feature article

Getting a hold on mechatronics

A blend of mechanics and electronics, mechatronics has come to mean the synergistic use of precision engineering, control theory, computer science, and sensor and actuator technology to design improved products and processes

By Steven Ashley, Associate Editor

The standard clothes dryer is typically controlled by a mechanical timer. The user adjusts the timer according to the size and dampness of the load. If the timing device is not set properly, the drying cycle may be too short and the laundry may come out wet, or the machine could run long and waste energy.

A clothes dryer, however, might be fitted with a sensor-based feedback system that lets the machine measure the moisture content of the fabrics or the exhaust air, and turn itself off when the load is dry. Operating performance is enhanced and energy use is lowered as a result. The redesigned dryer might even be cheaper to buy, depending mainly on the cost of the components that comprise the electromechanical control system.

The computer disk drive, such as Cheetah from Seagate Technology, is one of the best examples of mechatronic design because it exhibits quick response, precision, and robustness

Many U.S.-trained design engineers would say that the improved dryer is the result of up-to-date but conventional design practices. A reliable yet relatively inaccurate mechanical device was replaced by a "smarter" electronic control. In much of the rest of the world, however, design engineers would say that the dryer redesign followed the principles of *mechatronics*.

Mechatronics is nothing new; it is simply the application of the latest techniques in precision mechanical engineering, controls theory, computer science, and electronics to the design process to create more functional and adaptable products. This, of course, is something many forward-thinking designers and engineers have been doing for years.

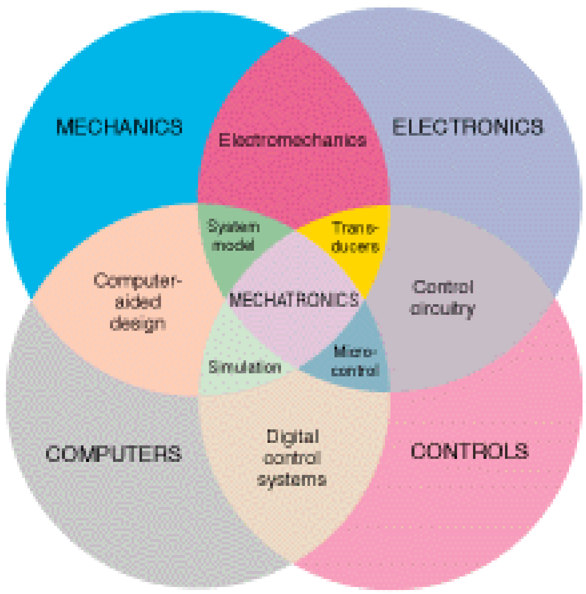
The vaguely awkward word was first coined in Japan some 30 years ago. Since then, mechatronics has come to denote a synergistic blend of mechanics and electronics. The word's meaning is somewhat broader than the traditional term electromechanics, which to many connotes the use of electrostatic or electromagnetic devices. It is also an amorphous, heterogeneous, and continually evolving concept with 1,001 definitions, many of which are so broad or so narrow to be of seemingly marginal use.

Mechatronics is more than semantics, however. It's a significant design trend that has a marked influence on the product-development process, international competition in manufactured goods, the nature of mechanical engineering education in coming years, and quite probably the success mechanical engineers will have in becoming team leaders or engineering managers.

Defining Mechatronics

For Takashi Yamaguchi, who works at Hitachi Ltd.'s Mechanical Engineering Laboratory in Ibaraki, Japan, mechatronics is "a methodology for designing products that exhibit fast, precise performance. These characteristics can be achieved by considering not only the mechanical design but also the use of servo controls, sensors, and electronics." He added that it is also very important to make the design robust. Computer disk drives, for example, are a prime example of the successful application of mechatronics: "Disk drives are required to provide very fast access, precise positioning, as well as robustness against various disturbances," he said.

For Giorgio Rizzoni, associate professor of mechanical engineering at Ohio State University in Columbus, mechatronics is "the confluence of traditional design methods with sensors and instrumentation technology, drive and actuator technology, embedded real-time microprocessor systems, and real-time software." Mechatronic (electromechanical) products, he said, exhibit certain distinguishing features, including the replacement of many mechanical functions with electronic ones, which results in much greater flexibility and easy redesign or reprogramming; the ability to implement distributed control in complex systems; and the ability to conduct automated data collection and reporting.



