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Mission-Oriented Research for Light Machinery

Delbert Tesar

Summary. The time of intelligent machines is upon us. But the United States is not actively pursuing this rich field of technological development. This is evidenced by the U.S. trade deficit of $9 billion in this market in 1977. The synergistic approach of Japan, Germany, Russia, and other countries to research, development, and demonstration among government, academic, and industrial groups is paying big dividends in vital U.S. markets. This article outlines a specific solution in terms of a U.S. national research policy for light machinery and robotics.

Recent reports on our weakening ability to compete in the market for consumer goods, many of which depend on new technology, indicate that the United States has rested on its industrial laurels for too long. In contrast to the $24 billion surplus of agricultural exports in 1977, manufactures produced a surplus of only $5 billion, dramatically down from $20 billion in 1975. Total research and development relative to the gross national product (GNP) is down 30 percent since 1963, while the percentage of industrial expenditure for basic research in the United States has dropped by a factor of 2.5. These are sobering statistics, since it has been documented that 45 percent of our economic growth from 1929 to 1969 has been due to technological innovation.

To be able to use energy resources to make products for world markets implies the use of machines. The purpose of this article is to show that high technology associated with production machinery is a means to the solution of our increasingly tenuous economic performance. Research for the development of a machine science has been ongoing for two centuries. It reached a functional level in its industrial application before World War II, but has become less effective relative to other technologies since that time. This article documents this lack of effectiveness of mechanical technology in terms of economic indicators and outlines the need to revitalize an important segment of our industrial manufacturing capacity (*1, 2*).

A Technological Opportunity

It is well known that massive technological growth has occurred since World War II in electronics, particularly, microelectronics. During the same period, machine-based industries in the United States have made nominal progress, since the government has put insufficient emphasis on machine technology for the production of commercial goods. Other industrial nations have done the opposite (*3*). Computers or their smaller counterparts, microprocessors, can make it possible to create production machinery which "thinks," to make machines more versatile and reliable. It will be argued in this article that two major opportunities face the industrial community. These are (i) the development and use of modern research and design tools to establish a resurgence in the fundamental field of machine science, and (ii) the full use of distributed electronic sensors and computers combined with mechanical production devices to create more effective production systems.

Mechanical devices enter into the manufacture of a very large spectrum of commercial products. For example, the manufacture of our sophisticated microelectronic circuits is increasingly depen-

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dent on high-precision mechanical positioning systems. The following is a list of many of the classes of machines that are centrally dependent on mechanical functions.

Textile machinery
Printing and paper machinery
Food and packaging machinery
Office machines, computer peripherals
Assembly operations, microprocessing
Machine tools, automatic screw machines, presses
Toys, models, games, sports equipment
Agricultural machinery such as harvesters and tractors
Internal combustion engines
Building machinery such as shovels, cranes, and earth movers
Conveyors, feeding, and handling devices
Vehicles, off-road locomotion, steering, braking
Railroad vehicles and machinery
Circuit breakers and switchgear
Prosthetics, orthotics, hands, man-augmentation
Robots, manipulators, numerical control machines

The weakness of U.S. mechanical technology may be partially illustrated by the sale in the United States of the industrial sewing machine Consew (owned by Toyota of Japan), which runs faster, is more reliable, has four times less downtime for bobbin interchange, and costs 25 percent less than a similar U.S. machine. (Note that the trade deficit for sewing machines was $141 million in 1977.) Another example involves a new tobacco manufacturing plant in Georgia that is the third largest in the United States. All of the machines are of Italian, German, or English origin and are maintained by foreign craftsmen. The plant manager confirms that appropriate technology did not exist in the United States in 1976 to fulfill the specifications for competitive machines.

The microelectronics revolution is a most welcome development (*4*). It is a $41 billion per year industry and has created 100,000 new jobs. Its effectiveness will increase immensely when microelectronics are coupled with versatile mechanical devices to make intelligent machines. Because of the weakness of mechanical technology, this is taking place either rarely or not at all. One step toward this coupling is represented by the commercially available "electronic" househould sewing machine (*5*). It uses complex sewing patterns previously stored in a solid-state memory that can be recalled by the operator simply by pushing a few buttons. Nonetheless, there is no sensor in the system that can send signals to a controller, which would then automatically adjust the machine's operation to fit the present condition of the sewing process. This sensing, adjustment, and task performance has its human analogy in our eyes, brain, and motor capacity. In the case of the electronic sewing machine, it is important to note that none of the critical high-precision motions are executed by electronic components. Hence, one must conclude that microelectronics have been "added on" or poorly integrated into the total system's function. Another step toward electronic coupling with mechanical function is the General Motors turbocharged V6 ignition timing control. In this example a sensor is used to monitor detonation in the engine. If a trace amount of detonation is exceeded, the electronic control retards the spark in 4-degree steps until detonation is below the specified limit. This system is perhaps electronically more elementary than that of the sewing machine, but it has all three elements necessary for a "thinking" machine: sensor, brain, and adjustable mechanical response.

