2006-1530: COSMM: AN UNDERGRADUATE LABORATORY FOR ENGINEERING AND MANUFACTURING COMPLEX, ORGANIC SHAPES USING NATURE AS A TEMPLATE

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COSMM: An Undergraduate Laboratory for Engineering and Manufacturing Complex, Organic Shapes Using Nature as a Template

Introduction

The COSMM (Complex/Organic Shapes and Multiple Materials) Laboratory at California Polytechnic State University, San Luis Obispo provides undergraduate biomedical engineering students with the equipment to import geometric and mechanical property data from existing biological structures into a virtual environment where they can be analyzed, modified and output using layerwise manufacturing techniques. *Input* (touch probe, laser scanner, destructive scanner for optical images of internal geometry, CT/MRI/Ultrasound Imaging), *Computer Manipulation* (surfacing, feature extraction, freeform modification of 3D geometry using a haptic device, CAD manipulation and feature addition using a combination of surface, solid, and voxel modeling, and FEA analysis), and *Output* (Rapid Prototyping equipment including commercial systems and custom equipment capable of creating complex composites and gradient materials) are combined into an integrated system for analyzing and incorporating biological data into product designs. This laboratory supports sophomore-level introduction to design classes, junior-level CAD/modeling/simulation classes, a two-quarter senior design sequence, and multiple Senior Projects, Masters Theses, and industry-sponsored applied research projects. Recent laboratory projects have included creating soft tissue models for medical device development, producing a mechanically accurate spinal replica, creating medically accurate FEA and physical models of the human heart, and manufacturing complex gradient composite materials and scaffolds for tissue engineering.

Intended Outcomes

California Polytechnic State University has an earned reputation as a proponent of the hands-on, laboratory-based, learn-by-doing approach to education. We have also won a reputation as a college whose students are steeped in open-ended problems and underpinned by an understanding of design and the process of design. As part of our newly-created Biomedical Engineering Department, it was our goal to create a flexible, modular, expandable laboratory that would provide support across the entire spectrum from early design exposure for students to advanced industry-sponsored applied research for teams of faculty, graduate students, and undergraduates.

The rapid pace of advanced manufacturing technology has resulted in highly sophisticated equipment that is both available, accessible with reasonable acquisition and operation costs, robust, and simple enough to use such that the basics can be mastered within a few laboratory periods. What began as an ad-hoc collection of this type of equipment has now sharpened focus to become an integrated system for obtaining, analyzing, and incorporating biological data into product designs. In designing the COSMM laboratory, the goals were to help retain students, provide for close industrial participation, and to provide an integrative vehicle at a critical stage in the student's educational career. The result provides a theme for learning, through hands-on experience, key aspects of Biology, Design, Communication, Manufacturing, Problem Solving, and Materials. The philosophy behind integrating the cutting-edge equipment of the COSMM laboratory into the curriculum as early as sophomore-level classes is that engineering tools and phenomena are used long before they are completely understood. By immersing themselves in tackling challenging problems with no clear solutions using state-of-the-art equipment, it is our experience that students become more willing as they continue their educational career to approach comprehensive problems seeking holistic solutions. The ideal outcome of the COSMM laboratory, then, is to provide a laboratory environment that supports increasingly sophisticated levels of engineering exploration as the student matures.

COSMM Laboratory Equipment

Figure 1 illustrates the integration of various pieces of advanced manufacturing technology into the COSMM laboratory. Geometric and mechanical property data are imported from existing biological structures into a virtual environment where they can be analyzed, modified and output using layerwise manufacturing techniques. Building a laboratory such as this at a State University is generally an expensive and daunting experience, but COSMM has been successfully assembled through a combination of equipment purchased to support sponsored research, creative arrangements with vendors, cooperation between engineering departments to purchase shared resources, and equipment that was purchased from student fee funds managed by the students themselves. Having a longer-term vision allowed the laboratory to be pieced together one component at a time, while carefully selecting each new component such that it added increased, general-purpose functionality while fitting within the integrated whole. Criteria for selection of equipment included, in order of importance, low acquisition cost, durability, general applicability as a stand-alone engineering tool, low operations cost, and expected life of technology to avoid obsolescence. It has been a general practice that the students, through the Biomedical Engineering Society club and committees, do the research and justification for the purchase of new equipment for the COSMM lab.

