Moving from Practice to Theory: Automatic Control after World War II

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Mind the gap.
London Underground

In the 1930s, automatic control was still an engineer's dominion. Engineers in a variety of fields used automatic control principles: process and instrumentation engineers used controllers to regulate temperatures and pressures, mechanical engineers used regulators to control the speed of engines, and telephone engineers designed feedback controllers to build linear amplifiers. Despite its common use, a large fraction of the control engineering process consisted of "trial and error" methods with little analysis involved if any at all. A. Ivanoff stated in 1933 that "the science of the automatic regulation of temperature is at present in the anomalous position of having erected a vast practical edifice on negligible theoretical foundations."[1] For many of the industries using controllers and regulators, economy and practicality led to a "good enough" approach to the discipline of automatic control.

Today automatic control emphasizes mathematical rigor and theory over the hands-on, application-oriented approach of the 1930s. For example, one sample undergraduate textbook requires previous knowledge of Laplace transforms, modeling and studying dynamic response with differential equations, and matrix algebra – all relatively advanced mathematical subjects.[2] While it remains ambiguous to classify papers as theory-based or application-based, only about 35% of regular (non-invited) papers presented at the 2004 American Control Conference were application/hardware-based.[3] On the other end of the academic/industry spectrum, when

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[1] A. Ivanoff, "Theoretical Foundations of the Automatic Regulation of Temperature," *Institute of Fuel -- Journal* 7, no. 33 (1934). Quoted in Stuart Bennett, "Development of the PID Controller," *IEEE Control Systems Magazine* 13, no. 6 (1993): 62.

[2] Gene F. Franklin, J. David Powell, and Abbas Emami-Naeini, *Feedback Control of Dynamic Systems*, 3rd ed. (Reading, Massachusetts: Addison-Wesley Publishing Company, 1994), ix.

[3] *American Control Conference 2004*, (2004, accessed); available from http://www.mie.uiuc.edu/acc2004/. This percentage was calculated by counting the conference sessions focusing on applications and not the individual papers themselves. It is interesting that approximately 85% of the invited sessions were hardware or application oriented. I attribute this to a desire to cater more to industrial members at the conference. In contrast, the first IFAC

automatic control is used in industry, newly developed theory is rarely used. Over 90% of industrial control applications use Proportional-Integral-Derivative (PID) controllers first described in 1922.[4]

By the early 1960s, control engineers already began to recognize a shift from their previously practically-oriented subject to an abstract and theory-oriented one. This phenomenon was even given a name – "The Gap." As evidence to support this gap, George Axelby, the editor of the IRE Transactions on Automatic Control, calculated that in the first six years of the Transactions from 1956 to 1961, 57% of the two hundred published papers could be classified as "highly theoretical." However, from 1959 to 1961 Axelby classified 80% of papers as "highly theoretical."[5] By 1965 Axelby would write another editorial describing "The Gap" and a special meeting was held on "Bridging the Gap Between Theory and Practice" in New York in 1964.[6,7]

However, questions remained about how, when, and why this gap formed. As in any engineering discipline, the synergy between a subject's theorists and practitioners is critical to the development of both the theory and practice of that discipline. Automatic control's shift from an experimental subject to a highly theoretical one finds its origins in the research organizations developed during World War II, the formation of automatic control as an academic discipline shortly afterwards, and the development of new tools to solve increasingly complex problems. The National Defense Research Committee (NDRC) and its successor, the Office of Scientific Research and Development (OSRD), brought together the diverse groups investigating automatic control in the 1930s. While each group had previously developed its own vocabulary

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conference (a predecessor to the ACC) held in 1960 presented 144 theory papers, 55 hardware papers, and 79 application papers for approximately 48% hardware/application papers.

[4] K. J. Astrom and T. Hagglund, "PID Control," in *The Control Handbook*, ed. W. S. Levine, The Electrical Engineering Handbook Series (Boca Raton, Florida: CRC Press, 1996), 198.

[5] George Axelby, "Image or Mirage?," *IRE Transactions on Automatic Control* 7, no. 4 (1962): 1.

[6] George Axelby, "The Gap - Form and Future," *IEEE Transactions on Automatic Control* 9, no. 2 (1964).