The sophisticated integration required for intelligent machines may be illustrated in terms of a modern electronically controlled shutter for a camera (*5*) that recently appeared on the market. The camera contains sensitive electronic sensors that detect levels of light and transmit this information to a digital microprocessor, which then automatically sets the *f*-stop and shutter speed. The user merely points the camera at the subject, while the electronic system senses the range, lighting, and reflectivity and takes the picture on command. All of these functions are taken care of by various sensors, a small electronic controller (or brain), a mechanical shutter, and a mechanical drive train, using springs and batteries as power sources. The precision built into the machine comes from the intricately designed mechanical shutter, which typically moves at a speed of 4 meters per second. This speed must be precisely repeatable over the life of the camera. The electronic controller must release the first shutter or curtain, wait the required time interval, and then release the second or closing curtain. The allowable error in this time interval may be as little as 1/10,000 second.

From the example above, it is clear that the mechanical motion of the shutter curtains is fundamental to the operation of the camera itself. No alternative method is easily adaptable in a commercial still camera. Hence, the commercial realization of a new product resulted from a very sophisticated mechanical design coupled with modern electronic sensors and controllers. (It may be noted that our trade deficit in 1977 for still cameras was $253 million.) The total system effectively builds on good mechanical structure and enhances it. The enhancement is obtained by a fully adjustable system that is capable of responding to a wide range of stimuli without human intervention. This is a proper integration of electronics with mechanical technology.

Many designers have given up on mechanical technology completely. Unfortunately, a very large percentage of commercial products are used directly by humans, and these products tend to be physical (shoes, clothes, food, and so on) and require mechanical processing in their manufacture or handling. Hence, mechanical operations are mandated by human existence. It would be far more appropriate to treat the science of machines as fundamental in its own right and then augment its application with every feasible combination of electronic sensing and control. This is the major opportunity facing light industry today. It is clear that our competing industrial countries are already pursuing this opportunity. If it is energetically pursued by the United States, a new generation of machines and their products could evolve to reestablish the relative vitality of American industry.

Machinery and Its Manufactures

The classes of machines listed in the previous section may be separated into the categories of light machinery and heavy machinery. It will be shown that because of its substantial research emphasis on heavy military machines and materials, the United States presently enjoys a $5 billion to $9 billion per year surplus in trade of heavy machinery. Perhaps because of minimal funding in the field of sophisticated light machinery design, the United States suffers a loss of $6 billion to $9 billion per year in light machinery and its associated manufactures. In view of our present annual expenditure for petroleum—over $42 billion—we should not tolerate so massive a loss in any class of manufactures.

Trade data for the major U.S. imports and exports are summarized in Table 1 and broken down for nonmanufactured and manufactured commodities in Tables 2 to 4. The principal applications that are associated with heavy machines are listed in Table 3. Systems related to these applications (such as heavy tractors, compressors, and turbines) tend to be robust and are frequently composed of sophisticated materials. They have represented a significant trade surplus ($8 billion to $9 billion) for the U.S. economy. Our long-term emphasis on research in materials, especially by the Department of Defense (DOD) (6), may be part of the reason for the success of these applications. Also, U.S. industry has actively pursued international heavy machinery markets (5) by providing reliable units and responsive service maintenance. The sight of a familiar yellow earth-moving machine of U.S. manufacture is known throughout the world. Our advanced modernization of agriculture supports our supremacy in farm tractors. Our heavy investment in water management projects and a national network of superhighways have produced a progressive construction machinery industry. Similar arguments might be made for the other categories listed in Table 3.

Table 1. Department of Commerce trade documentation.*

Commodity and 1975 standing	Trade ($ billion)				
	1975 Exports	1975 Imports	1975 Balance	1970 Balance	1977 Balance
Nonmanufactures					
Positive balance	23.124	2.341	+20.783	+ 5.846	+19.593
Negative balance	7.170	41.894	−34.724	− 8.111	−58.225
Total	30.294	44.235	−13.941	− 2.265	−38.632
Manufactures					
Positive balance	53.887	18.354	+35.533	+14.759	+33.507
Negative balance	9.876	25.034	−15.158	− 9.914	−27.944
Total	64.246	43.967	+20.279	+ 4.562	+ 5.563
Heavy mechanical machines or manufactures					
Positive balance	19.740	6.087	+13.653	+ 5.156	+11.691
Negative balance	0.889	5.622	− 4.733	− 2.536	− 7.063
Total	20.629	11.709	+ 8.920	+ 2.620	+ 4.628
Light mechanical machines or manufactures					
Positive balance	5.989	1.994	+ 3.995	+ 1.602	+ 4.426
Negative balance	8.775	18.532	− 9.757	− 6.660	−12.578
Total	14.764	20.526	− 5.762	− 5.058	− 8.172
Mechanical machines or manufactures					
Positive balance	31.900	8.600	+23.300	+ 9.142	+21.378
Negative balance	15.297	32.318	−17.021	−11.838	−25.944
Total	47.197	40.918	+ 6.279	− 2.696	− 4.566
Aircraft and spacecraft	6.171	0.519	+ 5.652	+ 2.384	+ 5.261
Passenger cars and trucks	5.633	8.164	− 2.531	− 2.642	− 6.283
All commodities	106.156	96.940	+10.216	+ 2.630	−29.885

*A complete tabulation supporting these results is available on request from the author.