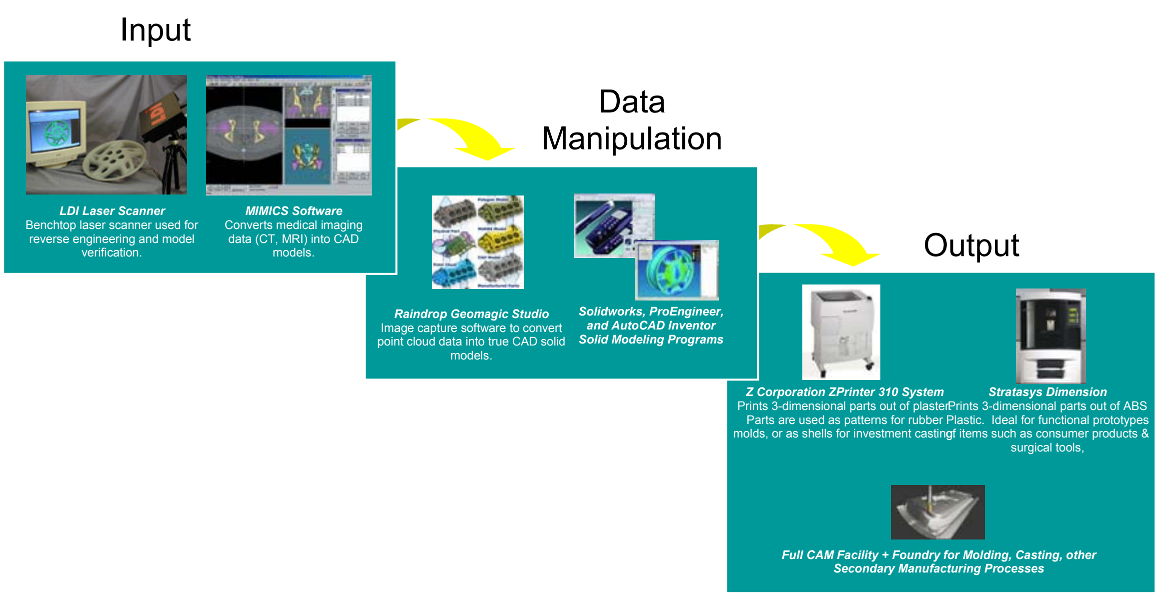

Figure 1. Integrated COSMM laboratory equipment and software.

Input

In the world of manufacturing, the concept of taking an object that already exists and from it reconstructing a modifiable CAD file is termed *Reverse Engineering*. While the manufacturing industry struggles with this legacy terminology (it is both a limiting explanation and implies unethical copying of competitors designs), the term is quite suitable for the mission of the COSMM lab, as we are using existing, generally biological, objects from the physical world as a "template" for design. Taking designs from nature achieves two different, but often complementary goals in the COSMM lab: 1) achieving designs that are personalized to individuals or environments and 2) creating freeform, organic shapes. Although solid modeling programs such as SolidWorks or ProEngineer are becoming much easer to use, they are still quite limited in their ability to create complex, flowing shapes and it is often desirable to use a truly organic form taken from nature as a starting point for a biomedical engineering design.

