HISTORY OF THE MIT SERVOMECHANISMS LABORATORY
AND ITS IMPLICATIONS FOR
MIT'S RELATIONS WITH GOVERNMENT AND INDUSTRY

by

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Introduction

Almost two years ago, I had the pleasure of meeting Dr. Julius Stratton and Ms. Loretta Mannix at their office in building 14. I asked them to tell me about the history of MIT. Their story was something of a surprise to me. Contrary to my simple assumption, MIT, until after the Second World War, was far from the huge education and research institute that it is now. Dr. Stratton told me that "MIT literally lived from hand to mouth" until the early part of the twentieth century. How did MIT grow from living "hand to mouth" to what it is today? What aspects of MIT activity caused this tremendous growth? MIT was able to grow because a relatively smooth system for achieving technological change provided MIT with the resources necessary for furthering research in the various science and engineering fields. The three major sectors that seem most involved in technology are the federal government, industry, and research institutions such as MIT. During the decade that followed the Second World War, each of these three sectors performed a specific function needed in bringing technological change. The functions can be divided into three simple categories: research, funding and application (or utilization). At the suggestion of Prof. Merritt Roe Smith, I began looking into the history of the MIT Servomechanisms Laboratory. The history of this laboratory is an example of the role that MIT played in implementing technological changes in the 1940's and 50's and how in this process it was able to achieve such rapid growth.

The MIT Servomechanisms Lab was founded in the spring of 1940 by Gordon Brown. Initially, he began with only two assistants, hardly a budget, and little idea where to start. By the end of the war, however, the Lab had over one hundred staff members and over a million dollars in contracts a year.[1] By the late 1950's, the Lab had helped to introduce a whole new manufacturing process called numerical controls and it initiated research in pioneer computer programming methods for design and production of various machine parts. How was all this achieved within less than two decades? How did the relationship between MIT, industry and government evolve and what effect did this change have on the Servomechanisms Lab? What in turn can we conclude about the way technological changes were brought about in this era? These are some of the basic questions which I propose to answer in this inquiry.

Several historians have examined MIT's historical relationship to industry and government both in the nineteenth and twentieth century. In his account of the history of MIT in the nineteenth century, Samuel Prescott showed that the close relationship maintained between MIT and the Boston community contributed to its survival during times when MIT faced financial difficulties, and its growth in the better years.[2] More recently, Prof. David Noble has revealed negative aspects of MIT's interaction with industry and government in the twentieth century. Prof. Noble has opened controversial questions concerning the processes in which technological changes are brought about and what sectors maintain control over technological change.[3] Looking at the history of technology from the industrial side, Dr. George Wise of the General Electric Company put together the history of GE's research laboratories and its role in technology.[4] Although these and various other historical interpretations exist concerning the relationship between the three sectors, no one has examined specifically the history of the Servomechanisms Lab for the purpose of understanding these relationships more clearly.

Throughout my research it has become evident that the growth of the Servomechanisms Lab depended on many factors. MIT's superb intellectual capabilities were of course a major factor. But the success of the Lab must also be attributed partly to government and industrial support and industrial utilization of the technological innovations that the Lab made. The Lab was established in anticipation of the war because the potential for military use of servomechanisms technology seemed strong. During the war years, MIT depended solely on government contracts and industrial subcontracts. After the war, however, the Lab inevitably needed to continue depending on outside funds because the tremendous growth that it experienced during the war increased the magnitude and complexity of the research proportionally, and MIT alone could not possibly meet the Lab's research costs. Undoubtedly, the government and the industrial sector too had become dependent on the Lab's technological expertise. Thus, in its first two decades, the Lab had established a unique relationship with the two sectors that made its growth and achievements possible.

Technology closely follows political, social, and economical situations of the era in question. Thus, in this paper, I will relate relevant historical facts of the time to events that took place at MIT, because MIT was greatly affected by the trends of American politics and economy. First, the MIT Electrical Engineering Department in the 1920's and 30's will be examined since it was there that the Servomechanisms Laboratory was founded. Then, the accounts of wartime Lab activities against the backdrop of U. S. mobilization of the scientific community for the war effort will be covered. Finally, I will examine the effects of wartime growth (of the lab) in the post war decade and the resulting changes in the relationship between MIT, industry and government. A close look at the history of the relationship will reveal the patterns in the change of technology and MIT's place in it.

Prewar Setting

Between 1902 and 1927, U. S. power consumption increased by 25 times. Following this trend, enrollment in the field of electrical engineering increased by 600% in the colleges around the country.[5] By the late 20's MIT took bold steps to strengthen engineering education by increasing research, expanding the Electrical Engineering Department, increasing enrollment, and awarding more graduate degrees. Dugald Jackson, as head of the electrical engineering department recruited men who through their research and teaching ability, helped to shape a "remarkably successful" department. Students were trained with the long term goal to expand the field of electrical engineering. This meant that facilities and programs had to be available to expand graduate research, so that students could understand and solve real problems of the electrical industry.

In the 1920's and 30's, the various laboratories and research projects at MIT were conducted with very little dependence on industry's financial backing. In the electrical engineering department, the birthplace of the Servomechanisms Lab, research projects were initiated for educational purposes. Research projects produced doctoral theses and research tools that would be beneficial toward furthering that research or initiating other research projects. Thus, a symbiotic relationship existed between research and education. Research was an essential component of education. And education provided the necessary tools to pursue research. In the three exemplary cases to be presented here, several common factors give a better understanding of the general relationships that the electrical engineering department established with the industrial sector.

The Differential Analyzer

The development of the differential analyzer by Vannevar Bush is a clear example of independently generated ideas that were successfully carried out and which in turn contributed to expanding research and educational opportunities with outside funding. Bush conceived the idea of building a differential analyzer during his years as an undergraduate at Tufts University. Finding an increasing need for a machine that could reduce the time to calculate integrals that frequently come up in engineering problems, Bush set out to build such a machine in 1924.

A differential analyzer, as it was later named in the 1930's, is an analog machine that manipulates differential equations of natural phenomena by representing the terms of the given equation electromechanically. Thus, given a differential equation, the differential analyzer simulates electomechanically the behavior of particular phenomena. Results could be observed instead of having to perform such time-consuming calculations. The basic components were an integrator(s) that would perform the actual calculations and a servomechanism(s) that would control the system electromechanically. The first machines had mechanical servomechanisms. When the differential equation involved solving complicated integrals, manual calculation could take days. As research progressed and became more theoretical, more complex phenomena had to be analyzed. This meant more factors to consider that involved calculations of nontrivial integrals. Although prior attempts had been made, Bush's work resulted in the first practical machine ever built.

The occasion to build the first of four differential analyzers was the subject of a thesis by Herbert Stewart in 1925. By this time, Bush had joined the MIT faculty. Built at Bush's own laboratory, the differential analyzer consisted of an integrator and a simple servomechanism. Named the product integraph, it performed various useful calculations involving first order differential equations. Though time consuming, the integraph could also perform second order differential equations by successive approximations.

With the success of the first machine, Harold L. Hazen, then Bush's research assistant, proposed the construction of a second machine that would be capable of solving second order differential equations much faster. Hazen designed the second machine in 1927 under Bush's supervision. The machine was constructed by Walter F. Kenshaw of the department machine shop. It consisted of two integrators (the original integrator and a newly designed one). Though the second integraph proved more applicable than the first machine, Hazen and Bush agreed that a third and more improved design was possible. The successes thus achieved in this area of research enabled Bush in the following year, to secure an Institute grant, outside of the normal department allotment for research, to build a third machine.

The third machine was completed three years later in 1931. Except for the servomechanisms (drives and controls), all operations were mechanical. Six integrators were installed, which enabled the machine to handle sixth order differential equations. Precision was improved tenfold and the installed servos that operated by feedback system were also refined. This machine could handle virtually all the integrations that were common to engineering problems. It proved so useful that other machines of similar capability were built at the Ballistics Research Lab of the United States Ordinance Department, University of Pennsylvania, General Electric, Schenectady, as well as in Ireland, Norway and Russia.

Within just a few years, the differential analyzer became widely accepted as an essential calculationg tool. But Bush and Hazen wanted to build an even better machine. They wanted to automate some mechanical components of the machine so manual interconnections of shafts would not be necessary to change from one problem to another. Fortunately, their goal was concurrent with Rockefeller Foundation's efforts to fund applied research. In 1935, with the sponsorship of the Rockefeller Foundation, a program was initiated to build a very large differential analyzer that would reset itself automatically from one problem to another through the directions given by punched tapes. When information was fed into the machine by three separate tapes, it would perform the needed calculation and most of the mechanical work without manual attention. The machine was successfully completed in 1941 and in operation in 1942. It was named the Rockefeller Differential Analyzer after its sponsor. Publication of that achievement was deferred, however, until the end of the war because the staff was heavily involved with war activities.[6]

The knowledge and experience gained from differential analyzer research enabled the completion of many theses that in turn developed further this field of research. Gordon S. Brown, who was to found the

Servomechanisms Lab, produced a doctoral thesis in 1938 on an improved design of servos for the cinema integraph that improved the speed and accuracy of photoelectric integraphs.