Table 2. Department of Commerce trade data for nonmanufactures.*

Code number†	Commodity	Trade ($ billion)				
		1975 Exports	1975 Imports	1975 Balance	1970 Balance	1977 Balance
04	Cereal grains	11.643	0.180	+11.463	+2.519	+ 8.604
08	Animal feeds	0.987	0.076	+ 0.911	+0.420	+ 1.477
22	Oilseeds and soybeans	3.134	0.037	+ 3.097	+1.211	+ 4.751
263	Cotton	1.010	0.018	+ 0.992	+0.275	+ 1.536
32	Coal and coke	3.343	0.202	+ 3.141	+1.027	+ 2.520
02	Fish	0.267	1.354	− 1.087	−0.700	− 1.580
06	Sugar	0.155	2.072	− 1.917	−0.784	− 1.145
07	Coffee	0.092	2.327	− 2.235	−1.571	− 5.387
28	Ferrous ores	1.355	1.960	− 0.605	−0.210	− 1.034
33	Petroleum	0.907	24.766	−23.859	−2.283	−40.213
34	Natural gas	0.214	1.435	− 1.221	−0.231	− 2.327
667	Pearls and diamonds	0.262	0.857	− 0.595	−0.362	− 1.275
68	Nonferrous alloys	1.312	2.580	− 1.268	−0.689	− 2.796

*All positive trade balances improved and all negative trade balances worsened. †Department of Commerce code number.

A brief list of the applications of light machinery and its manufactures is given in Table 4. These are the principal generators of our $6 billion to $9 billion per year trade deficit in light machinery, and almost every category shows a continuing worsening of the trade deficit since 1970. One of the common threads in these applications is the use of highly geometric devices of numerous design parameters that require sophisticated or high technology to achieve optimum results. Optimum may imply a product output of sufficient quality, a machine that uses minimum energy, a machine that operates at a very high speed without noise, and so on. For example, an emerging application may be miniaturized mechanical devices that are made by etching, in much the same way as microelectronic circuits. The designers of the first useful machines (James Watt and George Stephenson in 1800) spent their lives perfecting the complex valve control linkages associated with the steam locomotive. In many ways, today's designers frequently develop machines by the same trial and error methods, with a remarkable expenditure of time before a usable machine is obtained. An effective machine science would drastically reduce this design cycle time.

A recently developed $2-million textile carpet printer (7) uses a high-speed miniature valve to precisely control the flow of many color dyes to pattern a blank carpet with any selected digitized scene. It is a modern combination of computer control and mechanical devices. Ignoring several ancillary economic benefits, the system's return on investment is conservatively estimated to require 2 years of normal operation. Another example is a high-speed ammunition loader produced under a $26-million Air Force contract (8). The device loads a fighter aircraft in 6 minutes, a task that previously required 2 hours, thus making the aircraft significantly more cost-effective. The loader is driven by a motor in the aircraft and must maintain perfect synchronization with the gun mechanism during loading. Such a system must be based on rigid mechanical coupling to maintain a very high level of reliability. Principals in the development of these systems were recent Ph.D.'s in mechanical design. One of the conclusions that may be reached is that innovation in mechanical systems is possible today. The need for this level of expertise is illustrated by the fact that one of our major consumer products companies employing more than 1000 engineers has yet to hire a Ph.D. trained in mechanical design science.

Other attributes of purely mechanical devices (*9*) are their exceptional load capacity (ability to create large forces on a repetitive basis), precision at high speed, minimal energy consumption (by a factor of 10 compared to hydraulically driven systems), in many applications virtually no noise generation, long life, and high reliability (*10*). Apparent contradictions to these attributes can be shown to be due to poor design. For example, the precision of a textile machine depends on using quality bearings, rigid links for the mechanism, and a suitably strong crankshaft-flywheel combination. Unfortunately, the design of such highly nonlinear and multiparameter systems is not only complex (involving several levels of implicit higher-order algebraic equations) but only partially understood (rarely can a direct solution be obtained for a particular set of operating specifications). Subcomponent mechanical devices (cams and linkages) may easily contain 50 independent design parameters, making their optimal design a major unsolved task (*10*). For example, a basic six-link mechanism contains 14 geometric, 20 mass, 12 spring, and 10 friction damper parameters. Considering each parameter to have only ten distinct values, this would create an overwhelming collection of 10^{56} devices, all having unique properties that are potentially useful in solving a specified machine process.