COSMM equipment options for input of data from the physical world include a *Laser Scanner* and a *High-Resolution Touch Probe* to capture external features, as well as the ability to capture internal features using a custom-built *Destructive Scanner*, and/or *Medical Imaging* such as CT or MRI data obtained through a relationship with a local diagnostic imaging center. In many cases, various imaging modalities are combined. For example, CT images of a subject's knee may be combined with a laser image of the knee surface to achieve the detail required for a custom orthotic device. Another example is combining CT and MRI modalities to create detailed CAD models of biological systems such as the heart, where a single modality would be insufficient to capture all tissue types at the required resolution. The data obtained at this stage includes not only external and internal geometry, but also physical properties such as bone density (CT) or regions of mechanical property variation indicated by color changes (optical images under various stains/filters).

A recent Senior Project has been the development of a "destructive scanner" for extremely detailed input of biological structures. This scanner is a milling machine, combined with a high-resolution camera that mills 20 micron layers of a sample and images the resulting exposed surface using various filters to provide a z-axis series of 2D images. These 2D images can then be processed for feature extraction and interpolation between layers to create a 3D CAD file with 20 micron voxel (3D Pixel) resolution.

Computer Manipulation

The data obtained from various input modalities comes in a variety of forms, which must be significantly processed and combined before they can be used for further CAD modeling. Point Cloud and 2D bitmap images are the most common forms of data, which are processed using software tools such as Geomagics Studio and MIMICS (Materialise), respectively. Noise is removed, and features of interest are extracted. Even with sophisticated software tools, a significant amount of manual labor and expertise in physiology is required to identify and tag features of interest. This is a time-consuming process that must occur layer-by-layer. A number of current student projects are addressing this issue, applying Image Processing, Machine Vision and Object Recognition techniques to help automate feature extraction.

The form for computer manipulation depends on the intended use, and includes surface, solid, or voxel modeling. A polygon mesh surface (.stl) file is generally sufficient for moderate modification and manufacturing using rapid prototyping equipment (Figure 2). NURBS or IGES surfaces are more difficult to produce from the input geometry, but are necessary to create true solid models for more sophisticated simulation or analysis. Students are currently experimenting with voxel modeling, combining both the geometry and distribution of material properties.

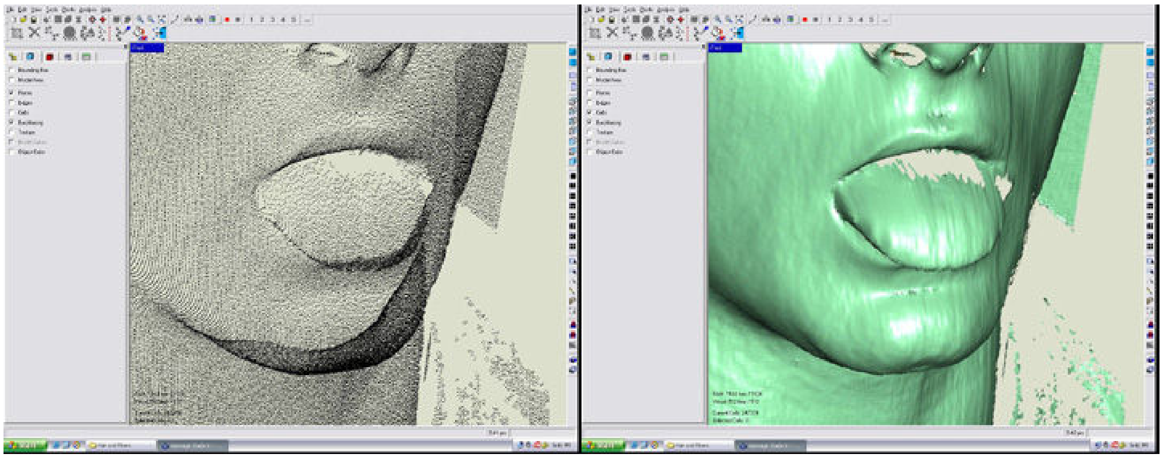

Figure 2. Example of point cloud (L) and polygon mesh (R).