Although funding for the Rockefeller Differential Analyzer came from outside MIT, the original purpose of pursuing research in analog calculating machines was for education. Research on the differential analyzer won attention because the machines proved to be very useful. What began as Bush's idea to facilitate engineering research came in time to link MIT to industry. MIT was relatively independent from industry, with respect to choosing topics of research. But inevitably, because both MIT and industry depended on similar fields of research, a close interaction resulted between the two sectors.

The Network Analyzer

The history of the network analyzer is in many ways similar to the development of the differential analyzer. In the early 1920's, there was a movement in this country to extend electric power to rural areas and to interconnect the system country-wide. It was called the superpower movement. Various power companies such as General Electric and Jackson and Moreland pursued ways to achieve these goals. Although the idea was simple enough, the superpower scheme posed new and complex problems due to the huge magnitude of such an operation. A new system could not be built merely by design ideas. In order to avoid disasters such as blackouts, the design needed to be tested until the system proved flawless. Consequently, engineers attempted to model simulations of a superpower system. In 1924, Vannevar Bush and Ralph Booth were asked by Jackson and Moreland Power Company to look into the superpower simulation problem. Bush and Booth's study produced several papers on the problem, which were presented at the American Institute of Electrical Engineers (AIEE) meeting of 1925.[7]

During his work on the superpower simulator, Bush decided to set up the power system simulation at MIT. There were several reasons for that. First, the problem existed without a solution. Second, with the help of those industrial labs already looking into the problem, it was feasible to set up a lab. Third, it would be a great research facility for graduate students and staff. With these ideas in mind, Bush discussed his proposal with Harold L. Hazen and Hugh H. Spencer. Consequently, the first design, construction, and testing of the power system simulation was the product of a joint thesis by Hazen and Spencer in 1925. After a short employment at the General Electric plant in Schenectady, Hazen returned to MIT as a research assistant. He was asked by Bush to expand his thesis work to simulate a large urban power network. Hazen pointed out several problems, including the fact that there existed no measuring instrument that could accurately analyze the system, but he was able to come up with a solution to those problems. And with the collaboration from engineers at the General Electric plant in West Lynn, Hazen was able to build an instrument that could accurately make needed measurements.

In order to carry out the project of building this large power system simulation, Bush realized that outside funding would be needed. Having solved the necessary problems, Bush raised the issue with the General Electric company, which for many years had been unable to overcome the various simulation problems in its own research. The final design and construction of a network was carried out jointly by MIT and General Electric and the name "network analyzer" was adopted.[8]

The network analyzer was intended as an educational facility. However, the successfully finished product performed so accurately and efficiently, that it was also useful for industrial needs. The network analyzer was made accessible to various companies for a small fee that covered operating and expansion expenses. General Electric Company, as well as several major power companies such as Jackson and Moreland, Illinois Power and Light Company, and the Tennessee Valley Authority, were frequent users of this device.[9]

In 1939, as a result of the federal government's proposal to set up a power grid for the United States, MIT received additional funds to do extensive studies on the analyzer. In 1940, the analyzer was moved into a larger room where the capacity of the machine was also greatly increased with the installation of additional parts. It served both MIT and industry in the nationwide effort of electification for over a decade. In 1952, Gordon S. Brown, as new head of the electrical engineering department, terminated network analyzer research on the grounds that it was no longer serving its purpose as a first rate research tool for staff and students. This decision came despite the fact that it was still very useful to industrial companies. The next year, the network analyzer was sold to Jackson and Moreland, which altered some parts and used it for many more years.[10]

It is important to note that despite MIT's dependence on industrial funding in constructing the network analyzer and despite the flowing source of income from power companies that utilized the analyzer, it was dismantled when it no longer served its primary purpose as a research tool. MIT was willing to depend on the industrial sector only when the project had promising research potentials. But when the machine no longer served as a research source, other factors proved less important.

High Voltage Reseach

The case of John G. Trump's high voltage research in the 1930's also exemplifies MIT's relative independence from industry. In 1932, Bush introduced John G. Trump to Robert Van de Graaf. At that time, Van de Graaf was in the process of refining his electrostatic generator. Specifically, he needed to improve the power source for more effective control. He proposed the idea of designing a vacuum-utilized energy converter that would be attached directly to the Van de Graaf generator. Trump began work on the prospect and delivered a proposal that would also serve as his thesis. With Van de Graaf as his supervisor, Trump designed and built an AC synchronous motor in the department's shop. As part of the thesis, he also studied Van de Graaf's idea of DC vacuum transmission lines. Trump's research showed that such a line could transmit a million kilowatts a distance of a thousand miles at one million volts with a mere 2.5% energy loss. Such a vacuum system would not bring on the ordinary problems of lighting faults or instabilities, and it would cost much less than an AC line.

Trump's success not only produced his thesis, but two patents. In 1935, a patent on the electrostatic generator was issued. In that same year, a second patent was issued on the electrical transmission systems. These results stirred a lot of excitement and many prospects for further research in the field. Thus, after the completion of his graduate work, John G. Trump remained at MIT to further high voltage research (as it was known then) as part of the general department research program.

By 1935, when the patents were issued, scientists in various fields were beginning to see the applicability of Trump's invention. The vacuum system could enable the generator to produce high voltage X-rays that could potentially be used to treat cancer patients. Voltage and current were easier to control so the system could be a very effective source of X-rays. After a successful demonstration, Harvard Medical School sponsored the construction of a one million megavolt air-insulated X-ray generator for their X-ray needs. The machine was completed in 1937. More than a thousand patients were treated with the machine in the first three years. The success of this machine resulted in sponsorships to refine the machine as well as collaboration between Trump's staff and the medical community of the Boston area. This marked the initiation of ties between Trump's lab and the field of medicine, particularly with high tech companies dealing with medicine. The war interrupted research, but after the war, Trump's lab became known as the High Voltage Research Lab. It became a respected graduate research facility of the department that had close interdepartmental ties with both the biology and physics departments.[11]

Interdepartmental cooperation was not unique to Trump's work. It was especially strong in the prewar decade when MIT was less dependent on outside funds. In the case of the Trump-Van de Graaf collaboration, each department mutually benefitted the other. And, in turn, their success opened new opportunities for further research by the availability of industrial funds. Note again, however, that the research originated independently of industrial considerations.

MIT's close cooperation in research with the industrial sector began during this era. Because the nature of research conducted at MIT was closely related to industrial interests, collaboration and thus a close association was inevitable. By the time the Servomechanisms Laboratory was established, a majority of the research projects being conducted in the electrical engineering department received industrial or federal funding. MIT was already becoming dependent on outside funding. It is important to note, however, that although they looked to industry and government for funds, they maintained control in deciding on the topics of research to pursue. MIT's unequaled expertise in scientific research was undoubtedly the reason why they were able to pursue research without first considering industrial needs. But more and more, industrial needs and interests became relative to MIT's and vice versa. MIT needed to prepare engineers and scientists for real problems that people in industry faced, and industry faced scientific problems that researchers at MIT could solve. Thus , toward the end of the 1930's the most important task MIT confronted was how to collaborate with industry so that it could benefit without losing the independence to consider their interests first.

A close system of cooperation with industry was both necessary and dangerous. The danger lay in the possibility that MIT's primary purpose as a research institution would be overlooked as projects without much educational value were undertaken. By educational value, I mean research that would uncover new scientific knowledge. In anticipation of such a situation, President Compton, joined with the faculty and the visiting committee of the Division of Industrial Cooperation (DIC) to revise and recodify MIT's policies with regards to industrial research at the Institute. The resulting text made clear what principles governed that research:

> (1) The primary purpose of all research projects conducted by the Division (of Industrial Cooperation) is the furtherance of the educational progress of the Institute.
> (2) Where the Institute has unique facilities of personnel and equipment, we have an obligation to make such facilities available to industry.
> (3) The Institute has a special obligation to render service to the Commonwealth, to the cities of Cambridge and Boston, and to the several agencies of the Federal Government.
> (4) It is unwise for the Institute to perform routine testing services. While to a limited extent it is sometimes necessary to do such testing...it must be recognized that competition by the Institute with existing equipment and labs, is improper.[12]

These guidelines were set up because many instances occurred where research without much educational value was being conducted. MIT had to determine the fine line between pursuing educational research that would result in new advancements in a field, and industrial research that was applicational more than educational. The relationship between MIT and industry and government was greatly affected by the Second World War in various ways so that the issue of maintaining independence became a pressing dilemma in the post war years.