It has been suggested that heavy industry systems are more dependent on quality application of materials, while light industry is more dependent on optimal parametric design of the system's geometry. Heavy machinery may be represented by large stationary steam turbines, which require very high quality castings, machining, and bearings, but also very sophisticated design of specially cooled turbine blades made of exotic materials. Light machinery may involve the manufacture of a complex multilayered product of paper, plastic, and woven stock. At 300 units per minute, the product is made by sequentially assembling the components, shaping them into the final form, collecting the products into salable quantities, and finally packaging them for shipment. Every product must meet stringent specifications of quality, size, and cleanliness. The processing line may involve ten unique stages, all of which must be precisely coordinated or no product will result. In this case, precision of operation is a dominant consideration to ensure that the product is salable.

Economic Factors

A brief study has been made of Department of Commerce trade figures for principal imports and exports (see Tables 1 to 4). From 1970 to 1976 the balance oscillated in the range of ± $4 billion, with a peak surplus of $11 billion in 1975 and an accumulated loss during this period of $2.6 billion. A drastic change took place in 1977. In that year our trade balance showed a $30 billion loss, and for 1978 it is expected to show a $50 billion loss. The primary cause of this severe deficit is petroleum, for which our trade figure was −$2.3 billion in 1970, −$7.0 billion in 1973, −$24.0 billion in 1975, −$40.5 billion in 1977, and is approaching −$45.0 billion in 1978 (see Fig. 1A). This oil deficit will not be significantly reduced in the next decade.

On the whole, manufactures rose from +$4.5 billion in 1970 to a peak of +$20.3 billion in 1975, but fell again to +$5.6 billion in 1977. Heavy machinery went from +$2.6 billion in 1970 to +8.9 billion in 1975 with a 3:1 ratio of positive over negative categories. It fell to +$4.6

Table 3. Department of Commerce trade data for heavy machinery and its manufactures.*

Code number	Commodity	Trade ($ billion) 1975 Exports	1975 Imports	1975 Balance	1970 Balance	1977 Balance
678.2 679, 691	Iron and steel manufactures	1.559	0.529	+1.030	+0.169	+0.596
712.5	Agricultural tractors	1.388	0.339	+1.049	+0.354	+0.797
715	Metalworking machines	0.919	0.367	+0.552	+0.232	+0.289
719.1	Heating and cooling equipment	1.309	0.186	+1.123	+0.428	+1.407
719.2	Pumps and compressors	1.505	0.344	+1.161	+0.476	+1.239
719.3	Cranes and handling equipment	1.845	0.226	+1.619	+0.508	+1.377
719.9	Metal foundry machinery components	0.806	0.307	+0.499	+0.275	+0.571
731	Railway vehicles	0.461	0.090	+0.371	+0.077	+0.223
732.8	Vehicle and tractor parts	4.384	2.507	+1.877	+1.047	+1.226
951.0	Arms of war	1.180	0.038	+1.142	+0.648	+1.406

*All categories shown exhibited trade balance improvement from 1970 to 1975, but many declined from 1975 to 1977.

Table 4. Department of Commerce trade data for light machinery and its manufactures.*

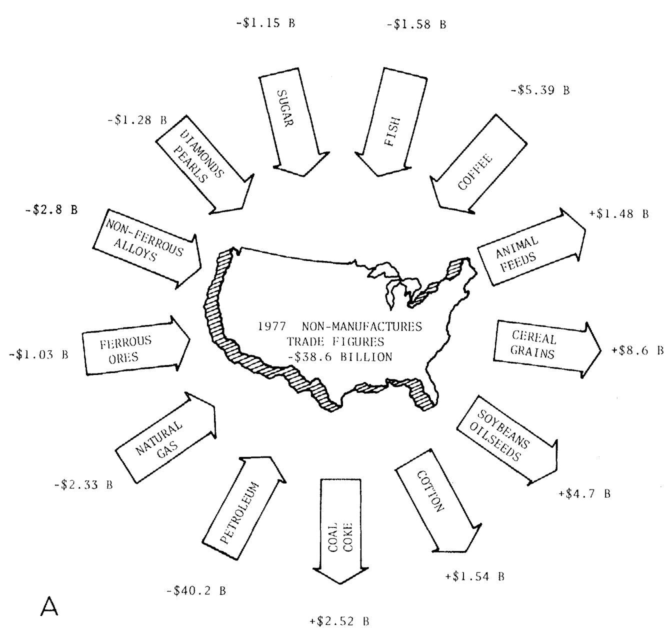
Code	Commodity	Trade ($ billion) 1975 Exports	1975 Imports	1975 Balance	1970 Balance	1977 Balance
629.1	Rubber tires	0.291	0.567	−0.276	−0.127	−0.677
694	Nails, tacks, and so on	0.146	0.388	−0.242	−0.110	−0.427
714.1	Typewriters and check-writing machines	0.033	0.149	−0.116	−0.072	−0.189
714.2	Calculating and accounting machinery	0.096	0.339	−0.243	−0.084	−0.263
717.3	Sewing machines	0.077	0.187	−0.110	−0.074	−0.141
732.9	Motorcycles	0.018	0.744	−0.726	−0.323	−0.673
82	Furniture	0.175	0.406	−0.231	−0.178	−0.410
83	Travel goods and handbags	0.037	0.217	−0.180	−0.096	−0.354
84	Clothing	0.402	2.550	−2.148	−1.066	−4.070
85	Footwear	0.095	1.301	−1.206	−0.620	−1.838
861.4	Cameras, still	0.103	0.175	−0.072	−0.035	−0.253
864	Watches	0.101	0.426	−0.325	−0.164	−0.538
891.1	Phonographs and tape recorders	0.195	0.603	−0.408	−0.302	−1.026
894.2	Toys and games	0.194	0.332	−0.138	−0.180	−0.358
894.4	Fishing and guns	0.156	0.239	−0.083	−0.007	−0.288