[7] Harold Chestnut, "Bridging the Gap in Control - Status 1965," *IEEE Transactions on Automatic Control* 10, no. 2 (1965).

and theory tied to specific applications, the convergence of ideas brought on by the war exposed the fundamental theories of feedback control. After the war, when academia absorbed automatic control, these theories were abstracted from their original applications in the military and industry allowing new insights to be shared and developed more easily. At the same time, engineers were taught more math and science so that concepts could be understood and examined at a more fundamental level. In addition, academia's demand for originality and rigor as well as new, complex application areas introduced a great deal of complexity into the problems automatic control was supposed to solve. To deal with this added complexity, abstraction through modeling and simulation using analog and digital computers was critical. This seemingly simple progression of events would determine not only how and when "the gap" formed, but also why theory took such a prominent role in a previously practical discipline.

Pre-War Controls Activities

Before World War II, developments in automatic control were divided among several diverse disciplines. Stuart Bennett and David Mindell have already described the state of automatic control during this time period in depth, and their research delves into the circumstances surrounding attempts to solve automatic control problems prior to the war which shaped the field during this time.[8] One of these problems, process control, emerged with a heavy industrial focus, and automatic control was used to create the highest quality product at the lowest cost. At the same time, feedback amplifiers were developed to make long distance telephone networks practical by faithfully and cheaply amplifying voice signals as they traveled

[8] Stuart Bennett, *A History of Control Engineering 1930-1955*, ed. P. J. Antsaklis, D. P. Atherton, and K. Warwick, 47 vols., IEE Control Engineering Series, vol. 47 (London: Peter Peregrinus Ltd, 1993). David A. Mindell, *Between Human and Machine: Feedback, Control, and Computing before Cybernetics* (Baltimore, Maryland: The Johns Hopkins University Press, 2002). Each of these authors has also written several journal articles about this time period although most of this information is also included in their books.

along a telephone line. Parallel to these other developments, servomechanisms evolved from analog computing projects at MIT to track a small signal through a power amplifier. Each area of interest provided a different culture, a different terminology, and different tools with which to solve its problems. It appears there was little, if any, communication between the engineers involved in solving these problems, or even an understanding that similar work was being undertaken elsewhere. Such a division between the groups prevented the discussion necessary to move beyond simple design of mechanisms and towards a theoretical foundation for automatic control.

Process Control

In order to improve the quality of their product at a lower cost, the process industries (chemical industry, metals, pasteurization, etc.), began investing in automatic controllers by the early 20th century. Temperature control provides a good example that was common to many industries. For example, the chemical industry might wish to maintain a reaction at a specific temperature (± 5^{o}C). Before automatic controllers, a human operator might have been used to adjust the flow rate of one of the reactants while watching a thermometer. If the reaction could be improved by maintaining a temperature within ± 1^{o}C, a human operator might not even be able to react fast enough. However, an automatic controller could both maintain this temperature and save the cost of the human operator.

The first controllers developed for the process control industries were simple on/off controllers much like a thermostat. Once a certain temperature was reached, the flow of the reactant would be turned off. When the temperature reached another given point, the reactant flow would be turned back on. Proportional control offered an improvement to on/off controllers by providing a continuous gain instead of binary switch. Instead of a human flipping a switch to turn the reactant flow off or on, he might use a knob to adjust it instead. If the difference between the desired temperature and measured temperature was large, the operator might turn the knob a lot. If the difference was small, a smaller turn would work. While on/off control was simple, it tended to have significant stability problems. Often the timing between turning something on and off was such that the system overcompensated for small changes in temperature which would lead to wild temperature swings. While proportional control was still intuitive, it was also an attempt to help solve this stability problem. Proportional controllers could also become unstable, although it was less likely that they would do so.[9]

The final improvement to proportional controllers before World War II was to add integral (reset) and derivative (rate) terms to the controller. An integral term was used to remove steady-state error from the system. Small errors between the desired temperature and measured temperature occasionally did not provide enough mechanical power to move the valve. Integral control allowed the error to build to a point where the valve would be moved and the error would become zero. Derivative control allowed for faster control by also using the error's rate of change in the controller.

While these controllers were generally specialized mechanisms designed to solve immediate industrial problems, there were also a small number of individuals examining the theory behind these controllers. Nicolas Minorsky analyzed the three terms (proportional, integral, and derivative) of PID controllers as early as 1922 while studying the automatic steering

[9] Instability from proportional controllers is somewhat less intuitive, but can be partially explained by examining positive feedback similar to when a speaker screeches if too close to the microphone. Instead of subtracting the output signal from the input signal to create an error signal, the two are added. This added signal is amplified and added again and so on. In a more general case, instability results from the output signal's phase shifting 180^o so it is being added instead of subtracted. For more information, general feedback control textbooks describe instability in much greater detail. See Franklin, Powell, and Emami-Naeini.

of ships at sea.[10] While not overly complex, his analysis used differential equations to model the dynamics of the ship and controller and provided some constraints to ensure stability. While Minorsky's work was not well known, in the early 1930s A. Ivanoff also attempted to provide a more theoretical basis for process controllers, specifically for temperature regulation.[11] Ivanoff provided a general rule for system stability involving phase shift and loop gain, but some inaccurate assumptions later in his text reduced the general importance of his analysis.