In Anticipation of a War

By 1938, the scientific community, along with the rest of the country, was anticipating the outbreak of war in Europe. At MIT, Vannevar Bush was about to depart for Washington, D.C., to take his newly appointed position as president of the Carnegie Institute. He was also appointed chairman of the National Advisory Committee for Aeronautics (NACA). Thus, Bush's position in Washington gave him a clear vantage point from which to follow and influence science policy-making in anticipation of the war.[13]

Other prominent scientists and administrators of science shared Bush 's concerns. They realized that the United States was not prepared for war. The military establishment did not have a clear idea of how scientists could participate in the war effort and scientists, too, had little idea how they could contribute to the war effort. For two years, between 1938 and 1940, Bush and several others such as Frank Jewett (President of Bell Telephone Laboratories as well as of the National Academy of Sciences), Karl T. Compton (President of MIT), James B. Conant (President of Harvard University), Isaiah Bowman (President of Johns Hopkins University), and Richard C. Tolman (Dean of the Graduate School at the California Institute of Technology), met frequently in Washington to discuss a plan to mobilize the nation's scientific resources to prepare for their contribution to the war effort.[14]

At that time, several government agencies handled science policies. The NACA carried out fundamental research and correlated military and civil activities concerning aeronautic research. The National Academy of

Sciences (NAS) advised the government on specific scientific problems. There was not, however an agency that could organize and correlate fundamental research in fields of military importance outside of aeronautics. The members of this informal group of scientists believed that this was an urgent national problem.

In late spring of 1940, the group proposed the establishment of the National Defense Reseach Committee (NDRC). Franklin Roosevelt, who had complete confidence in Bush's judgment, agreed that mobilization of the country's scientific resources for defense purposes would be crucial. NDRC was established that year by Executive Order. It consisted of "ambassadors" from the three sectors that governed American science: government, industry, and the universities. According to the executive order:

> the duty of the National Defense Research Committee (was) to coordinate, supervise, and conduct scientific research on the problems underlying the development , production, and use of mechanisms and devices of warfare, except scientific research on the problems of flight. The Committee is authorized to construct and operate research laboratories, and to make contracts for research, studies, and reports with educational and scientific institutions, with individuals, and with industrial and other organizations for scientific studies and reports in its field, and is authorized to conduct research and experiment in such laboratories as may be placed under its direction, and PROVIDED FURTHER, That the rules and regulations for the conduct of the work of the Committee shall be formulated by the Committee and approved by

> the President.
>
> Appropriations of such sums as may be necessary are authorized: PROVIDED, That an annual report to the Congress shall be submitted through the President.[15]

Bush was most responsible for convincing Roosevelt, his advisors and the heads of military forces of the need to prepare and organize the scientific community. And for almost a year, NDRC carried out its duties quite smoothly.

The next year, in 1941, Bush was again most influential in forming the Office of Scientific Research and Development (OSRD). This agency carried through programs of research in the various fields of engineering development and NDRC became a division of OSRD. While NDRC often administered research, OSRD administered and actively carried out the research. OSRD also handled research in the field of military medicine. Up until that time, there was no agency in the government that handled this field. OSRD, unlike the NDRC created an atmosphere in which scientific experts could link up and consult each other. Throughout the war, while the NDRC was the crucial governing agency for defense research, OSRD became the most important agency for carrying through research and development in collaboration with industry and universities.[16]

With both Bush and Compton's heavy involvement in OSRD, MIT took on a large number of the research projects that were distributed to major university research centers. By the end of the war, MIT had received $56 million dollars just in direct contracts through the agency. Karl Compton was also most influential in setting up the Radiation Laboratory at MIT, which sponsored the largest research collaboration by American scientists during the war.

The policies on industrial and government contracts of the prewar era had to be set aside temporarily. The war effort had to take precedent over education. President Compton justified and supported defense research and education in his President's report of 1941: "To each adjustment and modification in our program which has been considered and made, we have applied the test, 'Will it assist our institution in making its maximum contribution now to the winning of the war?' "[17]. Compton further planned carefully the "no profit, no loss" policy. According to President Killian, MIT was concerned about making sure that it managed its OSRD contracts on a no-profit no-loss basis. After extensive negotiations with OSRD, a contractual procedure was worked out that would be fair to both government and MIT.[18] This policy at first was put into effect for all governmen-related contracts until 1942, when a deficit resulted due to increased plant operations and additional educational expenses. Subsequently, Compton allowed for overhead expenses in contracts. OSRD did not like this idea and at first was reluctant to agree. Nevertheless, research contracts began to flow in at a rate that MIT could not handle. By 1943, Compton said MIT would take only those contracts that met the following criteria:

> 1. Contracts in which the original/basic research had been done at MIT so that MIT had first hand knowledge of the field in question.
> 2. Contracts for which there were no other

> possible place that could do the research.
> 3. Contracts for which MIT had the equipment and personnel available.[19]

MIT's defense contracts included not only research and construction projects, but also teaching duties. NDRC and large companies under government contract such as RCA, GE, Westinghouse, Raytheon, and Sperry attended seminars and fulltime courses at MIT. By 1943, there were a total of 4500 registered graduate, undergraduate, and special students. Among them, 1/3 were from the Navy, 1/3 were from the Army and only 1/3 were civilian students. Even among civilian students, the percentage that were offered jobs in the armed services increased steadily so that by 1943, the figure rose to more than 75%.[20]

All over the Institute and within the EE department, staff members gave time to defense work in one way or another. According to Philip Morse's, In At the Beginnings, more than half the staff took leave sometime during the war to contribute to the war effort. For example, Hazen was in charge of the Fire Control Division (Fire control devices used servomechanisms extensively) in the NDRC. The ties he established through research before the war enabled him to link NDRC with Sperry Gyroscope Company's Preston R. Basset and Albert Ruiz of GE as fire control experts, and, within MIT, he recommended Gordon Brown.

Within this environment, the research on so important a device as the servomechanism was inevitably an endeavor that MIT had to undertake. The ties that MIT had already established with the industrial sector helped the defense effort find the experts in the various fields of research and in organizing to begin the research as quickly as possible.

The war effort took precedent over previous policies and guidelines for the Institute, and it changed the pattern, magnitude, and contents of research at MIT so that MIT in the post-war era became a very different place. The advancements in servomechanisms technology made by the Servomechanisms Lab had a significant impact on the growth of MIT because its applicability for military uses were vast.

Servomechanisms

To understand better this impact of the Servomechanisms Lab, it is important to understand what the functions of the device and the meaning of terms associated with it. Servomechanisms were automatic control systems in which devices requiring high power for operation , such as the positioning of a gun or the setting of the rolls in a steel mill, were governed by commands given remotely through low powered devices. The power ratio between the high powered device and the low powered device was as much as a million to one.

Servomechanisms became increasingly important in the late 1940's and 50's in the manufacturing industry. During the war, they were mostly applied in the production of military weapons and equipment such as gyroscopic gun sites. After the war, servomechanisms were used for various commercial manufacturing needs such as machine tools, industrial chemical processing, and printing colored pictures. In the Servomechanisms Lab, the design and efficiency of servomechanisms were greatly improved, and that led to developments in other fields of research such as digital computers and numerical controls (which utilized digital computer technology as well as servomechanism technology).

A servomechanism can be divided into two major components. The controlled member, or the high powered device, and the command center, or the low powered device. The electrical command signals to the controlled member may be the variation of speed or position. The command signal could be the voltage from a radar echo or a pressure sensing device, or even the intensity of light.

The theory behind the operation of servomechanisms can also be simplified as feedback control. Servomechanisms were distinctive and revolutionary in the war era because the operation of the high powered device was achieved through measuring the difference or error between its desired state (command) and the current state. Thus the requirements given by the command center were continuously compared to the existing state of the high powered device. If the error or the difference was within the allowed value (the allowed value however, was always very small), the control center did not react. When the error is larger than the allowed value, another command is given to initiated a change.