The resulting organic shapes may then be modified in an organic way through the use of a Haptic Device (Figure 3). This device allows for features to be added or modified by "sculpting" in 3D with a stylus attached to an articulated arm, with tactile feedback provided to the user which makes the experience analogous to using clay. This type of freeform modeling is used as the interface or bridge between an organic shape such as a femur and a designed shape, such as an implant created using a traditional CAD program.

The modified geometry is then imported into SolidWorks, where it may be manipulated as a traditional solid CAD model. Significant work can be accomplished in this virtual environment, ranging from fit checks of surgical tool designs (e.g. stent placement) to complex Finite Element Analysis of anisotropic materials such as bone, to kinematic studies of the interaction of a design with the human body.

Figure 3. Sensable Haptic Device (www.sensable.com)

Output

Bringing the resulting geometries from the virtual world back into the physical world is a considerable challenge. These designs generally combine:

- Complex shapes, which are often physically impossible to cast, mold, or machine,
- Multiple materials or gradients from one material to another within the object,
- Inherently difficult materials to manufacture, such as soft elastomers or gelatin/collagen for tissue engineering applications.

Three commercial Rapid Prototyping machines are available to create the geometries, as well as a custom-developed 3-axis system with heads for inkjet deposition and multiple syringes to deposit materials in gradients. In addition, CNC machining is available for direct shape manufacture or to create tooling for injection molding. Rapid Prototyping is a particularly important tool, as it enables the fabrication of complex objects with novel properties directly from computer data. The basic operation of any RP system consists of slicing a CAD model into thin cross sections, translating the result into 2D position information, and using this data to control the placement of solid material. This process is repeated for each cross section and the object is built up one layer at a time (Figure 4). Although RP has historically been associated with manufacturing, where it is used for the rapid production of visual models, low-run tooling, and functional prototypes, the impact of RP goes far beyond these applications. Because this technology is both increasingly accessible and easy to use, and provides an immediate link from the virtual world to the physical world, it is seeing increased use as a tool for study and communication in fields as diverse as biomedical engineering, electronics, aerospace, architecture, and archeology.[1] For the purposes of the COSMM lab, we are particularly interested in using the layerwise nature of RP as a means to create objects with "impossible" geometries. The inverse of the desired shape is produced via RP, which is then used as an expendable mold to create the final geometry in an appropriate material. Examples include soft polyurethanes/silicones to simulate tissue, as well as gelatin compositions which serve as the scaffold for tissue engineering. Beyond complex geometries, layerwise manufacturing enables the creation of objects with multiple materials or gradients. Student projects have included varying the binder material and content within a part to create both variable-density and two-component ceramics on the Z-Corporation 3D Printer.[2] A team of undergraduate students is in the process of developing a multiple-syringe extrusion head for a 3-axis milling machine, which will allow for the layerwise production of objects with controlled material gradients.

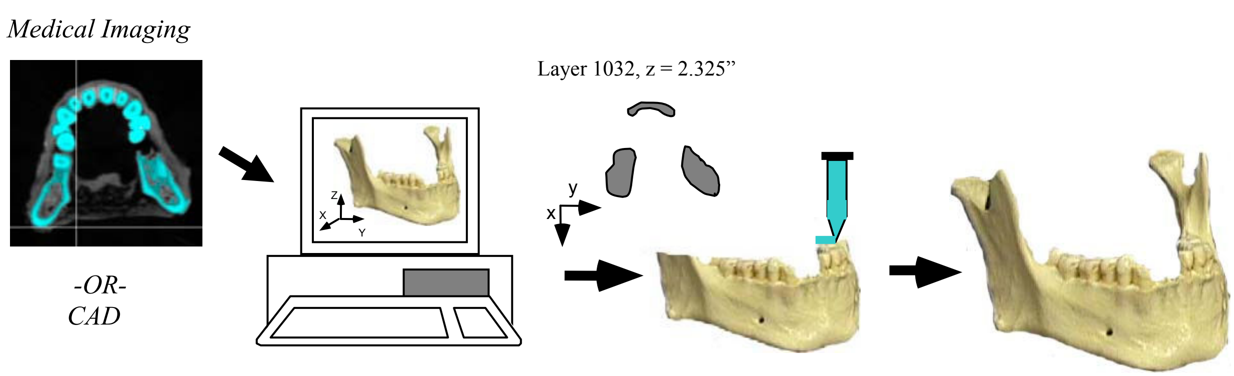

Figure 4. The Rapid Prototyping process.