Despite this small theoretical base, most of the controllers built and used in industrial applications prior to the war used a more heuristic approach to development.[12] In the minds of most process control engineers, the controller was replacing a human operator and was therefore designed to accomplish what a human would accomplish in the same position. In addition, Bennett argues that theoretical advances were few due to heavy competition between companies and the lack of publication or information sharing that resulted. Low profit margins in the process industries may also have kept basic research to a minimum.[13] In the 1930s, process control remained heavily skewed towards practice over theory.

Feedback Amplifiers

Process control was only one industry where feedback controllers were taking root. Bell Labs and AT&T had a significant impact on the development of feedback controllers while

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[10] Stuart Bennett, "Nicolas Minorsky and the Automatic Steering of Ships," *IEEE Control Systems Magazine* 4, no. 4 (1984).. Minorsky's system was actually tested on the *New Mexico* and while the results were generally successful, the Navy removed the equipment from the ship with the explanation of "…the operating personnel at sea were very definitely and strenuously opposed to automatic steering, and they wished us to have nothing further to do with it…." Bennett, "Nicolas Minorsky and the Automatic Steering of Ships," 13.

[11] Ivanoff. described in Bennett, *A History of Control Engineering 1930-1955*, 50-51.

[12] This observation is based on general descriptions of process controller technology described in Bennett, *A History of Control Engineering 1930-1955*, 28-69.

[13] Ibid., 61-61.

trying to build a nation-wide long-distance telephone network.[14] By 1915, the first transcontinental phone line had been established between the East Coast of the United States and San Francisco. While this was a significant achievement by itself, the line only delivered a minimal bandwidth and a three minute call cost approximately twenty dollars. Obviously, new techniques were needed to turn long-distance phone service into a commodity.

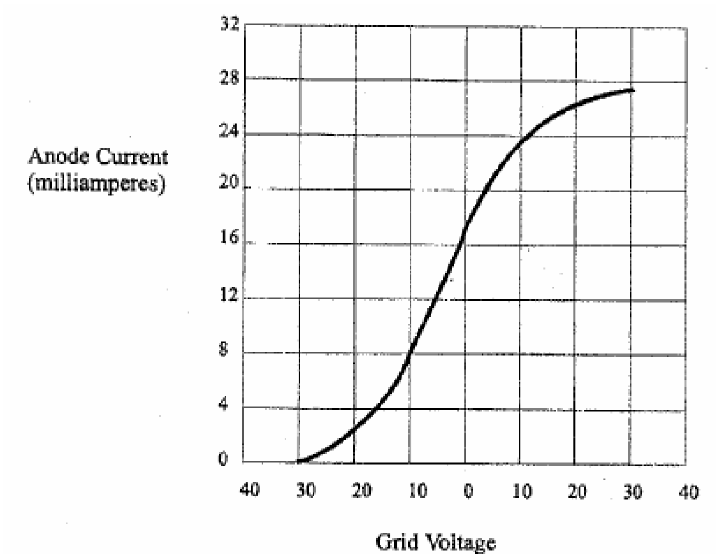

Figure 1 Vacuum tube nonlinearity. In a linear device, the anode current would be proportional to the grid voltage and this curve would become a straight line.[15]

The first transcontinental phone line required loading coils and repeaters to maintain the voice signal over a certain distance while transmitting. These components were necessary because resistance inherent in any transmission line will cause a signal to decay as it moves through the wire, requiring the use of signal amplifiers along the wire to maintain the signal. However, these amplifiers had their own set of problems: as seen in Figure 1 the vacuum tube amplifiers used in the 1915 transcontinental line were highly nonlinear which reduced quality as

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[14] Much more information on the development of feedback amplifiers and references to Bell Labs may be found in David A. Mindell, "Opening Black's Box: Rethinking Feedback's Myth of Origin," *Technology and Culture* 41, no. 3 (2000): 411-412.

[15] Ibid.: 417.

well as the ability to use one line to carry several different voice signals (required to reduce cost). This nonlinearity meant that if one person sang a perfect C into the amplifier, it would sound quite different at the output. In order to improve quality and allow several voice signals to be sent over the same line, a linear amplifier was required.