The error sensing property of servomechanisms enable the high operating accuracy under diverse operating conditions. Feedback Control Systems involve the use of error sensing devices to control a high powered device. In all servomechanisms, the condition of the output is fed back into the command center for comparison with the initial input. Then the error information is used as the next input signal to actuate the power amplifying part of the system to bring about the desired amount of control. Thus, all servomechanisms contain a measuring device to produce the difference between input and output, a transmission device from command center to the controlled center, and thirdly, a mechanism to amplify the difference signals so that the high powered device can be controlled. Servomechanisms usually are comprised of electrical, mechanical, hydraulic, optical or thermal components, both singly or in combinations.[21]

The uses of servomechanisms go back as far as 1850, when simpler models of automatic control, such as Watt's flyball governor, already existed. The theoretical analysis of these devices was attempted by James Clerc Maxwell in 1868. Until 1922, however, when N. Minorsky published a paper on continuous control, there was no significant progress in the field. According to Hazen, Minorsky's paper analysed the "rudder-hull dynamic system in the ship steering problem". When Hazen began his research in servomechanisms, the Minorsky paper was the only previous work significant enough to deserve close examination. In 1934, Hazen published two papers on servomechanisms. These papers were the product of his research on servos for both the differential analyzer and the network analyzer. Hazen's paper " gives a systematic quantitative treatment of each of the categories--relay-type servos, definite-correction servos, and continuous-control servos-- and shows how the theory is applied in the design of a specific servo that was needed to balance against each other the light fluxes of two photoelectric cells in the cinema integraph"[22]. This same servo was used in the automatic curve follower for the differential analyzer. Harold Travers worked on the automatic curve follower for his master's thesis in 1933. The servos developed at MIT were exhibited at the Chicago World's Fair in that same year, along with Trump's Van de Graaf generator. Gordon Brown participated in this research and produced his master's thesis in 1934. In addition to the 1934 publication, Hazen announced the results of his research to the American Association for the Advancement of Science as well as through various other papers. The Franklin Institute awarded him the Levy Gold Medal for his work in 1936. He was also the first to establish contacts with industrial companies interested or in the field of servomechanisms.[23]

Hazen and his students, however were by no means the only ones that studied servomechanisms. Scientists and engineers at various industrial labs such as the GE laboratories were also looking into servomechanisms development. Moreover, by 1938, Sperry Gyroscope Company was already producing and selling the most advanced form of servomechanisms of the time. One of their big customers was the British Merchant Marine, which needed to protect convoy vessels that sailed up to Murmansk around the coast of Norway. By this time, the Germans were already occupying Norway and using the country as a base to attack British freight ships. This contract was not only for the production of servomechanisms, but also to develop the device further through research. C. Stark Draper collaborated with Sperry on this research. Along with Hazen , Draper (who also had established extensive industrial connections) too was an expert in this field.[24]

By the time Hazen was approached by the Navy to teach servomechanism theory to its officers, much work had been done. Industrial applications, too, were already in progress. Thus, it is not surprising that the U. S. military saw potential application of servos to military equipment. Without doubt, servomechanism was new technology and its applications were not widely spread throughout the electrical and mechanical industry. However, there was enough involvement with it in large companies and reseach institutes so that the federal government had sufficient confidence in each sector to explore potential applications.

The Servomechanisms Laboratory during World War II

Harold Hazen's JFI papers on the theory of servomechanism established him as MIT's foremost expert in the field. Consequently, in the spring of 1939, the U.S. Navy asked him to establish a special course to teach servomechanisms theory to four naval officers. Hazen's recent appointment as the EE department's head made it unfeasible for him to take on this additional responsibility. He recommended instead Assistant Professor Gordon S. Brown, who worked with Hazen in developing servos for the differential analyser, the automatic curve follower, and the cinema integraph. Brown had just completed his doctoral thesis on the development of the cinema integraph during the previous year. Thus, next to Hazen, he was best qualified to teach servomechanism theory. The Navy took Hazen's recommendation and approved Brown to teach the course.

Titled "Servomechanisms", course 6.605 was first offered in the fall semester of 1939.[25] Along with Lts. Edwin B. Hooper, Lloyd M. Mustin, Horatio Rivero, and Alfred G. Ward, seven graduate students signed up for the course. Never having put together in "some unified form the methodology of analyzing feedback systems"[26] of various types of servos, Brown recalled that he was learning and teaching at the same time:

> The first term was spent with the students, and all of us tried to learn something about Servomechanisms together. One of our principal texts was Hazen's JFI papers. We spent quite a bit of time studying them and getting a feel for the dynamics of these feedback control systems.[27]

> We also, of course, surveyed the literature , heard about Minorsky's papers, and read and studied (them)...[28]

That additional literature (other than the Hazen and Minorsky papers) was available indicate once again that servomechanisms research was being done elsewhere. Sperry already contracted with Draper to develop the Gyroscopic Lead Computing Sight and at GE, Seldon Crary had just published a paper on automatic voltage regulators on large alternators. Although Brown had had extensive knowledge and experience with the actual devices, teaching required the additional work of developing fundamental theories and testing in a laboratory setting. During the first semester, there was no lab, however. In lieu of experimental learning, Gordon Brown deviated from the rigid structure of normal courses by giving students the opportunity to explore their ideas and presenting them in class.[29] There was no syllabus to follow. Instead, classes were predominantly discussions rather than lectures. Brown's method of teaching attracted many talented students, increasing the enrollment significantly during each subsequent semester.[30]

Naval students had to write theses during their stay at MIT. They were interested in gyroscopic stabilization, follow-up mechanisms, and positioning machinery for heavy guns. Unlike the regular graduate students enrolled in the course, the naval officers were limited to thesis research in the field of servomechanisms. Thus, in order to explore these topics, a laboratory had to be set up. At that time, however, MIT had no outside funding or project contracts from which to draw money for the equipment they would need. Nevertheless, during the spring semester of

1940, Brown began putting a lab together. Fortunately, Prof. Draper and Sperry Company, who were already involved with the Navy, were also interested in setting up the lab. Both Draper and Sperry saw great potentials for collaborative research. Draper introduced Brown to the people he knew at Sperry, including Hugh Willis who donated various old equipment. Other large components were scavenged wherever possible.[31]

> I don't remember all the details at the time, but I did somehow fall heir to a five horsepower hydraulic piston pump/piston motor assembly. Harry Lawrence (of the EE department shop) found a large bed-plate for me, and we borrowed or begged a five horsepower 600 rpm motor to drive it. This was an enormously bulky piece of equipment, but it was certainly the beginning, and it was all assembled on the floor of Room 4-234.(Brown's office)[32]

The first experimental devices were set up in Brown's own office because they had no additional space. In the second semester, the naval officers were able to begin working on their thesis. Moreover, course 6.606, the continuation of 6.605, consisted of two hours of class and three hours of lab each week, so that the lab became a major part of the educating process.

The Servomechanisms Lab from its beginning was fortunate enough to attract many talented students and staff. Brown originally started the lab with two assistants. George Newton, then an undergraduate, was assigned to the lab half time. He wrote his bachelor's thesis under Brown's supervision the following year. In a little more than a decade he was to become Assistant Director of the Servomechanisms Lab under director Francis Reintjes. Ed Dawson, who was sent over from Sperry, was the only full-time technical staff in the beginning. He had had extensive experience developing hydraulic valves used to operate power pistons. Within the year, Jack Silvey joined Dawson as another full-time technical staff. Brown recalls that Silvey was very skillful with all kinds of devices. Previously, he had worked at the Lombard Governor Company in Ashland, Massachusetts, building governors, so he had the industrial experience that the lab needed.[33]

Some very talented students began to join the lab. Donald Campbell, a new graduate student from Union College joined Brown during the first year in teaching the course. Throughout the war years, he was predominantly in charge of teaching. He and Brown wrote and revised notes for the course instead of using textbooks. Brown recalls that textbooks were used only when referring to the basic sciences. By 1948, the revised notes were refined well enough to publish as a textbook. Under the joint authorship, Theory of Servomechanisms was published. It was the first text of its kind and was widely used for more than two decades. Al Hall and Jay Forrester were also graduate students whose research helped the lab to expand. Towards the end of the war, the magnitude of their research necessitated a split off from Servomechanisms Lab. Al Hall founded the Dynamic Analysis and Control Lab, while Jay Forrester headed the MIT Digital Computation Lab. During the war years, other students and staff joined the lab and made significant contributions both to the war effort and to the field of automatic controls. William Pease and Robert Everett were among them.[34]

The large majority of the research staff was students. There were no researchers from the various companies interested in the research and only a few technical personnel were needed because students undertook to do every aspect of the research, including machining and building. As Brown recalls, it was a "hands on" lab. Brown gave his students freedom to pursue research in whatever way they wanted. Moreover, he assigned projects to each student in order to encourage their research capabilities and to give them a sense of responsibility. Students competed with everyone else. "It was every man for himself", Brown remembers. By that, he meant that each person was given a chance to pursue his research without being restricted as one would be in an industrial setting. Precisely because the lab was at a university setting, students' goals merely had to be to further the research project in some manner.