The diagram at left illustrates that mechatronics is where mechanics, electronics, computers, and controls intersect

"Mechatronics is really nothing but good design practice," said Masayoshi Tomizuka, professor of mechanical engineering at the University of California, Berkeley. "The basic idea is to apply new controls to extract new levels of performance from a mechanical device." It means using modern, cost-effective technology to improve product and process performance and flexibility. In many cases, the application of computer and controls technology yields a design solution that is more elegant than the purely mechanical approach. By having a good idea of what can be done using other than mechanical means, design freedom increases and results improve, according to Tomizuka, who is also editor-in-chief of the quarterly IEEE/ ASME Transactions on Mechatronics jointly published by the Institute for Electrical and Electronics Engineers and ASME.

The journal, first published in March 1996, is another indication that the importance of this interdisciplinary area is being recognized. Transactions covers a range of related technical areas, including modeling and design, system integration, actuators and sensors, intelligent control, robotics, manufacturing, motion control, vibration and noise control, microdevices and optoelectronic systems, and automotive systems.

The Roots of Mechatronics

Mechatronics was first used in terms of the computer control of electric motors by an engineer at Japan's Yaskawa Electric Co. in the late 1960s. The word has remained popular in Japan, and has been in general use in Europe for many years. Although mechatronics has been slow to gain industrial and academic acceptance as a field of study and practice in Great Britain and the United States, its increasingly prominent place worldwide is shown by the growing number of undergraduate and postgraduate mechatronics courses now being offered.

Many engineers would contend that mechatronics grew out of robotics. Early robotic arms, then unable to coordinate their movements and without sensory feedback, benefited greatly from advances in kinematics, dynamics, controls, sensor technology, and high-level programming. The same battery of modern technologies that made robots more flexible and thus more useful was then brought to bear on the design of new generations of high-performance, adaptable machinery of all kinds.

In the 1970s, mechatronics was concerned mostly with servo technology used in products such as automatic door openers, vending machines, and autofocus cameras. Simple in implementation, the approach encompassed the early use of advanced control methods, according to *Transactions* editors.

In the 1980s, as information technology was introduced, engineers began to embed microprocessors in mechanical systems to improve their performance. Numerically controlled machines and robots became more compact, while automotive applications such as electronic engine controls and antilock-braking systems became widespread.

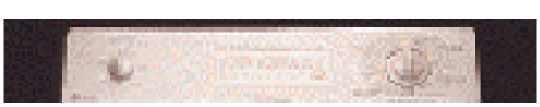
By the 1990s, communications technology was added to the mix, yielding products that could be connected in large networks. This development made functions such as the remote operation of robotic manipulator arms possible. At the same time, new, smaller--even microscale--sensor and actuator technologies are being used increasingly in new products. Microelectromechanical systems, such as the tiny silicon accelerometers that trigger automotive air bags, are examples of the latter use.

As significant as these developments may seem, a good deal of skepticism remains about the idea of codifying them in an engineering field called mechatronics. "It's certainly a catchy word," said controls expert Ernest O. Doebelin, professor emeritus at Ohio State and an ASME Fellow, "but it's an evolutionary, rather than revolutionary, development. Now that computers are small and relatively cheap, it just makes sense for designers to build them into products. Mechatronics is really the familiarity with all the other technologies--computers, software, advanced controls, sensors, actuators, and so forth--that make the advanced products possible."

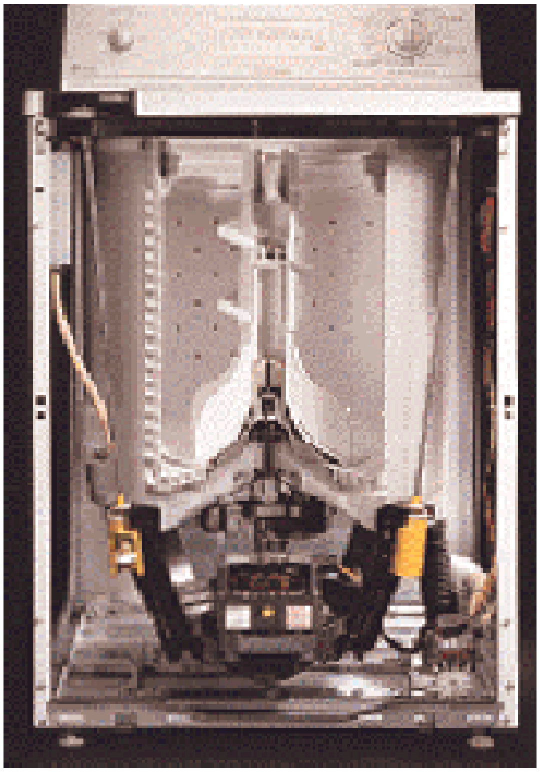
Similar sentiments were expressed by Davor Hrovat, senior staff technical specialist at the Ford Research Laboratory in Dearborn, Mich.: "The word singles out an area that perhaps is not a single area. Mechatronics is mixture of technologies and techniques that together help in designing better products."

