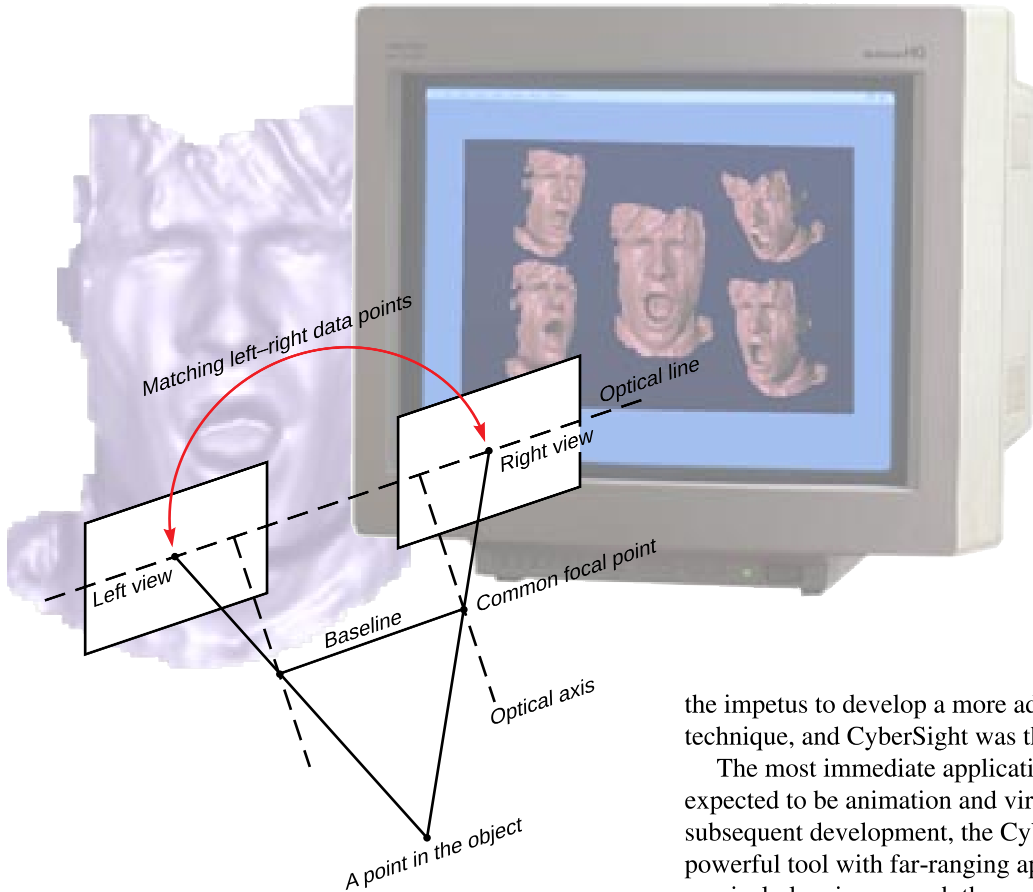


Figure 3. Triangulation is used in the CyberSight computer code to locate the data points in space.

the impetus to develop a more advanced motion imaging technique, and CyberSight was the result.

The most immediate applications for CyberSight are expected to be animation and virtual reality projects. With subsequent development, the CyberSight code will be a powerful tool with far-ranging applications from orthopedic surgical planning, speech therapy, and physical therapy to security applications such as facial recognition systems. This image-processing technology could also be used in manufacturing to provide rapid prototyping of new products and to personalize products such as prostheses, gas masks, clothes, and shoes. It has potential nonhuman-related applications as well. Surface deformations of materials could be monitored during the manufacturing process, or stress and strain analyses could be performed on materials and structures (such as vehicle air bags or the vehicle itself) to determine safety and functionality. The ingenuity of the CyberSight data collection technique, supported by its complex computer code, portends numerous and exciting future applications.

Key Words: 3-D visualization, biomechanics, image processing, motion study, movement reconstruction.

For further information contact Shin-Yee Lu (510) 424-3796 (lu2@llnl.gov) or Robert K. Johnson (510) 422-8375 (johnson60@llnl.gov).

Studying the Earth's Formation: The Multi-Anvil Press at Work

MANY things that scientists study are invisible to them. Announcements about the discovery of planets around other stars do not come because astronomers have seen the planets, although they would certainly love to. The discovery is more likely based on observations of the star's motion that indicate strong nearby gravitational forces. So it is with discoveries about the Earth's core and mantle. Because the deepest well ever drilled extends down just 12 kilometers, not even pricking the mantle, researchers have to employ indirect methods to study the Earth.