In anticipation of U. S. participation in the war, the Army Ordinance Department contracted with Sperry to build automatic gun sights for the 37 millimeter anti-aircraft guns. Sperry in turn participated in setting up the Servomechanisms Lab because it foresaw MIT as a potentially useful research source for this work. In the summer of 1940, Gordon Brown spent a great deal of time at Sperry, in order to observe how automatic control systems were currently being used. Sperry furnished Brown with additional equipment. Sperry also introduced Brown to the people at the Waterbury Tool Company and the Ford Instrument Company who donated piston type motors to the lab.[35]

In September of the same year, Sperry asked Brown to build an all hydraulic servomechanism to be used with the 37 miliimeter guns. They provided the lab with the knowledge they had on hydraulic transmissions, which were used as models to build the actual device that would be used for 50 caliber twin turret mounts in B24's and B17's. Although work on this project began immediately in September, the actual contract was signed in December.[36] In addition to Sperry funding, Brown was able to secure funds from the NDRC Division 7 (Fire Control), which was headed by Hazen.[37] Whether Hazen's expertise in servomechansims influenced NDRC in MIT's favor is likely but uncertain.

Progress in the project was very quick. In less than three months, the lab's achievements were promising enough for Sperry to arrange for the Army to supply the Lab with the actual 37 millimeter gun on loan from the Watertown Arsenal. At that time, a space shortage left only a storage room in the basement of building 10 to set up the gun to test the servomechanism. Jay Forrester and a crew assembled the gun, but "to their horror" it was too big to be able to rotate it the full 360º in the azimuth plane. This problem however, eventually worked out in their favor. An innovative mechanism was devised to bypass this problem. Through this project, Forrester came up with the idea of the "error correcting mechanism" that reduced the error margin of the servomechanism to zero. A patent was issued jointly to Forrester and Brown after the war as a result.[38]

In December, a formal contract was signed between the Servomechanisms Lab and Sperry through the Division of Industrial Cooperation (DIC). It is likely that although the work was initiated three months earlier, Sperry was cautious not to risk anything until they saw promising results. The delay in signing the contract however did not bother Brown, nor any of his lab team. In March of the following year, a demonstration of the completed hydraulic servomechanisms to drive the guns were given at Watertown Arsenal to representatives from Sperry, the Navy, and Vikers, Inc. A separate demonstration was held a few days later for representatives from the Army Ordinance Department. Brown remembers that these demonstrations impressed them so much that from that point on, the lab had abundant funding sources.

By this time, the naval officers had long finished their theses (with much help from Draper), and returned to the Navy. Jointly, two theses were submitted. Lieutenants Lloyd Mustin and Horatio Rivero's joint thesis, "A Servomechanism for a Rate Follow-up System", was classified "confidential" and unavailable outside of the Navy until 1972, while Lieutenants Edwin Hooper and Alfred Ward's "Control of an Electro-Hydraulic Servo Unit" was unclassified. Somehow, word got around to Commander France, who was the Navy's chief fire control officer, that Brown did not keep the subject of the Mustin-Rivero thesis confidential. Alarmed about this false rumor, Brown made a personal visit in Washington to Vannevar Bush. Bush reassured him that the matters would be settled. At that time, Brown did not realize, however, that this incident turned out to his and Draper's benefit because Bush was not only able to smooth over that specific matter, but he also convinced Navy to pay more attention to what was going on at both the Servomechanisms Lab and Draper's lab. As a result, Draper received a contract to furnish gun sights for the 20 millimeter Oerlikon mounts. During the Battle of the Pacific, this device helped to stop numerous Japanese Kamikaze planes from crashing into naval vessels.[39]

By April 1941, MIT had received another major contract from the

Army Ordinance Department. The Army was planning to build its own 40 millimeter Oerlikon mounts which had previously been supplied by the British. They questioned the reliability of the British hydraulic drives and wanted to use American-made equipment. The lab was again successful in developing hydraulic servomechanisms with the error correcting mechanism that had just been developed. Unlike the previous servo, this one was made to be interchangeable with the British devices in order to maintain flexibility.

Already, there was not enough space to carry out the needed experiments. President Compton provided building 32 for Servomechanisms Lab. Originally intended as a storage building for various departments, it was occupied instead by the Servomechanisms Lab on one end and the Radar School on the other. Building 32 was the perfect setting for servomechanisms research because the large rooms and high ceilings could allow even a tank to be brought in. And it was.[40]

Contracts were growing more complex and collaboration between the military sector, industry, and MIT also began to increase. Their next project, to install drives on the guns that were mounted on M4 tanks, involved contracts from Sperry, the Navy, as well as the Army. A tank was driven from the Charlestown Freight Yard to building 32, via Vassar Street. According to Brown, "it created quite a stir" . The mounts on these tanks were made to rotate 360º and elevate to almost 90º. In the process of building the drives, the limit-stop mechanisms were also refined.

Towards the end of the war, some projects were growing too big and relying on the attention of other fields in addition to servomechanisms theory. The origination of Jay Forrester's project to build a digital simulator that eventually became Project Whirlwind was one such example.

Through Nathaniel Sage, then director of DIC, Admiral Louis de Flores asked Brown to explore the idea of building an analog simulator of the complete dynamic performance of multi-engined bombers.[41] The simulator was to be used by Navy pilots as flight trainers. The idea was to enable such a simulation by building a device that would take into account approximately 36 equations that were known to be involved in the design. This project was one of the more complex endeavors for the lab.[42] Forrester, who was at that time collaborating with Raytheon developing hydraulic mounts for radar mounts, took the job.

Even before attempting to build such a device, Forrester and his team could anticipate many tough problems. One was that an analog device, because of the complexity required as well as the sheer weight of the components, would not be able to produce reliably accurate results. Then Forrester and Everett began sketching a digital simulator. According to Forrester, a great deal about digital computation was discovered. Among the major achievements of this project was the development of reliable memory storage devices. At first, Forrester used an electrostatic storage system. But its capacity and reliability were seen to be improvable by using instead, coincident magnetic core memory. Forrester's development of this devise eventually became the standard memory device for all digital computers, and a patent for Forrester resulted from this work.[43]

Although achievements made the project promising and unstoppable, it was growing too large in many aspects to be handled by the

Servomechanisms Lab. Consequently, a split occurred. Forrester set up the MIT Digital Computer Lab and continued his research while he remained as an associate director of Servomechanisms Lab.

Another major split took place around the same time with Al Hall's projects. Hall became an expert in missile control. He developed automatic control of missile guidance systems, which had a huge demand with the military. In a similar way that Forrester's project split off into another sector, so did Hall's. His lab became the MIT Dynamic Analysis and Control Lab.[44] He too, however remained as an associate director for the Servomechanisms Lab. In this way, as a result of great progress within the field of servomechanisms research, specialization was beginning to take place. By the end of the war, servomechanisms were only beginning to be introduced into the industrial sector, but the potential for industrial use was unbounded. For the Servomechanisms Lab, however, servomechanisms research was approaching its final years.[45]

The contributions of the lab toward the war effort was undoubtedly invaluable. The progress in servomechanisms theory too was a great achievement. In addition to the major accomplishments mentioned, wartime projects brought on improvements "in British oil gear servos, design of a speed-gear servo, construction of prototypes, construction of azimuth and elevation control units, design and construction of a servo for a fusesetter rammer, design and construction of mount power drives for the 40-mm guns, and many other gun related developments."[46] It was fortunate that the lab was founded at the time the United States was about to enter war. Because of the political situation, a sense of urgency and insecurity gave the lab team the extra incentive to produce results.

When asked about the problems and difficulties that he faced as administrator and director of research during the war, Brown stated that he could not recall many bureaucratic problems. He suggested three reasons for the lack of such problems. First, in the beginning, researchers had not yet established a set way of conducting servomechanisms work because they were all beginners in the field. Thus, there were very few conflicts among the lab staff. Second, the various sectors involved in the projects kept much of the bureaucratic complications out of the way due to the importance of the servomechanisms research for national defense. The lab did not feel financially restricted, nor did it feel obligated toward the Institute as Compton supported them inside and men like Bush supported them outside of MIT. Finally, there was never a sense of losing one's face when mistakes were made. This gave the lab team more freedom for creativity.[47]

The progress in servomechanisms theory too was an invaluable achievement. Careful measurements of device performance during each project enabled the researchers to figure out the "complete dynamic hydraulic equation for the piston type motor."[48] Basic principles of servomechanisms were derived and organized into a comprehensible form. As Brown recalled:

> We did a lot of work to formalize the theoretical foundations of feedback control systems, (such as) the idea of writing equations in dimensionless form.[49]

The thesis work of various graduate students during the war also broadened the theoretical aspects of servomechanisms. For example, Al Hall undertook for his thesis the frequency-domain analysis and synthesis. In looking back, Brown stated that:

> until Al Hall joined us as a member of the staff and undertook for his doctorate thesis the comprehensive analysis of control-type error proportion to velocity zero error derivative response and the like, we did not do very much about frequency response method. When Al undertook to pursue this in his thesis, the competence of the Laboratory broadened. By then, I think, we had become one of the best places in the country for an understanding of where the so-called differential equation approach merged in with the frequency approach in giving one better competence to synthesize these devices, which by that time, were being called upon for many highly-sophisticated kinds of operations.[50]