However mechatronics is defined, it means "we now have viable technology for computer control of mechanical systems at all levels, from toasters to autos," said David M. Auslander, professor of mechanical engineering at Berkeley. "Today we have mechanical systems for which performance is defined by what's in a computer, whether it's software algorithms, neural networks, or fuzzy logic. That alone makes it different from anything you could do 25 years ago."

Auslander takes a very generalized view of the topic. "Any system in which you control or modulate power is a candidate for computer control. For any mechanical component you can ask the question: What is its purpose? Does it transmit power? Or is its purpose control and coordination? Computers, software, and electronics can generally do this second function more efficiently--simpler, cheaper, with much more flexibility." This approach, he emphasized, constitutes a totally different view of how mechanical systems work compared with previous conceptions. "This is a machine viewed from the controls outward.



Following mechatronic



principles, General Electric's Profile Super 32 clothes washer features a sensor-based feedback control that maintains correct water temperature no matter the load size

"Consider the standard multicolor printing press this magazine used to be printed on," Auslander added. "Until recently, web presses had line-shaft controls in which a long shaft coordinates operations from station to station. Now it's done all by computer control, which makes it much easier to change the machine over to a new setup."

The view of Belgian robotics researcher Hendrik M. J. Van Brussel, published in Transactions (June 1996), follows a similar fundamental theme but with a different emphasis. "In the past, machine and product design has, almost exclusively, been the preoccupation of mechanical engineers," he wrote. Solutions to control and programming problems were added by control and software engineers, after the machine had been designed by mechanical engineers.

This sequential-engineering approach usually resulted in suboptimal designs. "Recently, machine design has been profoundly influenced by the evolution of microelectronics, control engineering, and computer science," Van Brussel wrote. "What is needed, as a solid basis for designing high-performance machines, is a synergistic cross-fertilization between the different engineering disciplines. This is exactly what mechatronics is aiming at; it is a concurrent-engineering view of machine design." He then offered his working definition of the term: "Mechatronics encompasses the knowledge base and the technologies required for the flexible generation of controlled motion."

An essential feature in the behavior of a machine, Van Brussel continued, is the occurrence of controlled and/or coordinated motion of one or more machine elements. "The generation and coordination of the required motions, such that the increasingly growing performance and accuracy requirements are satisfied, is the raison d'etre of mechatronics."

Van Brussel pointed out that traditional mechanisms are limited in their flexibility in generating a wide variety of motions. Also restricted is their potential for creating complex functional relationships between the motion of the actuator and that of the driven element. Yet another limitation of purely mechanical drive systems is their inherent lack of accuracy, caused by friction, backlash, wind-up errors, resonances, dimensional errors, and so forth.

"These restrictions can be alleviated by eliminating or simplifying the 'forced-motion' mechanism between actuator and driven elements," he wrote. Instead, each driven element is provided with a drive motor and a position sensor. A motion controller generates the required relationships between the motions of the different driven elements. "The motion synchronization function is shifted from the error-prone hardware mechanism to the flexible software controller. By applying the mechatronics approach, a large number of motions can be synchronized, even at long distances away from each other."

Under external forces, a range of secondary effects such as vibration and noise can adversely affect the functional behavior of machine elements and instruments, according to Van Brussel. Passive damping treatments are available, but they have limited applicability. "The mechatronic approach can provide more effective solutions. Based on the state information about vibration and noise levels, captured by appropriate sensors, the vibrations are counteracted by actuators distributed over the structure. The machine elements become active (smart structures)." The term adaptive structures can be used "when the behavior of the structure can be changed at will, without mechanical modifications."

Institutional Implications

Beyond design theory, Auslander said, "mechatronics is also saying something about industrial structure." In the new paradigm, "the focal point is not traditional machine design, which is what industry and therefore universities are presently geared to teach. In the future, the focal point will be the mechatronics specialist."