To accomplish this task, Harold Black of Bell Labs' System Development Department developed the first negative feedback amplifier in 1927. By using a passive feedback network whose components were relatively linear to reduce the gain of a standard nonlinear amplifier, he could also increase the linearity of that amplifier. While it remains unclear how well Black understood the implications of his discovery, his feedback amplifier became a basic building block for long-distance telephony.[16] However, despite significant improvement to linearity, feeding the output signal back into the input of Black's amplifier produced the same stability problems seen in process controllers. With the large research staff of AT&T and Bell Labs available to study this problem, Harry Nyquist of AT&T Research soon devised a graphical technique to test if a particular amplifier design would become unstable. Hendrick Bode followed this by a developing a graphical design method where amplifiers could be built to avoid instability. Both of these techniques provided tests on loop gain and phase shift similar to Ivanoff's work in process controllers. However, it is important to note that while both Nyquist and Bode developed techniques that could be used generically in automatic control, they did so with the specific aim of supporting vacuum tube amplifiers and were not necessarily aware of the wider implications of their work.

[16] Ibid.: 421-426. Black may not have even understood the basic problems of instability that could result from his amplifier.

Servomechanisms

Yet a third application of automatic control may be found in the development of analog computers at MIT in the 1930s. Analog computers were used to define a model of a much larger system such as an electrical power grid in the case of Vannevar Bush's Network Analyzer.[17] In order to solve the mathematics associated with these large network problems, Bush also began designing machines to calculate certain integrals. These machines, such as the Product Integraph, solved integral equations by requiring human operators to track a given signal by sliding a pointer attached to a linear potentiometer. This tracking was subject to human errors as well as being incredibly tedious. To alleviate this problem, one of Bush's students, Harold Hazen, automated this process with the servomechanism.

In his 1934 seminal paper on the theory of servomechanisms, Harold Hazen defined a servomechanism as a device whose output element "…is so actuated as to make the difference between the output and input indications tend to zero."[18] In this sense, the servomechanism tracks, or follows, a given input signal. Hazen also described the servomechanism as a power amplifier where low power inputs could be used to control high power outputs. While this statement seems to draw a connection to the feedback amplifiers at Bell Labs, Hazen did not make this connection originally. Instead, describing a servomechanism as a power amplifier simply meant that a small knob connected to a potentiometer drawing very little current could be used to control the position of a high current, high torque motor as shown in Figure 2.

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[17] Much more information on the development of analog computing at MIT may be found in Mindell, *Between Human and Machine: Feedback, Control, and Computing before Cybernetics*, 138-174.

[18] H. L. Hazen, "Theory of Servo-Mechanisms," *Journal of The Franklin Institute* 218, no. 3 (1934). This theory paper was published in conjunction with a separate paper on the design and test of a servomechanism. H. L. Hazen, "Design and Test of High-Performance Servo-Mechanism," *Journal of The Franklin Institute* 218, no. 5 (1934).

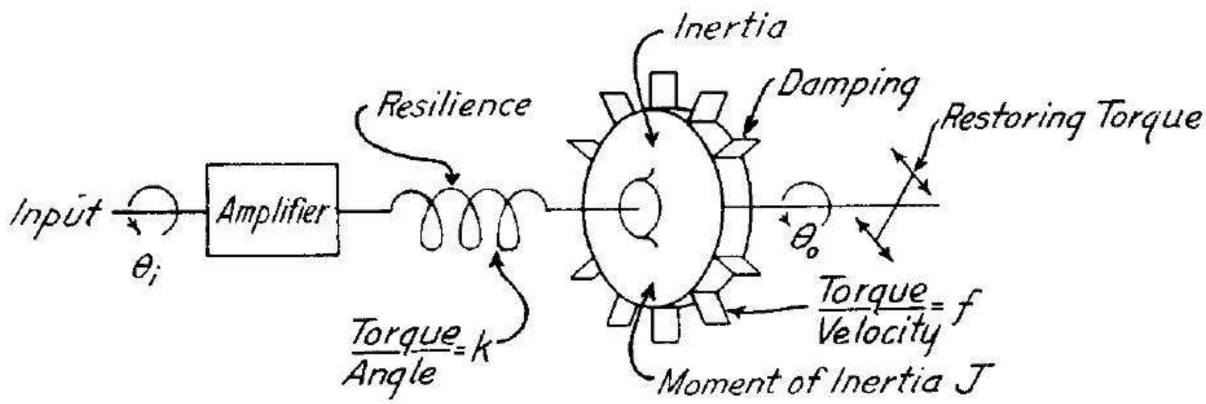

Figure 2 Hazen's drawing of a generic servomechanism. The output angle θ_o follows the input angle θ_i even though θ_o may be the shaft of a large motor and the input may be controlled by a small knob.[19]