Essentially, Hall devised a way to measure and describe the internal dynamics of servomechanisms using the frequency of the system measured. Thus, although the immediate problem during the war was undoubtedly to meet their contract requirements, the long range goal of developing a unified theory of servomechanisms was not forgotten. New knowledge got incorporated so quickly into the teaching program that Brown and Campbell constantly had to revise their course notes. Moreover, it was not merely Brown and Campbell who were interested in the scientific and educationnal aspects of the lab work. By 1948, when the jointly authored textbook was published, various members of the lab, such as George Newton and William Pease, who taught sections of 6.605 and 6.606 had contributed to the material covered . Moreover, Al Hall was by far not the only significant thesis contributor. William Papion, working under the supervision of Jay Forrester, did his thesis on the use of magnetic core for coincident memory. Another student, William Linvill, wrote his thesis on the "analysis of stability considerations of pulsed data servomechanisms"[51]. Thus, students and staff helped in refining and perhaps simplifying servomechanisms theory, so that immediately after the war, in the academic year 1945-1946, Brown and Campbell were able to offer undergraduate course 6.213, Automatic Control Principles and Applications.[52]

The effort to incorporate new knowledge into education was a task that MIT had always taken because unlike in an industrial setting, it was MIT's responsibility to turn research into education. Brown and his researchers looked for a unifying theory of servomechanisms because in order to teach, theories and models had to be developed. Industry was mainly interested in the production and applicational aspects of servomechanism, but as scientists, Brown and his researchers looked further to relate servomechanisms theory to basic science.

Several major consequences of the Servomechanisms Lab's participation in the war effort becomes clear. For example, stronger and more personal ties were established between the lab and the industrial and government sectors with which they collaborated . The lab, and in turn MIT, won the trust and confidence of both the federal government and the industrial sector. The collaboration between the lab, industry, and military showed the beginning of a new system of achieving technological change, namely, through interdependence and specialization. Interdependence and specialization here imply that technology in this country was beginning to settle into a system whereby three forces governed its condition. During the war, when technological advancements had to be at its maximum, it was necessary for each sector to specialize in accomplishing a certain task. Through specialization of task, servomechanism technology was rapidly advanced. In the case of the MIT Servomechanisms Lab, this applies. The federal government took on the task of funding and correlating research projects, while the industrial sector concentrated on production. The Servomechanisms Lab served as the research and educational base.

Interdependence was an inevitable effect of specialization. By the end of the war, MIT had received over $100 million for research projects.[53] The Servomechanisms Lab alone was receiving well over a million dollars a year in industrial and governmental contracts. The huge sums reflect the magnitude and complexity of research undertaken. The topics of research became so advanced and specialized that more sophisticated equipment and larger research teams were needed. It was impossible to go back to the limits of the prewar research conditions. Consequently, dependence on outside funding inevitably continued at MIT. The federal government and industry also faced the same interdependence situation. Scientific research in this country had become so sophisticated that neither of these sectors could handle both scientific research and production or funding at the same time. Industry was facing more fierce competition, and thus it became economically unfeasible to handle both production and research at the same time. At the time the

Servomechanisms Lab was set up, Sperry had much more knowledge on military applications of servomechanisms than Brown's group. Yet they chose to leave much of the research to Brown's group. As Brown himself pointed out, the lab's first contract was a Navy subcontract through Sperry. Sperry and MIT did not compete against each other because they each realized that maximum mutual benefit could be obtained by a sensible division of tasks. The federal government too faced this situation. Although the military had always produced and/or supervised the manufacture of its own equipment, such as the 37 millimeter gun, it became dependent on industry and universities while governing and organizing science.

Each sector modified their tasks so that the three sectors could handle scientific progress with maximum benefits for all. In this process, however, each sector maintained their primary motive:industry with production, government with policy making, and MIT with education and research. By the end of the war, MIT faced the same problem of maintaining independence to pursue research projects of their choice without the interference of industry and government. Because of the growth that MIT experienced during the war through outside support, the problem of trying to maintain this independence had become more pressing and delicate.

Adjustments to the Peacetime Setting

In the decade after the war, the Servomechanisms Lab had to adjust to a system of collaboration different from that of wartime. A balance had to be achieved between pursuing research and finding fund sources out in industry and within the federal government. As a result of war time progress in the field, the magnitude and complexity of research pursuits had become far too costly for MIT to fund alone. Moreover, the nature of the research maintained a common ground of interest between MIT and both industry and government. Achieving a balance between their two needs turned out to be a difficult task, but the story of this transition period between the end of WWII and the late 1950's reflects "institutional patterns" and "ultimately, the shape of technology itself."[54]

The first major project that the lab took on after the war was the designing and construction of "instrumentation and driving equipment for the new graphite nuclear reactor" at Brookhaven National Laboratory in Long Island. With the help of a group of engineers from Jackson and Moreland, William Pease, James McDonough and Prof. Truman Gray (who took a year off from his own research in the Electronic Instrumentation Lab to participate in the design process), built hydraulic motors, hydraulic power drives, and an automatic shutdown mechanism called Scam for emergency situations. The actual construction took about two years between 1946-1948, but the MIT staff continued to act as consultants for Brookhaven until the early 50's. Although the total cost was first estimated at around one million dollars, by the completion of the project, the actual cost totalled more than two million dollars. Despite the huge difference, Brown recalls that there was not much concern, because the equipment worked so well even when the reactor was brought up to critical state.[55]

The Lab was still dealing with the federal government, which could provide virtually unlimited funds for needed projects. Consequently, because MIT did not have to concern itself with financial sources too much, a more careful budget was not necessarily the main consideration. In dealing with industrial contracts, however, MIT had to learn to work closely within the limited funds available. The first numerical control project is an example of the problems (including budget problems) that the lab faced in post war years. It is also an example of the differing and conflicting approach between MIT and industry.

In late 1948, John Parsons called Gordon Brown about the possibility of constructing a milling machine that would be controlled by numerical data that would be fed into the control center of the machine. Parsons headed a machine tools manufacturing company called the Parsons Corporation in Traverse, Michigan. His intentions were to build an automatic milling machine that would simplify the task of machining components such as helicopter blades. Parsons had planned to contract with MIT to build such an automatic milling machine to meet his contract with the Air Force and then to manufacture it for the commercial market together with Snyder Tool and Engineering Company. Parsons chose MIT because at the time MIT possessed the two fields of expertise needed for such a project.

Numerical Control (N/C), as it was termed by McDonough and Pease, involved the use of servomechanisms and digital technology. By that time, servomechanisms that used continuous signals with respect to time were well analyzed and understood. However, servomechanisms that would use discontinous input signals were not well understood. Previously, some research into servomechanisms that would use pulse signals (a form of discontinous input signal) had been examined, but not in depth, and a lot remained to be learned. As a result of the Whirlwind Project, digital technology was another field of expertise for MIT. Digital signals, a form of discontinuous input signal, was thus a perfect source for exploring servomechanisms that used discontinuous input. Numerical control devices were thus a product of discontinuous type servos and digital computers.[56] At the time that Parsons approached Brown with his idea, MIT had not yet begun exploring this new field of research. Notice, then ,that Parsons was assuming, without any previous demonstration of work, that MIT would be able to produce what he wanted in a given period of time. As a result of MIT's achievements in science and technology, MIT had earned enough faith from the outside to gain such outright confidence.

A contract was signed between Parsons and the Servomechanisms Lab in June 1949. (This contract was not a subcontract but a unilateral agreement between MIT, Parsons, and the Air Force.) The Lab was to study the general problems of controlling machine tools from numerical data and also to assist Parsons in the design and construction of certain components of the automatic milling machine.[57] William Pease and James McDonough, who had just returned from Brookhaven, were put in charge of the project. The idea for the project was Parson's own. Having had no previous experience in numerical control technology, the lab took almost a year to come up with a design and specifications for the automatic control milling machine that would receive commands from punched paper tape. In June 1950 Parsons authorized the design and gave the go-ahead to construct an experimental milling machine according to specifications.