Using meteorites and seismological evidence as clues, scientists have known almost since the beginning of the century that the Earth has a solid, mostly iron, inner core and a molten outer core with a mantle and crust of rocky, silicate material. But for just as long they have been puzzled about how the core and mantle separated. The primordial planet Earth grew out of bits of gas and dust, aggregating over time into a larger, more solid body. Was there then some cataclysmic event billions of years ago that melted much of the planet, prompting the metals and silicates to separate as oil and water do? Or was the separation the result of a more gradual process, a trickling down of the denser molten metals between solid silicate mineral grains to the center of the Earth?

Recent research at Lawrence Livermore National Laboratory by geochemist William Minarik has helped to dispel the second, "trickle down," theory. Using the larger of Livermore's two multi-anvil presses to mimic the pressures and temperatures that exist deep in the Earth, he has shown that metals like those in the Earth's core could not have trickled down (see figure at right).

The materials used in the experiments were olivine, a silicate mineral that makes up much of the Earth's upper mantle, and an iron–nickel–sulfur–oxygen combination to represent the core.

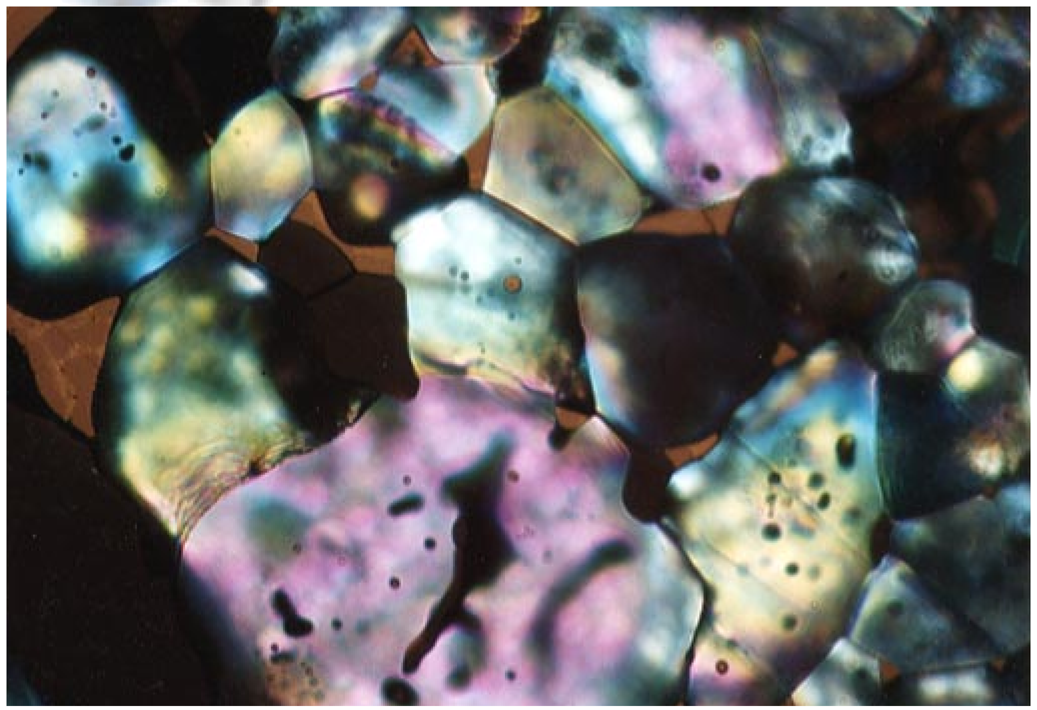
The multi-anvil press is a relatively rare research tool. Livermore's two presses have been used for a variety of material property studies, including diffusion and deformation of ceramics and metals, deep-focus earthquakes, and the high-pressure stability of mineral phases. The larger, 1,200-ton hydraulic press can produce pressures of

(a)

(b)

(c)

(a) The ceramic octahedron with the sample material inside it fits inside eight tungsten carbide cubes that in turn sit inside (b) the split cones of the multi-anvil press. (c) The closed press is also shown.



A 30-micrometer-thick slice of an experiment sample in double exposure. The field of view is about 500 micrometers. Transmitted light reveals the colorful olivine grains, while light reflected from the top shows the brown sulfides at the corners of the olivine grains. The sulfides have not wetted the edges of the olivine grains. Oxides appear black.