Servomechanisms grew up in an academic culture quite different from the industrial culture of process control and feedback amplifiers. As such, while Hazen was primarily concerned with the mechanism itself, he also took time to develop some corresponding theory to support his mechanism. In “Theory of Servo-Mechanisms,” Hazen studied the dynamic response and stability which were important aspects of his application. In addition, in a relatively thorough literature review, Hazen cited a large number of papers on process control and automatic steering, recognizing the fact that his work might have a broader outlook.[20] Despite this effort, he did not find the connection to Nyquist’s previously published paper from Bell Labs, and it would take a war to bring these groups together.

Because the hardware and mechanisms used for process controllers, feedback amplifiers, and servomechanisms were so different, connections between the three subjects were not immediately obvious. However, all three applications attempted to solve similar problems through the use of feeding an output signal back to the input. For example, process controllers were generally designed to maintain a certain measurement or reference point, but this is simply

[19] Hazen, "Theory of Servo-Mechanisms," 317.
[20] Ibid.

a subset of the signal tracking that feedback amplifiers and servomechanisms accomplished. Hazen made the connection between his work and previous studies of gyro stabilization and industrial controllers in his theory paper, but it appears that in general, very little was communicated between the three groups which emerged independently. Each group contributed its own account of the theory that supported its mechanisms although the theory was heavily tied to the particular application or mechanism. Because of this, pre-war work in automatic control remained rooted in its practice instead of theory.

Automatic Control during World War II

In order to move beyond the intuition and simple techniques used previously in designing automatic controllers, the fundamentals of automatic control would be developed for the first time during World War II. In general, the war was a transformative time for science and engineering in the United States. The scale associated with efforts like the Manhattan Project and MIT's Radiation Laboratory was beyond what had previously occurred in scientific inquiry. In a 1944 letter to Vannevar Bush, who had since taken over the job of organizing wartime research, President Roosevelt praised Bush for the "unique experiment of team-work and cooperation in coordinating scientific research and in applying existing scientific knowledge to the solution of the technical problems paramount in war."[21] While the results of this research were extraordinary, the organization and coordination required to accomplish them was perhaps more so.

In particular for automatic control, the war offered a unique convergence of previously independent studies. During the war, control engineers were tasked with solving the specific

[21] Vannevar Bush, *Science: The Endless Frontier* (Washington, DC: United States Government Printing Office, 1945), vii.

problem of fire control – shooting down enemy aircraft from land or sea. Many of the mechanisms developed before the war would find further application on this project. For example, precise control of large guns was an excellent application for Hazen's servomechanisms, and the techniques developed at Bell Labs to test and design for stability became an important component in stabilizing these new weapons. In addition, process control engineers donated previous expertise on analog simulation and pneumatic components. Bissell summarized well when he described this merger of diverse groups as generating "an enormously fruitful cross-fertilization of ideas."[22]

In addition to simply sharing ideas among the different groups, World War II also provided the impetus to effectively merge these groups create an entirely separate discipline of automatic control. Previously, organization had been lacking in the field, but automatic control was folded into Bush's National Defense Research Committee (NDRC) powerhouse along with other scientific endeavors. While groups working on separate applications had previously developed their own terminologies based on the application itself and the application culture, the war forced the creation of a new and universal vocabulary for automatic control along with a unified theory to build upon. To fund this early effort in basic automatic control research, the contract system used during the war by NDRC and OSRD benefited the exploration of the theory of automatic control by ensuring that basic research was not neglected. After the war, this contract system would continue to provide the money necessary for automatic control engineers to place a greater focus on theory than application in the coming years.

Before the United States even entered World War II, President Roosevelt preemptively approved the establishment of the NDRC on June 27, 1940 as an organization to coordinate

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[22] C. C. Bissell, "Spreading the Word: Aspects of the Evolution of the Language of Measurement and Control," *Measurement and Control* 27, no. 5 (1994): 149.

defense research. The committee was separated into four divisions to help solve immediate defense concerns: Division A for armor and ordnance; Division B for bombs, fuels, gases, and chemistry; Division C for communications and transportation; and Division D for radar, fire control, and instruments. While Division D is undoubtedly most famous for the contributions of MIT's Radiation Laboratory, the fire control section, Section D-2, would provide the backdrop for developments in automatic control.