Courses Supported by the COSMM Laboratory

Design exposure for Biomedical and General Engineering students starts in the second quarter of the freshman year. The COSMM laboratory supports this introduction to design, as well as focused-topic sophomore/junior-level CAD/modeling/simulation classes, a two-quarter senior design sequence, and multiple Senior Projects, Masters Theses, and industry-sponsored applied research projects.

Engineering 270: Applications of CAD and RP for Biomedical Engineering

The enormous potential of being able to scan existing objects, including complex organic features, modify them or create new designs using CAD technology, and "print" a functional part is self-evident to anyone who has seen the equipment in operation. We have found that RP holds extraordinary fascination to students and industrial visitors of all backgrounds, capturing the imagination and providing a strong attraction into the fields of science, engineering and technology. The equipment in the COSMM Lab provides an attractive environment for multi-disciplinary activities and projects, crossing traditional engineering and science boundaries. The Biomedical Engineering Program at California Polytechnic State University has used this technology as the focus for a four-unit, one-quarter introductory design experience for its freshmen students. The course is centered around a hands-on, project-based approach to product development. Teams of students are exposed to introductory engineering communications and to basic design through the vehicle of Rapid Prototyping. The students develop competencies over an eleven-week quarter, which allows them to produce prototypes of solutions to design challenges. The class strengthens teaming and communication skills. Industry sponsors partner with faculty to provide and define challenges for students, to provide intellectual support and a sounding board for students and to provide financial resources necessary to address challenges in a real way. The class provides and excellent segue for subsequent design-based courses.

3 hours of lectures per week provide the required background in both the "big picture" concepts of modern product development and the special needs of products in the Biomedical Engineering industry, as well as a basic tool kit of *materials & manufacturing processes*, *use of CAD in design*, *problem solving and good design practices*, *technical communication*, and introductory *project planning and management*. 3 hours per week of laboratory time following the same topical sequence is where the theory is put into practice.

BMED 455/456: Biomedical Engineering Design I & II

In the ENGR 270 course, the results of the projects remain at a fairly high level; in subsequent Senior design courses, BMED 455 & 456, the design challenges are generally industry-sponsored projects, and the results are of professional quality and delivered to the sponsoring company as end products. Company sponsors have been particularly interested in the student's use of COSMM facilities, as their industrial challenges often require incorporating organic shapes and biological data into product designs – designs that must work intimately with the body both physically and functionally (e.g. surgical tools such as a steerable catheter).

Similar to ENGR 270, 3 hours of lab parallel and supplement 3 hours of lecture per week. In early lab sessions, students gain the necessary competency in advanced CAD design, operation of COSMM equipment, and casting/molding techniques. They are then supported by instructors as they prepare their designs for industrial challenges, both individually and in self-selected teams of four students. By the 2nd half of the quarter, the formal laboratory training is complete and the equipment is made available for individually-directed student use. Within the first four weeks of laboratory exercises, students have the ability to go from “art-to-part” for simple CAD designs, and can turn their attention to the higher-level goals of integrated product design (Figure 5).