25 gigapascals (GPa), which is equivalent to 250,000 times the atmospheric pressure at sea level, or the pressure that occurs 700 kilometers deep in the Earth. In addition to pressing on the sample, the experiment passes an electric current through a furnace within the assembly to generate temperatures up to 2,200°C.

These experiments using the multi-anvil press generated a high pressure of 11 GPa, or 110,000 times the atmospheric pressure at sea level. This corresponds to 380 kilometers deep into the Earth, or pressures at the center of moons or asteroids 2,500 kilometers in radius (about the size of Mercury). The sample was also heated to a temperature of 1,500°C. Under those conditions, the metal melts and the olivine remains solid.

The geometry of the press is key to creating these enormous pressures. For the 11-GPa experiment, a ceramic octahedron had a 10.3-millimeter-long hole with a tiny rhenium furnace, a thermocouple to measure temperatures, and a graphite capsule containing the olivine and iron–nickel–sulfur–oxygen sample inserted in it. The octahedron rested in the center of eight 32-millimeter tungsten carbide cubes whose inside corners were truncated to accommodate the sample. (Tungsten carbide is used for the cubes, or anvils, because of its hardness, which is close to that of diamonds but at a much lower cost.) Tiny ceramic gaskets were placed at the edges of the carbide cubes to contain the pressure. This assembly of an inner octahedron and eight carbide anvil cubes was put in the press's split-cone,

steel buckets as shown in the figure on p. 21. In several stages, the steel buckets pushed on the carbide cubic anvils, which pushed on the octahedral volume inside.

The multi-anvil press is not Livermore's only device for studying the behavior of the Earth's innards, but in many ways it is the best for this type of study. The diamond-anvil cell can produce 100-GPa pressures, comparable to the pressures at the center of the Earth (see *Science & Technology Review*, March 1996). But it can accommodate only a 20-micrometer sample, too small for much post-experiment evaluation. With the piston-cylinder press, the sample volume is about 500 millimeters^3, but it has only a 4-GPa pressure capability, which is comparable to a depth of just 120 kilometers. The multi-anvil press is in the middle, providing pressures useful for studies of this type and accommodating a sample large enough for evaluation after the experiment.

In Minarik's experiments, the press took about 4 hours to bring the samples to full pressure, after which the samples were heated for periods ranging from 4 to 24 hours. During this time, the porosity of the sample collapsed, and the stable microstructure developed. Then the unit was cooled down and allowed to decompress for about 12 hours. During this process, the graphite capsule turned to diamond, which must be ground off before the sample could be sliced and polished for evaluation.

Despite being molten and much denser than the olivine, the metallic melt showed no signs of separating and draining to the bottom of the capsule. For the molten metal to drip down along the silicate grain edges, it has to be able to wet the edges. But in none of the experiments did wetting occur.[1] Rather, the iron–nickel mixture beaded up at the corners of the silicate grains like water does on a waxed car, as shown in the figure on p. 22.

Livermore's findings agree with similar, lower-pressure studies that have melted meteorites and iron–nickel–sulfur–oxygen mixtures and failed to wet the silicate minerals. Together, these experiments indicate that much higher temperatures were required to separate the Earth's core and mantle—temperatures high enough to melt most of the Earth.

All of these data lend credence to the theory that the young, growing Earth was repeatedly bombarded by large planetoids, with some of these collisions generating temperatures high enough to form a magma ocean from which drops of dense molten metal separated. The largest collision may have been when a large celestial body, about the size of Mars, collided with Earth nearly 4.5 billion years ago, melting most of it and causing the core and mantle to separate. The leading theory today for the Moon's formation postulates that some material from that collision was ejected into orbit and condensed into the Earth's Moon.

Livermore scientists have long studied material properties and the effects of high temperatures and pressures. Their work has resulted in some mighty big bangs but none as large as the ones Minarik has postulated.

"We plan to look next at the geochemical aspects of this project, the partitioning of trace elements between molten metal and silicates at the same high temperatures and pressures," says Minarik. "There are many scientists in this country and elsewhere studying the formation of the Earth, and all of us are in the same boat. With all of the direct evidence of the Earth's formation buried far beneath our feet, these laboratory experiments are our only way to recreate what might have happened."

Key Words: Earth core formation, multi-anvil press.

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For further information contact William Minarik (510) 423-4130 (minarik1@llnl.gov) or Frederick Ryerson (510) 422-6170 (ryerson1@llnl.gov).