To lead D-2, Vannevar Bush quickly chose the Rockefeller Foundation's Warren Weaver.[23] To fill out his new section, Weaver in turn chose Edward J. Poitras who had spent time working with servomechanisms used on the Palomar telescope in Pasadena as well as Thornton C. Fry and Samuel H. Caldwell. Fry was the director of mathematics at Bell Labs and Caldwell led MIT's Center for Analysis. Each of these individuals had a strong background based in mathematics and theory, and the group immediately began to tackle the fire control problem from a mathematical perspective by examining systems, statistical analyses of errors, and analog electronic simulators instead of focusing on specific hardware.[24] This mathematical and theory-based attitude towards fire control was the first time the problem had been approached in that manner and the beginning of a long tradition of mathematics in automatic control.

However, this group was broken up within a year when the NDRC had grown so large that it required reorganization into the Office of Scientific Research and Development (OSRD). Section D-2 became Division 7 and Warren Weaver joined the Applied Mathematics Panel

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[23] Weaver had been a mathematics professor at the University of Wisconsin prior to joining the Rockefeller Foundation. While Mindell describes Weaver as not interested in funding engineering projects, Weaver was heavily involved in the funding of Bush's differential analyzer, a successor to the network analyzer. From Mindell, *Between Human and Machine: Feedback, Control, and Computing before Cybernetics*, 170,189.

[24] David A. Mindell, "Engineers, Psychologists, and Administrators: Control Systems Research in Wartime, 1940-45," *IEEE Control Systems Magazine* 15, no. 4 (1995): 92.

instead of staying directly within fire control. In his place, Harold Hazen was chosen to lead Division 7 and the work moved towards more immediate and practical concerns than the mathematics studied by members of D-2.[25] Following this shift away from theoretical concerns, many of the new members of Division 7 had strong ties to industry: Duncan Stewart of Barber Coleman, Ivan A. Getting from MIT's Radiation Laboratory, George Philbrick of the Foxboro Company, Gordon Brown from MIT's Servomechanism Laboratory, Walter MacNair of Bell Labs, John D. Tear of Ford Instrument, and John Taplin.[26]

Despite its new shift towards more immediate practical objectives, Division 7 was perhaps more influential than D-2 in moving automatic control towards a new theoretical foundation by providing the first real organization of automatic control's diverse disciplines. Representing process control, Foxboro was a major distributor of process control systems, and George Philbrick had built the earliest electronic simulators to study process control. Feedback amplifiers were represented by several Bell Labs members who passed around Bode's text on feedback amplifier design during the war.[27] For servomechanisms, Hazen, Brown and Poitras all had extensive experience through their connections to MIT. In one of its most important contributions to automatic control, Division 7 organized previously independent groups into a newly unified organization in which communication and discussion were finally possible.

However, while communication was at last possible between the separate groups in Division 7, it was certainly not easy. Despite wartime secrecy, Mindell argued that Section D-2 and Division 7 spent a great deal of effort on standardization of both symbols and vocabulary to

[25] From Mindell, *Between Human and Machine: Feedback, Control, and Computing before Cybernetics*, 198.. 44% of contracts issued before 1943 went to universities while that number dropped to 18% under Division 7.
[26] Interestingly, Taplin was an MIT student who was the first to use Nyquist's methods for a servomechanism in 1937. From Bennett, *A History of Control Engineering 1930-1955*, 90.
[27] Hendrick W. Bode, *Network Analysis and Feedback Amplifier Design*, The Bell Telephone Laboratories Series (Princeton, New Jersey: D. Van Nostrand Company, Inc., 1945), iii.

create "a common language of fire control."[28] While a common vocabulary was by no means decided upon during the war itself, the process began just before the war and continued into the 1950s. First to act, the American Society of Mechanical Engineers (ASME) created the Industrial Instruments and Regulators Committee under Ed Smith in 1936 to begin working on nomenclature for process control. As a work in progress, Smith's group issued interim reports in 1940, 1944, and 1945.[29] By 1946, the ASME branched into areas beyond process control; a 1946 report stated that while it was primarily providing terminology to deal with industrial process control, in many cases the definitions are "sufficiently broad to have wider application."[30] In another important development to the broader language of automatic control, The British Servo-Panel, Britain's equivalent to Division 7, produced the Glossary of Terms used in Control Systems with Particular Reference to Servomechanisms as early as 1944.[31] While standardizing language was important to communicate, it also defined those engineers who spoke the language. In an article describing the evolution of language in automatic control, Bissell states:

> After the war, the comparatively small circle of engineers who had become adept at what we now call 'classical control' and 'the systems approach' found that they could hardly be understood by many of their colleagues.[32]

Developing a new vocabulary proved to be important in defining automatic control as a discipline distinct from its diverse roots.