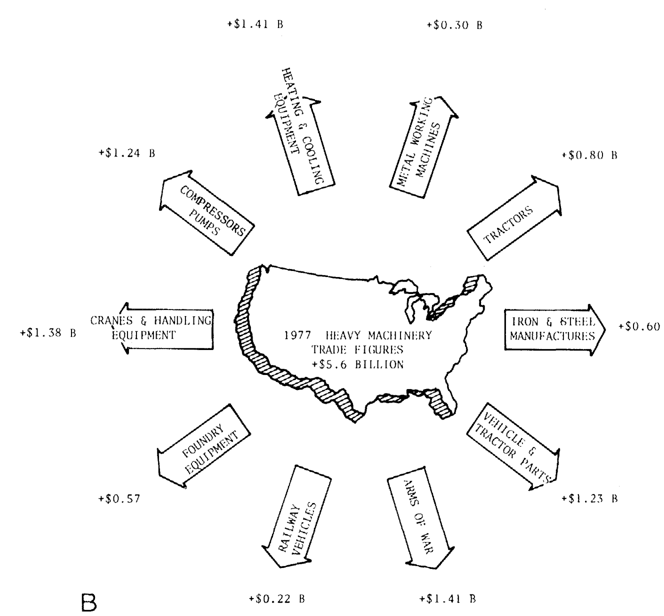
*All categories, except motorcycles, exhibited a worsening negative trade balance.

billion in 1977, showing that even the heavy class systems are increasingly vulnerable (see Fig. 1B). Light machinery exhibited a nearly constant deficit of −\$5.5 billion from 1970 to 1975 with a 3:1 ratio of negative over positive categories. In 1977 this deficit increased to −\$8.2 billion, showing that it is alarmingly sensitive to international trade competition (see Fig. 1C). Heavy manufactures reflect long-term industrial excellence, proved return on investment, and long-term research support by government (DOD) for materials and alloys. Light manufactures reflect a long-term slide in research activity while other countries have expanded their efforts.

One special manufacture that is a mix of the heavy and light classes of mechanical systems is aircraft, which has grown from +\$2.4 billion in 1970 and +\$5.6 billion in 1975 to +\$5.3 billion in 1977. One could argue that DOD involvement was a principal reason for this surplus. Another such category is passenger cars and trucks, which had a stable −\$2.5 billion deficit from 1970 through 1975 but fell to −\$6.3 billion in 1977. It has been argued that the Detroit auto industry forfeited part of its market by not energetically developing small cars. Once the market is prejudiced, it is very difficult to reverse it.

A remarkable report on our international trade was carried by the *New York Times* on 5 July 1978 (*11*). During the first 5 months of 1978, imports of machinery and manufactures were up 37 percent and were double our oil imports, which were 10 percent lower than in the same period in 1977. Our exports rose nominally about 12 percent to match inflation. Our trade deficit increased alarmingly from −\$8.2 billion to −\$14.8 billion during this same period, a 79 percent rise. A valid assessment of our manufacturing decline is the following conclusion, based on a poll of industrial R & D managers: "A grim mood prevails today among industrial research managers. America's vaunted technological superiority of the 1950's and 1960's is vanishing, they fear, the victim of wrongheaded federal policy, neglect, uncertain business conditions, and shortsighted corporate management." It is clear that a technological opportunity exists which, if pursued vigorously, can partially reverse this decline and stabilize the relative economic position of the United States in the world market for machinery and its manufactures.





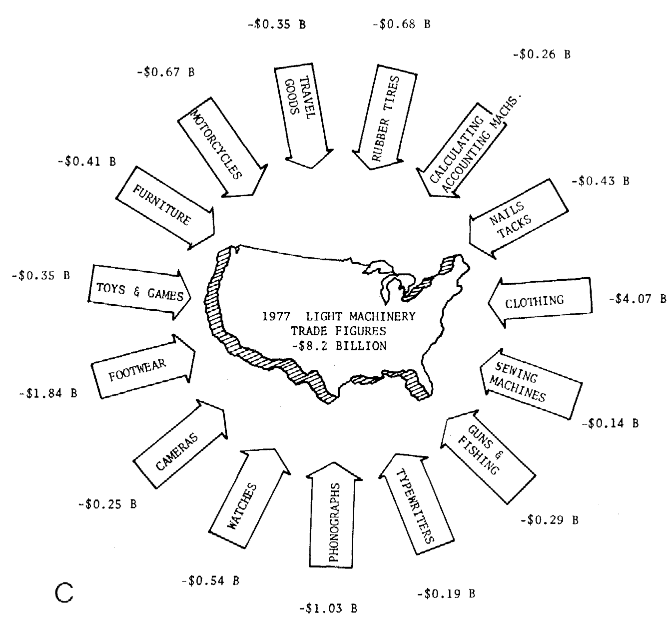


Fig. 1. Distribution of U.S. product flows for nonmanufactures, heavy machinery, and light machinery.