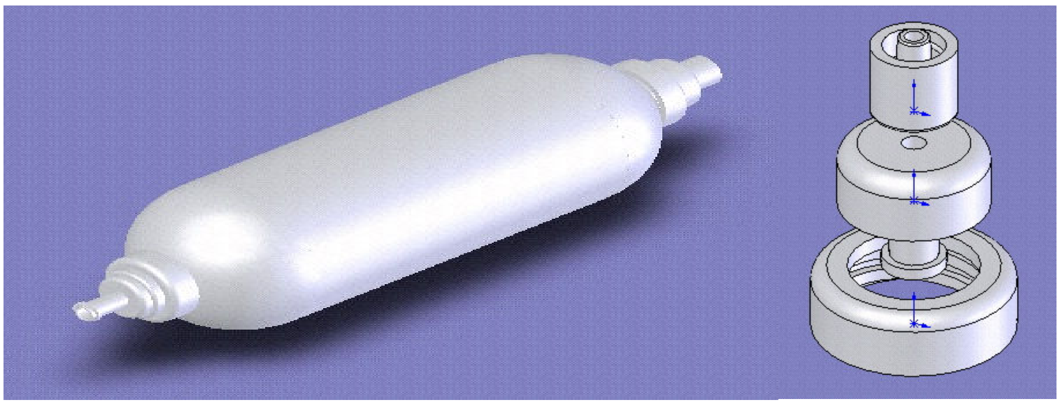

Figure 5. Pain Pump developed as part of BMED 455.

BMED 430: Simulation and Modeling for Biomedical Engineering

This year, the COSMM facility is being introduced into an existing course on the topic of simulation & modeling for Biomedical Engineering. Finite Element Analysis (FEA) is the natural use of the geometry developed in the COSMM facility. Natural materials are complicated in that there are differing material properties within the same structure. The mechanical properties of tissues such as bone are known functions of the CT number, and can be used in FEA models developed using software such as MIMICS (discussed previously). This enables more precise modeling of material properties and mechanical behavior of the structure. However, modeling the gradient nature of biologic tissue requires more computational effort. Fortuately, advanced FEA packages, such as ANSYS, Abaqus, and LS Dyna are well suited to perform complicated stress analysis even using personal computers. These codes can perform structural as well as fluid/structure interactions.

In one such simulation, students examined how a total knee replacement effects the stress distribution on the bone tissue (Figure 6, Left). Using the heart model (Figure 6, Right), we could conceivably model the flow through the heart. Simulations such as the knee replacement enable the students to work on problems that are technically challenging, have open-ended solutions, and are of direct interest to industry to develop product designs that ultimately enable medical devices to better integrate with the host.

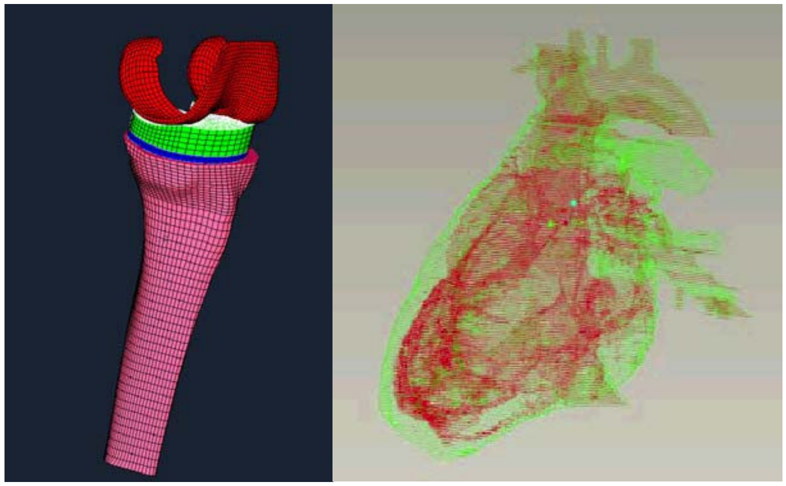

Figure 6. (L) Complex FEA of knee implant, including anisotropic properties of femur. (R) FEA mesh for heart.