Because Parsons had a contract with the Air Force to build this milling machine, a unilateral agreement was set up for MIT. The Air Force gave MIT a Cincinnati Hydro-Tel milling machine that was to be altered to experimental specifications. The "conventional controls for positioning the cutting tools were replaced with three hydraulic powered servos that received separate commands from their director."[58] The director would decode the given command into angular positions of each servo that governed the particular coordinate (x, y, or z) of the milling machine. Jay Forrester and Robert Everett from Whirlwind helped with their digital computer expertise, while members of the Center for Analysis and the Research Lab for Electronics were constantly consulted.[59]

After six months of work, the machine was about 30% finished. Although the successful completion of the project seemed imminent, Parsons could no longer fund the project because it had already cost more than twice what Brown originally estimated. At the same time Parson's company was having financial troubles. Consequently, he withdrew. Parsons, however, was awarded a joint patent with Frank Stullens (an engineer with the Parsons Corp.) in 1958 on Motor-Controlled Apparatus for Positioning Machine Tools. Another patent on Numerical Control Servo Systems was jointly awarded to Jay Forrester and William Pease in 1962.[60] Parsons acquired the rights for both patents and made Bendix Corporation its exclusive licensee. The construction of the milling machine itself was completed under Air Force grant six months thereafter in March 1952.

In the process of building this machine with Parsons sponsorship, various conflicts arose between Brown's group and Parsons because the two sides had differing goals and intentions. Parsons wanted the automatic milling machine to be most efficient without costing more than the quoted research expense. In addition, he wanted the current machine to be altered as little as possible while still being able to accomodate automatic control devices. For his purposes, the machine also had to be simple to operate so that even unskilled workers could operate it. The MIT engineers on the other hand, wanted to explore new ideas that would produce a machine with maximum accuracy and speed without necessarily worrying about the cost factor. The lab was also not in the habit of taking on industrial jobs that merely required the application of research already done. Excited by the potentials of this research project, the lab group did not consider Parson's position on the industrial side. Parsons, on the other hand, did not understand why there would be a conflict of interest. He continually accused Brown of scheming against him. Pease recalled:

> We attempted to look beyond the immediate problem of machining wing problems, and concentrated on the broader information theoretical aspects. We hoped to solve the more general problem of carving a shape from solid material. Parsons was unnerved by this because he wanted quick tangible results.[61]

Of course, Parsons needed to meet his Air Force contract specifications, but he failed to do so, partly because he did not understand MIT's position and attitude as a research institute. Moreover, he planned to put together a milling machine using different components from various companies. He expected MIT to provide only the electrically controlled components of the machine. MIT, on the other hand wanted to conduct fundamental research on numerical control devices. To produce just the electrical component would be merely to apply old research and not to initiate new research in the field. Concurrently, MIT was beginning to adjust to research with limited sources of funding.

The conflict between Parsons and MIT was inevitable. However, it would be misleading to lay the blame on either side. Both sides needed to understand the evolved system of technological development as a result of the war. In order for technological innovations to take place, a system of three components would have to function harmoniously, keeping in mind the difference in purpose of the other sectors. The three components remained the same: the research component, such as the Servo Lab, the funding component, which would be the federal government or industry, and the manufacturing component, or industry.

The Parsons conflicts were only the beginning of a series of conflicts between MIT and the industrial sector. By the time the milling machine was completed, the Lab had launched a second series of educational endeavors (The first series took place immediately after the war in MIT's efforts to spread state of the art servomechanisms technology) to spread and promote the idea of numerical control technology to the industrial sector. Two and three week summer courses, workshops, seminars, and demonstrations were held for both the Air Force and various machine tool companies and automobile companies.

Reactions of the industrial manufactureres were less than promising, however. According to Brown:

> During that period, the laboratory undertook to educate the machine tool industry. They periodically had groups of thirty or forty people from the aircraft companies attend school in the ServomechanismsLaboratory from three to four weeks. The Laboratory also had to carry on the education of industry. From time to time, we had visitors from major machine tool manufacturers. Some of the manufacturers expressed violent opposition to the work: one of them even wrote Dr. Stratton (then President of MIT) protesting that he was crazy to let Brown waste MIT's facilities and resources on such boondoggle. The machine toolmakers who came from General Motors simply brushed it off and said, "it's a pretty poor way to build a million Chevrolet fenders!" It was never intended to build a million Chevrolet fenders.[62]

As Francis Reintjes recalled, industry chose not to take the risk with numerical control. In most cases, these machine tool and automobile manufacturers were not equipped to handle drastically new manufacturing technology such as N/C. Consequently, MIT, after Parson withdrew, had only the Air Force to turn to for funding.[63]

After the successful completion of the first automatic milling machine project, much was done by the lab staff to promote numerical control. In addition to the educational programs, demonstrations were set up both at MIT and at various companies. According to Wilde, "McDonough and his group set out on a persistent quest for jobs that would demonstrate the superior abilities of numerical controls".[64] The efforts continued despite lack of interest and discouraging responses by industry. With support solely from the Air Materiel Command of the Air Force, several projects continued nevertheless.[65]

One of the most significant projects from the Air force support was Douglas Ross' Automatically Programmed Tools (APT) project. In 1955, while continuing the numerical control research it became obvious that a library of computer subroutines for various machining operations would prove very useful. Ross and his group assembled a library of subroutines in the computer memory of the Whirlwind. Thereafter, a skeletal system program for general applications was added on. This enabled the operation of various machining processes just with the addition of different subroutines from the library. By 1957, a "family of systems" had been developed around a central process, all on the Whirlwind.[66]

By this time, the magnitude of the project had grown too big for just the Lab to handle. Reintjes organized a collaboration workshop in which various aircraft companies were invited to MIT for one week. Each company was responsible for programming a certain component of a large flight control program. The Lab then assembled the programs into one large program. In April 1958, the assembled product was shipped to 17 companies for test runs. The success of this project followed a contract from Giddings and Lewis, a machine tool company in Wisconsin, to build and program a digital director system for Air Force jets. The APT project itself was transferred to the APT Coordinating Group, which was set up by the Airdraft Industries Association, for the purpose of furthering this project.[67] By 1959, it became clear that the promotion efforts were beginning to pay off. More demonstrations were requested by numerous companies. In March of that year, Reintjes and Ross even went on television to show their latest developments.

At about the same time that Ross was working on the APT projects, another breakthrough occurred for numerical control. According to Brown:

> a group from North American [Aviation] came in rather accidentally, perhaps. They had come to Boston to seek vendors to make the machine tools for a very complicated component of an engine to sail on the F85 Fighter. The drawings were seen by the Servomechanisms Lab boys, and they asked if they could borrow them over the weekend. McDonough and the others worked quite diligently, wrote the program, obtained a solid block of aluminum about 8 inches cube, went to work in not very many more hours, and actually machined a sample piece. This so impressed the North American people that, if my memory is correct, the Servomechanisms Lab made the remaining 35 or 40 pieces that were needed and the whole job was done in a month or so compared with six months at a minimum which it would have taken to have carried out the work by the ordinary procedure.[68]

The Mcdonough effort caused another breakthrough. Thus, in the late 50's more and more people began to understand the role that numerical control could play in design and construction of complicated machine parts.

The Lab was not successful in all its endeavors to convince industrial contractors of the potentials of numerical control. Leonard Gould, who took over the chemical process control research, said that after initial funding from IBM and Texas Butedyne Inc. ended, it was very difficult to get the chemical industry interested in chemical process control. Some funding came from the Navy and the Air Force, but by 1957, other measures had to be taken to receive funding. Gould unsuccessfully tried to set up a consortium of chemical manufacturing companies to support general research in industrial chemical process control. With what little funding they could get, research continued. Gould's projects included designs for control devices for chemical reactors and other optimal control devices for chemical reactions. He believed that process-control engineers could greatly increase their efficiency by studying the chemical process first, and then building a mathematical model to find an applicable control technique. Gould was at that time one of the forerunners of modern optimal control theory. As a result of his work, Gould was able to locate some funds from the National Science Foundation (NSF), despite the fact that NSF did not normally support applied research. By 1968, Gould published his book: Chemical Process Control: Theory and Applicaitons, and many theses came out of chemical process control research. In the 1970's this field of research was passed on to the Chemical Engineering Department which was able to develop it further as a result of the progress made by Gould.[69]

The story of Gould's chemical process control work exemplifies the Lab's continuing struggle to maintain control over deciding which areas of research to pursue. After the war, the Lab undeniably had to cooperate with industry more than ever. But it was not only financial support that the lab needed. In the 1950's it was even more clear than in the 1940's that technological change depended on the collaboration of each of the three sectors. For the research projects to be successfully implemented , thus constantly improving the state of the art of technology, each sector needed to depend on the other two. By 1959, when the Servomechanisms Lab changed its name to Electronic Systems Laboratory (ESL), reflecting the wider interest of the group, both MIT and the industrial sector realized the essential interdependence. But they also realized the importance of not compromising their priorities.