Brief Historical Review of Light Machinery Design

During the late 15th century, Leonardo da Vinci developed a remarkable conceptual model of a cable-operated mechanical arm (manipulator) for mechanical intelligence at the input (human muscle power) and mechanical function at the output (the duplication of the complex motions of a bird's wing). Today, 500 years later, the modern equivalent is capable of receiving all forms of control input intelligence—human, electronic, pneumatic, and so on. In the last quarter of the 18th century, the increasing availability of dependable steam power made possible the duplication of simple human motions (such as weaving motions to make a fabric) on a cyclic basis by mechanism-based machines. The Industrial Revolution, centered in England, was the result. Similar progress occurred in agricultural machinery in the United States during the second half of the 19th century, and was clearly a factor in the rapid opening of the West.

A pivotal book, *Theoretische Kinematik* (*12*), published in 1875 by Germany's top scientific officer, F. Reuleaux, established the basis for the science of machines. This work has been ongoing in Germany for 100 years, and Swiss and German textile machines are representative examples of the result. In this country in the first half of this century, companies hired expert designers from central Europe to compensate for our inactivity in machine science. Consequently, there was little pressure on the universities to provide excellence in education or technology in this field. In 1922, the renowned theoretician in analytical mechanics, S. Timoshenko, arrived in this country from Russia. During the next 10 years he published several books dealing with such subjects as elasticity, plasticity, plates and shells, strength of materials, classical dynamics, and vibrations. The machinery community found it difficult to embrace his revolutionary methods, and as a consequence his initiative attracted many from the study of machines into these fascinating fields of theoretical research. Academic research on the study of machines finally got under way during the decade 1955 to 1965, motivated by the early research of F. Freudenstein, the teaching example of A. S. Hall, Jr., and the leadership of F. R. E. Crossley in developing international relationships. However, their effort is only now bearing fruit. With the arrival of Sputnik in 1957 and the consequent enhanced government research programs, the machine community was ill-prepared to obtain sizable research support.

Generally, the university community has seen a 20 percent effective reduction in federal funding during the past decade (*13*). Even during periods of research expansion, the field of machine science has never enjoyed a significant portion of this funding. This contention is supported by the fact that the National Science Foundation (NSF) funding for basic research is 30 times higher per fundable faculty member in physics than in mechanical engineering and mechanics. It is indicative that the word mechanical is rarely used in the titles of major federal research programs. To my knowledge, there is no federal program dealing with the science of mechanical design. The result of this modest activity is increasingly obvious today, as illustrated by the economic data cited in this article.

Our development of mechanical design science has been so neglected that cycles of 5 to 7 years from design to production are commonplace. It took 30 man-years to generate the dynamic model for the space shuttle manipulator (*14*). Our computers are modern, but the mechanical science to design and manufacture tommorrow's products is outdated. To revitalize the science of design will require a major commitment from several mission-oriented agencies as well as NSF. It is known that significant programs for electronics, materials, and mathematics already exist for enhancement of university research. I suggest that two major areas be added: mechanical design science, which is documented in this article, and the related field of manufacturing processes (*15*). Both could do a great deal to enhance our productivity in basic manufacture, which is the nation's largest technological endeavor. Since these areas are distinctly mission-oriented, government funding must allow for close industrial relations to make the results more immediately applicable.

Robotics as a Catalyst for Light Machinery Development

Those who attended the NSF Workshop on Robotics last February concluded that the scientific base now exists for dramatic advances in mechanical design technology and its associated industrial spectrum (*16*). They deplored the fact that the United States, in its vast research and development program, is not promoting the development of this technology but, by default, is yielding the field and subsequent markets to Japan, Germany, and Russia. They strongly recommended that a directed national policy be established to substantially accelerate the development of advanced technology for robotic systems.

The robotic system is in many ways the technological equivalent of the human system, having components such as sensors (eyes), actuators (muscles), and a computer (brain), which allow the system to perform mechanical functions by reacting to needs in its environment that it perceives and interprets. Such systems are of particular importance for one pressing problem, the remote maintenance of nuclear systems (*17*). Two nuclear power plants in Florida have repairs under way with a cost approaching $0.6 billion (*18, 19*). Human maintenance is either inadequate, too expensive, or limited by radiation regulations. It is legally required of plant operators that all available technology must be used to reduce the radiation exposure to maintenance personnel. Estimates of the operation of fusion reactors indicate that they will require replacement of the plasma shields once every 2 years. There is no available precise documentation of the functional requirements for disassembly and assembly, but it appears they will be very difficult to achieve by near-term robotic technology. Remote inspection and maintenance require the highest level of mechanical generality (more geometric parameters for design means a more versatile device) and operational precision. Because of this necessary complexity, the robotic manipulator is not controllable by a human operator; his role must be augmented by digital computation. This, then, will be one of the most demanding engineering problems yet to be fully addressed by any machine research group in the United States.