The organization of D-2 and Division 7, as well as efforts to develop a common language, emphasized that there was now only one problem for control engineers to solve –

[28] Mindell, *Between Human and Machine: Feedback, Control, and Computing before Cybernetics*, 202.
[29] Bissell.
[30] "Automatic-Control Terms," *Mechanical Engineering* 68, no. 2 (1946). It should be noted that the paper also counted "servo" as a non-standard term for power unit.
[31] While this glossary was, in fact, a British effort, the commonality of the English language also makes its introduction relevant to control efforts in the United States.
[32] Bissell: 149.

accurately pointing a gun at a moving target. Unlike the 1920s and 1930s when theory and devices were application-specific, solving a single problem allowed the diverse members of Section D-2 and Division 7 to take a fresh approach. Mindell writes:

> The novel organizational conditions of the NDRC allowed them to see fire control as a particular case of a general problem of control: a feedback problem, a stability problem, and a problem of representing the world in machines using electrical signals.[33]

As a proponent of this more generic and mathematical approach to fire control, Weaver admitted later in the war that "certain groups in the National Defense Research Committee have for some considerable time been interested in stimulating the writing and/or in sponsoring the distribution of mathematical treatments of servo theory."[34] Despite a shift in emphasis away from this general abstraction which the mathematicians of D-2 originally pursued, Division 7 did not move completely away from basic theory. In fact, Division 7 even contained a separate subsection, 7.5 Fire control analysis, which was intimately connected to Weaver's Applied Mathematics Panel. In addition, Division 7 funded several contracts which leaned heavily towards mathematics and computation. Norbert Wiener and John Bigelow worked on predicting the future location of airplanes to improve shooting accuracy under the contract heading of "General Mathematical Theory of Prediction." Stibitz worked on building calculating machines to more accurately represent trajectories, and there was a great deal more work done on differential analyzers. Defining automatic control as a general problem and developing a general theory to support it helped solidify a base on which the new discipline of automatic control could be built.

Despite study of basic theory in automatic control during the war, this research was not likely to continue without a method of funding. True to its emphasis on practice over theory, pre-war funding in automatic control was primarily industrial. Taylor Instruments and Foxboro

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[33] Mindell, *Between Human and Machine: Feedback, Control, and Computing before Cybernetics*, 197.
[34] LeRoy A. MacColl, *Fundamental Theory of Servomechanisms* (New York: D. Van Nostrand Company, Inc., 1945), xiv.

were two of the largest companies involved in process control and instrumentation, and each developed their own technology. The push to extend telephone lines across the continent dictated the funding to linear amplifiers, and therefore Black's discovery of the negative feedback amplifier. The impetus for Bush and Hazen's first network analyzer was to study the behavior of electrical power grids. In fact, while Warren Weaver was at the Rockefeller Foundation, he believed that engineering "was close enough to profit-making industries to support itself."[35]

In a new development during the war, the NDRC utilized a contract system to award money to researchers. This tactic deviated significantly from pre-war government funding which usually involved procurement of some kind and therefore required physical results. While in general, these contractors were tasked to build or study a specific component of the fire control system, projects without an obvious piece of hardware attached were still common, especially at universities like MIT and Columbia. Claude Shannon received funding for "Mathematical Studies Relating to Fire Control" and Norbert Wiener used Section D-2 contract money to delve into mathematical prediction theory.[36] Just prior to the war's end, Vannevar Bush sent a report to the president advocating the formation of a new funding agency, citing past results funded by the NDRC and OSRD. He also emphasized the need to fund basic research, which he defined as "research…without thought of practical ends," as well as supporting the role of the university as a foundation for this new endeavor.[37]

Thus, the war provided both an intersection for the various groups studying automatic control up to this point to meet and discuss new ideas, as well as the foundation from which a new discipline of automatic control would emerge. While World War II was certainly not a

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[35] Mindell, *Between Human and Machine: Feedback, Control, and Computing before Cybernetics*, 189.
[36] Ibid., 328.
[37] Bush, 18-19.

specific turning point, it was the beginning of one. The organization provided by the NDRC and OSRD encompassed most groups working on automatic control, but not all. A notable exception was Sperry Gyroscope which continued previous contracts for stabilization with the army and did not receive any money through Division D-2 or Division 7. The war saw the beginnings of an attempt to merge previous vocabularies, and new paradigms for research funding were established. Despite the caveats, common theoretical ground brought together a small band of individuals to develop new, more general theories. Organization, vocabulary, the use of mathematics to solve problems, and funding did not automatically motivate a sudden shift in emphasis to theory over the previous emphasis on mechanisms and application-specific approaches. Instead, these factors helped motivate the emergence of a new discipline of automatic control in which the proportion of study devoted to practice versus theory was still unclear.