Senior Projects / Masters Theses / Sponsored Research Projects

A critical component of the classes described above is a high level of industry participation. In both 270 and 455/456, representatives from local companies involved in biomedical engineering are invited to the class early in the quarter to 1) introduce students to their products and product development challenges and 2) provide challenges to the student teams. These industrial challenges are both open-ended, which removes the student from the textbook environment, and "real-world", which provides excitement to the term projects that the student teams will prepare. These industrial project topics often serve as the seed for further development as Senior Projects or Master's Theses. A typical pattern is that a student will participate in ENGR 270, do a CO-OP, and come back to complete Master's Thesis as a sponsored research project. Industry sponsorship by participating companies also underwrites the material costs for the laboratory, and provides funding for acquisition for additional special materials or software. By fostering strong industry participation early in the curriculum sequence, students establish a continuing relationship which often segues into CO-OP / Internship positions, T.A. positions as an upper division student, or undergraduate research positions for follow-on industry sponsored projects.

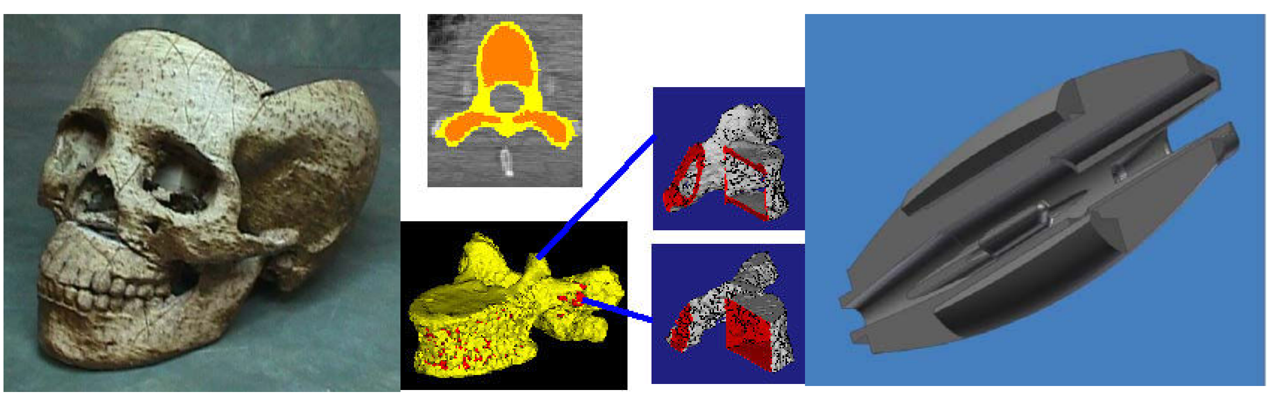

Figure 7. Sample Sponsored Projects (L) Forensic Skull (C) Mechanically Accurate Vertebra (R) Surgical Tool Prototype.

Case Study: Accurate Heart Model

The impact of this laboratory on individual students can best be illustrated by an example from our first trial experience. A typical case involves a Biomechanical Engineering student with no previous research experience, and pre-class survey results illustrating her belief that she had below-average aptitude for computer use and independent learning. The industrial challenge offered to her team came from a pacemaker manufacturer: *create both an accurate CAD model and a mechanically-accurate physical model of the human heart to be used in the development of pacemakers*. Background information was presented during lecture sections detailing previous attempts to use Rapid Prototyping combined with medical imaging to produce CAD and physical (plastic) models of bones. Because the heart is soft tissue and thus more difficult to differentiate, and because the final model needed to be in a flexible rubber, this was an extremely challenging