"It's always a bit embarrassing to talk about mechatronics," said Kevin Craig, associate professor of mechanical engineering at Rensselaer Polytechnic Institute in Troy, N.Y. "As far as engineering practice goes, there really isn't anything new here, except evolutionary advances in computers, sensors, actuators, and the rest. What is new from the educational viewpoint is that we're teaching mechanical engineers how to use electronics, how to program computers to do real-time control, how to do control design, and then to integrate all this into the design process.

"It's an interdisciplinary approach," he added. "Do the integration right from the beginning; don't just add a control system at the end. Controls used to be left to specialists--mostly electrical engineers. That's not true anymore." Besides teaching a three-day short course on mechatronics as part of an ASME Professional Development program, Craig has also worked on two videotape series on the topic.

"Mechatronics does not change the design process," Craig said. "It gives the engineer greater knowledge, so the concepts that are developed are better, and communications with other engineering disciplines is improved. The result is a highly balanced design."

"One thing that is not at all not clear is how all this additional material should be delivered to the student," observed Ed Carryer, consulting associate professor at Stanford University in Palo Alto, Calif. "Most mechanical engineering curricula are already stuffed to the gunnels," he said. "It's either overload the undergrads or make it the focus of a certificate program at the master's level."

Few academics expect mechatronics to attain the level of a formally accepted engineering discipline. "Our academic system tends to resist the forming of new disciplines," Auslander said. "For example, controls has been a well-recognized and important discipline since the Second World War. However, there are few control departments in the United States. It's mostly taught in mechanical engineering, electrical engineering, and some chemical engineering departments. Yet we graduate lots of people who do the controls function." He concluded that mechatronics' place in the academic hierarchy is really an organizational and bureaucratic issue.

In the short courses he teaches, "besides students you get the occasional professor who wants to learn what the universities are doing in mechatronics, so they can set up their own programs. The rest are practicing mechanical engineers who basically want to know 'What's this mechatronics stuff we keep hearing about?'

The practicing engineers Craig meets still tend to rely on results of experiments--build and test methods. Surprisingly, "they don't do much modeling or analysis. We're saying that they won't be able do that much longer, because you can't get products to market quickly enough in today's markets. You need to model and predict, build a prototype, then validate your predictions."

Ford's Hrovat also stressed the need for mechanical engineers to learn advanced modeling and simulation methods. He cited particularly the use of bond graphs--transfer-function block diagrams that denote power flows and information flows--to depict "means shifting," the process of finding alternative means to accomplish a design goal. For example, if there is no suitable electrical means of providing some desired actuation, the designer could go to a pneumatic or hydraulic system--the means to an end are shifted to a substitute technology. "From what I see, the use of bond graphs is definitely the trend," Hovrat said.

Career Paths in Mechatronics

"Mechanical engineers are often at a loss to communicate and understand the issues electrical engineers and the software specialists bring up" at meetings of interdisciplinary product teams, said Carryer. "The idea is to get rid of the uncertainties associated with electronics and computers. We want to develop people who are comfortable making the necessary trade-offs among a wide range of approaches based on the given design constraints."

"Maybe the mechanical engineer is not going to do the detail work in any specialty," Craig said, "but they could do it, and they certainly could lead a team doing it. That's what we're trying to train mechanical engineers to do."

With a focus on these kinds of skills, mechatronics is seen as a prime career path for mechanical engineers of the future. "I believe that mechanical engineers with a mechatronics background will have a better chance of becoming managers," said Thomas S. Moore, general manager for liberty and technical affairs at Chrysler Corp. in Madison Heights, Mich. "We see mechatronics as the career of the future for mechanical engineers."

"Classically trained mechanical engineers will run the risk of being left out of the interesting work" carried on by multidisciplinary product design teams, according to John F. Elter, vice president of strategic programs at Xerox Corp. in Webster, N.Y. "At Xerox, we need designers who understand the control theory well enough to synthesize a better design. These people will have much more of a chance to lead." Elter added that "the mechanical engineers who know some computer science are far more valuable than the computer scientists who know some mechanical engineering. The mechanical engineers have a better feel for the overall system and do a better job of making the crucial trade-offs. One possibility is that the mechatronics practitioner will prototype the whole design, then the specialists in the various disciplines will take over the detail design."