Offshore oil well drilling faces similar problems. The establishment of the country's offshore economy may eventually hinge on remotely operated surface and sea floor stations, both of which require the use of the manipulator for inspection and maintenance. The only alternative is to use divers, who must operate in a hazardous environment, have endurance limitations, and are very expensive (*20*). Similar problems exist for coal mine accident missions, as illustrated by the March 1976 methane explosions in the Kentucky Scotia mine. In this case, a search party of 11 people were killed trying to determine the status of a group of trapped miners. Robotic survey systems would have been able to perform the same task without jeopardizing the lives of additional personnel.

Other applications of robotics are for

defense-related functions such as deep submergence vehicles and surveillance vehicles in space, microsurgery to enhance the mechanical precision of the surgeon's hands, human augmentation in manufacturing and prostheses for the incapacitated, and industrial automation and assembly. Generally, the use of robotic systems (industrial robotic manipulator arms) as a manufacturing aid in automation is considered to be marginally cost effective today in the United States (*21*). Hence, most applications involve either human enhancement (to increase endurance in a particular task, as in handling heavy, hot forgings) or human protection (to remove the operator from a dangerous or toxic task, as in painting automobile bodies). In Japan, robotic devices are most likely to become economical because of that country's impending labor shortage (*21*). Japan has invested \$2 billion on government and industrial R & D in robotics (*22*). This far exceeds U.S. efforts. Each major Japanese company is now pursuing specialized robotic devices for its present or future needs. These companies are actively developing completely automated self-contained factories to be sold to developing countries.

The robotic system requires the technologies of several engineering disciplines (such as machine design, vibrations, strength of materials, automatic control, and computer science). Consequently, a team research effort is essential for meaningful progress. Since this is an emerging technology of great interest, it could become the vehicle for technological development in the whole field of mechanical design science. It is expected that as more electronics are integrated into basic machines and as robotic devices are more widely applied, a general blending of the whole spectrum will occur. Because every mechanical function of the robotic system must be electronically controlled, the robotic device will perhaps represent the ultimate marriage of these two technologies.

One of the major tooling efforts in the United States has been numerical control machines. These systems are computer controlled and are capable of automatically duplicating the function of several distinct machine tools (such as the lathe, mill, and plane). Such devices may be considered as unsophisticated robotic systems. The auto industry is now attempting to pursue advanced technology machines (modern numerical control machines and robotic mechanical arms), but it is finding that our tool industry is inadequately prepared for such a large surge of orders and may have to go to foreign sources (*23*). It is interesting to note that in 1968, 50 percent of the cost of a numerical control machine was due to electronics. Today, that portion of the cost is down to 15 percent. One may thus argue that the security of return on research investment is much better for the mechanical portion of this system. This highlights the relative stability of return on investment in mechanical technology in general.

Function of Major Long-Term Research Teams

The present federal funding structure has been criticized on the basis of "fragmented work, no long-term commitment, not enough equipment money, restrictive control, short-term payoffs, critical size projects are rare, younger faculty are not well involved, government research reports sit on the shelf, and industry is not involved in establishment of research priorities" (*24*). It is clear that the growing technological superiority of foreign light industry is the chief factor to be considered. Within the United States the role of venture capital has all but vanished, so innovation has diminished. In most developed countries, Japan and West Germany in particular, government and industry cooperate on common goals, usually with universities as the research vehicle. There has been a significant decrease in recent years in unrestricted general research in all sectors of the U.S. research community. In fact the presidential science adviser, Dr. Frank Press, claims that industrial research has become defensive—developing new technology to satisfy environmental regulations—rather than innovative. Edward Kennedy, the Senate champion of NSF, has asked for an expanded role for industry at NSF (*25*), and that agency has indicated its willingness to cooperate (*26*).

How should the ideal government, university, and industrial research interaction be established? The DOD has had considerable success with its Joint Services Electronics Program (JSEP), which "provides a valuable and continuous flow of research ideas in electronics, decreased load on researchers because of long-term commitment, minimum restrictions and commitments to administer, and maintain leading edge effort in electronics for national defense long-range capability" (*24*).

A new Defense Science and Engineering Program (DSEP) has been proposed by DOD. It will have many of the structural features of JSEP, except that it will have no specific technological mission. Because of this flexibility and its interdisciplinary basis, DSEP should be able to address any future technological need.

The means of technology transfer in this case is close cooperation between interested DOD laboratories. Any major research team should have several active outlets for its developing technology. For example, a defense contractor dealing with ammunition handling, an industrial robotics manufacturer, a high-technology R & D company, and a research team dealing with robotics. To be effective, these interactions must be mutually beneficial. The research team would have immediate knowledge of industrial problems, and industry would have an early review of evolving technology. In cases where development and demonstration are the dominant considerations, it might be appropriate to have ten times as much applied research in the industry group as basic research in the scientific group. If new scientific results are the primary goal, this ratio may be suitably changed. Partially supporting some of the industrial members under the grant to pursue prototype development and experimental testing activity should be seriously considered.