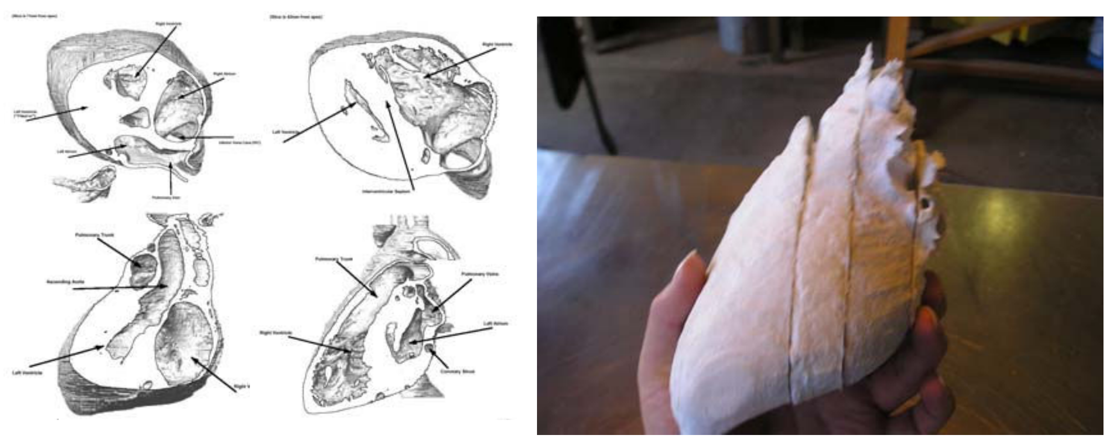

Figure 8. Left: CAD file of Heart. Right: Rubber heart model (expendable pattern produced on 3D Printer).

problem. Solving this challenge required the team to perform library research, hold discussions with faculty advisors, and solicit phone/e-mail correspondence with scientists and engineers at the sponsoring company. The team ultimately developed a method to use existing software to create detailed, accurate CAD files of the exterior and interior of the heart, as well as use modified rubber casting techniques to create a detailed physical model. By working as a key contributor to this team, the student in question increased her confidence dramatically, as evident by her continuing interest in further research and the potential for graduate studies. The topics she learned from her experience include the scientific method, product development, anatomy, physiology of the heart, biomaterials, medical imaging, use of specialized software (3 types), project management, technical communication, advanced manufacturing, and Rapid Prototyping. Note that the laboratory equipment is only a small part of her acquired skills, but it provided the core of an extremely complex problem requiring a multidisciplinary effort.

Linkage to Problem-Based Learning

The COSMM laboratory is designed to support application of Problem-Based Learning (PBL) to engineering education. PBL has been defined as "learning which results from the process of working towards the understanding of, or resolution of, a problem."[3] PBL has been an extremely successful model for medical education: over 80% of medical schools currently use some form of Problem-Based Learning[4]. Although primarily applied to the biological sciences to date, PBL is an appropriate methodology for technology education[5]; our experiences with using the integrated COSMM techniques in a Problem-Based Learning environment confirm this. PBL begins by presenting a challenging, realistic problem to a small group of students. The group defines or redefines the problem and analyzes it systematically. The concepts required to solve the problem are then agreed upon, and group members assign themselves specific tasks to acquire that knowledge *on the basis of what needs to be known to solve the problem*.[3] Knowledge acquired must be shared among group members, then integrated with existing information to develop possible solutions to the problem. This process is iterated until a satisfactory resolution to the problem is reached. Throughout the process, an educator is present to assist as a *facilitator* rather than as a primary source of knowledge.[6] It has been shown that under this model, students acquire skills essential to continue self-directed learning, rather than trying to remember information that has varying levels of relevancy.[3] The outcomes of programs applying Problem-Based Learning have been extensively evaluated in educational literature[3-8]. PBL-educated students have a more holistic approach to their subject, more readily integrate new information, adapt to change, and work well as members of a team.[3] For PBL to be successful, certain requirements must be met; we have found that the COSMM environment is a natural fit to these requirements. If executed properly, PBL can be a powerful tool to meet the goals of future engineering education, and it is our belief that integrated laboratories such as COSMM that provide advanced engineering tools to students for facilitated, self-directed exploration are well worth the investment.

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