Conclusion

The Electronic Systems Laboratory (ESL) moved on to various computer-program-related fields. It tackled highly theoretical projects such as library automation and computer aided design. Today, the Lab is no longer called ESL, but LIDS, Laboratory of Information and Decision Systems. It has evolved from a hardware centered lab to a theoretical software oriented lab, where one cannot even see a trace of its previous endeavors. Gordon Brown believes that the Lab was able to stay in operation for so long because of its dynamic character-the ability to pass on knowledge gained from research and move into new fields of research. There was active circulation of ideas and people. At any given time, the Lab was equipped with the most advanced technological knowledge in its field of interest. Throughout its first twenty years, the Lab stayed about a decade ahead of industry in technological endeavors. During the 1950's when the Lab was developing numerical control technology, servomechanisms technology was finally being spread throughout industry. By the time numerical control technology was being adopted industry-wide, the Lab had already begun pursuing research in computer programming methods for design and construction. Consequently, it was beneficial and feasible for industry and government to support the research being pursued.

The Lab was able to maintain technological expertise because of the growth that it experienced with government and industrial support. And in turn, the Lab became a component of a system that moved and thus controlled the direction of technology. But the dependence on outside funding did not force the Lab to have to consider industrial and government research interests before their own. Instead, it maintained independence in this aspect by successfully convincing their sponsors through the education process. The Lab educated not only students who would soon take jobs in industry, but it also campaigned to spread their technological innovations by educating their sponsors. Given that the growth of the Lab relied heavily on research, and as education played a crucial role in the expansion of the Lab and advances in the field of research, one cannot deny that education (both of industry and within MIT) was an important component of the growth of the Servomechanisms Lab. And furthermore, it is clear that MIT benefitted greatly from the growth and achievements of laboratories such as the Servomechanisms Lab. In 1973, Gordon Brown wrote an article in Technology Review, pointing out the importance of a systematic collaboration between the three sectors. He wrote:

> we recognize increasingly a need at the broad policy-making level in each establishment for a better understanding of the structure and the dynamics of the total socio-techno-economic system; and we recognize that, on all scales and at all levels, there must be less autonomy and more trade offs.[70]

Apparently, Brown also realized through his hands-on experience that technological change was effected by several components of society taking on specific responsibilities. As he stated in his paper, technological changes, in turn, had brought government, industry and research institutions closer together into a system where each sector had to consider not only their needs but the needs of the other sectors. By the 1960's, this systemic method became the predominant pattern in achieving technological change.

FOOTNOTES

[1] Gordon S. Brown, interview by author, Tape recording (four hours), Grantham, New Hampshire, July 1986.

[2] Samuel Prescott, When MIT Was Boston Tech: 1871-1916 (Cambridge: MIT Press 1954), chapter 3-6.

[3] David Noble, America By Design (New York: Oxford University Press, 1979).

_____, Forces of Production (New York: Alfred Knopf, 1984).

[4] George Wise, General Electric and the Origin of US Industrial Research (New York: Columbia University Press, 1985).

[5] Karl Wildes, A Century of Electrical Engineering and Computer Science at MIT, 1882-1982 (Cambridge: MIT Press, 1985), chapter 5.

[6] *Ibid.*, chapter 4.

[7] *Ibid.*, chapter 5.

[8] Gordon S. Brown, "Elonge: Harold Locke Hazen, 1901-1980", Annals of the History of Computing, vol. 3, no. 1, January 1981.

[9] Karl Wildes, A Century of Electrical Engineering and Computer Science at MIT, 1882-1982, p. 103.

[10] *Ibid.*, pp. 103-104.

[11] *Ibid.*, pp. 160-165.

[12] Reports of the President, 1939-1940, MIT Institute Archive and Special Collection, p. 24.

[13] The Politics of American Science 1939 to the Present, eds. James Penick, Carroll Pursell, Morgan Sherwood, and Donald Swain (Cambridge: MIT Press, 1972).

[14] Karl Wildes, A Century of Electrical Engineering and Computer Science at MIT, 1882-1982, pp. 182-184.

[15] The Politics of American Science 1939 to the Present, eds. James Penick, Carroll Pursell, Morgan Sherwood, and Donald Swain, pp. 57-58.

[16] Karl Wildes, A Century of Electrical Engineering and Computer Science at MIT, 1882-1982, p. 185.

[17] Reports of the President, 1941-1942, MIT-IASC, p. 5.

[18] James Killian, Education of a College President (Cambridge: MIT Press, 1985), p. 55.

[19] Reports of the President, 1941-1942, MIT-IASC, p. 12.

[20] Reports of the President, 1942-1943, MIT-IASC, p. 7.

[21] Gordon S. Brown, Gordon Stanley Brown Papers, MIT-IASC, MC24, Box 8, Folder 368, Gordon Brown's article on servomechanisms published in Encyclopedia Americana, 1954.

[22] Karl Wildes, A Century of Electrical Engineering and Computer Science at MIT, 1882-1982, pp. 212-213.

[23] Gordon S. Brown, Elonge: Harold Locke Hazen, 1901-1980.

[24] Gordon S. Brown, interview by Karl Wildes (July 1971) Transcription, GSB Papers, MIT Institute Archives and Special Collections, MC24.

[25] GSB Papers, MIT-IASC, MC24, Box 8, Folder 367, Course descriptions.

[26] Gordon S. Brown, interview by Karl Wildes, Transcription, GSB Papers, MIT-IASC, MC24, p.2.

[27] *Ibid.*, p.1.

[28] *Ibid.*, p.2.

[29] Jay Forrester, interview by author, Tape recording (one hour), Cambridge, Massachusetts, March 1987.

[30] GSB Papers, MIT-IASC, MC24, Box 3, Folder 88, Enrollment records.

[31] Gordon S. Brown, interview by author, July 1986.

[32] Gordon S. Brown, interview by Karl Wildes, Transcription, GSB Paper, MIT-IASC, MC24, pp. 2-3.

[33] *Ibid.*, p. 4.

[34] Jay Forrester, interview by author, March 1987.

[35] Gordon S. Brown, interview by author, July 1986.

[36] _____, interview by Karl Wildes, July 1971.

[37] John Burchard, QED: MIT in World War II (New York: The Technology Press, John Wiley and Sons, Inc., 1948).

[38] Jay Forrester, interview by author, March 1987.

[39] Gordon S. Brown, interview by Karl Wildes, July 1971.

[40] Jay Forrester, interview by author, March 1987.

[41] David Noble, Forces of Production, chapter 6.

[42] Gordon S. Brown, interview by Karl Wildes, July 1971.

[43] Jay Forrester, interview by author, March 1987.

[44] Karl Wildes, A Century of Electrical Engineering and Computer Science at MIT, 1882-1982, p. 227.

[45] Francis Reintjes, interview by author, Cambridge, Massachusetts, March 1987.

[46] Karl Wildes, A Century of Electrical Engineering and Computer Science at MIT, 1882-1982, p. 216.

[47] Gordon S. Brown, interview by author, July 1986.

[48] Gordon S. Brown, interview by Karl Wildes, July 1971, p.12.

[49] *Ibid.*, p. 12.

[50] *Ibid.*, p. 12.

[51] Gordon S. Brown, interview by author, July 1986.

[52] GSB Papers, MIT-IASC, MC24, Box 3, Folder 88, Course descriptions.

[54] David Noble, Forces of Production, p. 113.

[55] Gordon S. Brown, interview by author, July 1986.

[56] Francis Reintjes, interview by author, March 1987.

[57] Karl Wildes, A Century of Electrical Engineering and Computer Science at MIT, 1882-1982, p. 218.

[58] *Ibid.*, p. 220.

[59] Jay Forrester, interview by author, March 1987.

[60] Karl Wildes, A Century of Electrical Engineering and Computer Science at MIT, 1882-1982, p. 221.

[61] David Noble, Forces of Production, p. 117.

[62] Gordon S. Brown, interview by Karl Wildes, July 1971, p. 19.

[63] David Noble, Forces of Production, chapter 6.

[64] Karl Wiles, A Century of Electrical Engineering and Computer Science at MIT, 1882-1982, p. 224.

[65] Leonard Gould, interview by author, Tape recording (one hour), Cambridge, Massachusetts, April 1988.

[66] Francis Reintjes, interview by author, March 1987.

[67] Leonard Gould, interview by author, April 1988.

[68] Gordon S. Brown, interview by Karl Wildes, July 1971, p. 19.

[69] Leonard Gould, interview by author, March 1987.

_____, interview by author, April 1988.

[70] Gordon S. Brown, "Engineering and Societal Software - A New Imperative", Technology Review (reprint), vol. 75, no. 3, January 1973, p. 5.

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A NOTE ON SOURCES

The interviews of Gordon S. Brown, Jay Forrester, and Leonard Gould, conducted by the author are on tape. They will be available at the MIT Institute Archives shortly.

The whereabouts of Archival Collection 34 on the Servomechanisms Laboratory filed at the MIT Institute Archives are unknown as of 1988. This collection, which contains both technical papers and progress reports of the Servomechanisms Laboratory as well as the Electronic Systems Laboratory, were consequently unavailable to the author.