Conclusion

Light machinery and its manufactures are showing an increasingly negative trade deficit, approaching \$9 billion per year with a 3:1 ratio of negative over positive categories. In the past, heavy machinery has had a positive trade balance, although 1977 data show that this is weakening. The importance of this technology has been recognized in recent months by many key national research policy-makers. This article suggests that a primary corrective step to be taken involves universal strengthening of the field of mechanical design science. Integration of the expanding microelectronics technology with the mechanical system is an essential ingredient. This integration may best be demonstrated in terms of the demanding robotic system.

Recent manpower forecasts (*27, 28*) indicate that high-technology programs have weakened during the past decade and will have been significantly curtailed by 1985. Corrective steps must be taken now to rectify this expected deficiency. Agencies such as NSF in its Engineering and ASRA (Applied Science and Research Applications) divisions, DOD, NASA, and the Department of Energy all have existing missions related to mechanical design science but have not yet been enabled to fund major research programs. Major long-term academic research has proved to be cost-effective and productive of new technology, and it is now essential for rapid development. At this time, no centers for light machinery research are known to exist in the United States.

It is apparent that in the light machinery field, foreign manufacture has outstripped U.S. technological development. This continuing weakness of our machinery and manufactures is clearly evident from the trade balance which reached a peak of $20 billion in 1975, went down to $5 billion in 1977, reached parity in the middle of 1978 (*11*), and may continue its downward slide. Correcting this condition should be a national concern. Parity is not a sufficient goal. Accepting parity would imply an eventual reduction of our standard of living. The overwhelming burden of oil imports suggests that no major deficit category in manufactures should be tolerated. A national policy to establish a cohesive program for light machinery research (or intelligent machines) is not only desirable but necessary.

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NEWS AND COMMENT

Ever So Cautiously, the FDA Moves Toward a Ban on Nitrites

The hazard to animals and man of eating excessive amounts of nitrates and nitrates has been known for more than three-quarters of a century, ever since N. S. Mayo reported in 1895 on the deaths of cattle in Kansas that had eaten nitrate-laden cornstalks. It was confirmed by scientists much later that nitrates, when consumed by man or animals, break down in saliva and in the digestive tract into nitrites, which many subsequently combine with amines present in foods or other sources to form nitrosamines. Nitrosamines have caused cancer in laboratory animals.

Now it appears that the federal government is about to ban the second of the substances in this hazardous chain—nitrites—as an additive in everyday foods because of a study that demonstrates that it, too, may cause cancer in laboratory animals. Both the Food and Drug Administration (FDA) and the U.S. Department of Agriculture (USDA) have recommended such a ban, although they have proposed to implement it over an as-yet unspecified period of time. The ban is being held up, however, through an unprecedented decision by Secretary of Health, Education and Welfare (HEW) Joseph Califano to submit the regulatory proposal to the Justice Department for final review. FDA and USDA officials were incensed by Califano's decision, because it has delayed formal announcement of the plan and opened it up to sniping by congressional and other critics before the rationale had been laid out before the public. Because the Justice Department review is still pending, a final decision on whether or not the nitrites will be banned remains up in the air.

Initially, nitrites were added to meat, poultry, and fish by food processors because the substance reacts with bacteria to impart an appealing pink or red color. Subsequently, it was found that nitrites retard the growth of botulinum spores, which are ubiquitous in food and nature and which can cause botulism in humans, a food poisoning that is fatal in between one-third and one-quarter of all cases. The addition of nitrites to meats, fish, and poultry accounting for 7 percent of the entire U.S. food supply is generally thought to have reduced the risk of botulism poisoning to almost zero. Concern in the past over the additive has stemmed from the fact that nitrates, the precursors of nitrites, are also ubiquitous in nature—in air, water, and many edible plants. And nitrites are the direct link to nitrosamines.

These circumstances have all of the makings of a classic dilemma for federal regulators, who for some time have been asked by public interest groups to minimize the existent but unquantified hazard of adding nitrates to food. Within the last year, FDA and USDA have both moved to ensure the absence of nitrosamines from poultry and bacon, targeting in typical fashion the most certain hazard in the nitrate trio. (Nitrosamines are not added to food, but there is evidence that added nitrites may be converted to nitrosamines even before the food is eaten.)

These actions left the public interest groups—principally the Environmental Defense Fund and Ralph Nader's Public Citizen Litigation Group—determined to seek greater concessions, and the industry—represented in Washington primarily by the American Meat Institute—just as determined to prevent further nitrite restrictions.

Now, whatever delicate equilibrium that existed between these opposing forces has been forever upset. In late spring of this year, Paul Newberne, a toxicologist at the Massachusetts Institute of Technology, completed an FDA-sponsored study that furnishes, for the first time, solid evidence that nitrites are themselves carcinogens. The study, which cost $500,000, involved 1954