Building a Discipline

While the foundation of a new discipline was built during the war, efforts after the war helped to truly establish the field of automatic control. As a consequence of these efforts however, this new discipline would develop into a field largely removed from its origins in the laboratory. Although universities played a large role in D-2 and Division 7 during the war, they would have an even greater impact afterwards by educating a new breed of scientist-engineer and providing a venue for basic research. At the same time, contacts made during the war and general expansion of knowledge on the subject led to an increasing call for new societies, conferences, and journals in which to share ideas. Academic rigor enforced in these new organizations placed greater emphasis on exactness of theory over implementation of the theory on a real device.

During the war, approximately 36% of the contracts from D-2 and Division 7 went to academic institutions.[38] After the war, these institutions continued to play a primary role in the education of future control engineers as well as new control engineering research. In addition, engineering education at this time was going through its own revolution, specifically in its regard of mathematics and basic science. As an example of the prevailing attitude towards mathematics in education before the war, a mechanics professor at Ohio State, P. W. Ott, described the mathematics necessary for engineering education as arithmetic, geometry, trigonometry, algebra, and analytical geometry. Calculus and differential equations were considered rare in usage, yet valuable. Probability, vector analysis, Fourier series, etc. were to be considered in the realm of "diminishing returns."[39] Yet, by the early 1950s, a required class in ordinary differential equations was common for engineers educated at major universities. More generally, previously "advanced" mathematical topics such as stochastic variables, Fourier series, and large systems of linear equations were now critical to the study of many engineering subjects, including automatic control.

Part of this trend towards learning more complex mathematics may be attributed to electrical engineers' envy of physicists during the war. Jealous of watching physicists control wartime research, Frederick Terman returned to Stanford and immediately revamped the engineering curriculum to include more science and mathematics.[40] Daniel Abramovitch and Gene Franklin reminisce:

> Much of the work at the Rad Lab was led by physicists because the education of most electrical engineers did not include the necessary math or physics called for by these problems. It was said

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[38] Mindell, *Between Human and Machine: Feedback, Control, and Computing before Cybernetics*, 203.
[39] P. W. Ott, "Usefulness of Mathematics to Engineers," *General Electric Review* 38, no. 3 (1935): 139.
[40] Ronald Kline, "World War II: A Watershed in Electrical Engineering Education," *IEEE Technology and Society Magazine* 13, no. 2 (1994): 17.

> by some, and perhaps only partially in jest, that in the standard American EE curriculum of the time, $2\pi f$ was taken as a constant equal to 377; that is, f was always 60 Hz.[41]

Electrical engineers desired the generic mathematical and scientific tools that would move them beyond their vocational ties to the power grid and into the newer and more exciting fields of radio, communications, and automatic control.

However, envy was only part of the equation. Seely argues that new trends in academic engineering research after the war also encouraged engineering education to move closer to scientific principles and away from a traditional "practical" education.[42] Such academic engineering research was largely affected by the new role of post-war government funding, and the National Science Foundation even included a place in its charter to fund basic research in engineering science.[43] Yet another explanation for the trend towards more science and math was the sharp increase in graduate education after the war. Greater numbers of graduate students influence undergraduate curricula by moving advanced topics to undergraduate classes so that graduate students may be better prepared for research.[44]

Specifically in automatic control, numerous debates were raging at early conferences, on college campuses, and in textbooks as to the best method of introducing the subject to new students in order to prepare them for the work ahead. In an open panel discussion at the 1957 PGAC Symposium on Nonlinear Control, the conversation continually returned to the subject of mathematics in a control engineering education. If engineers focused too much on mathematics, a simple practical approach to solving a problem might be overlooked. On the other hand, if

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[41] Daniel Y. Abramovitch and Gene F. Franklin, "Fifty Years in Control: The Story of the IEEE Control Systems Society," *IEEE Control Systems Magazine* 24, no. 6 (2004): 20. 60 Hz is the frequency used in power lines which was the primary educational track in electrical engineering prior to the 1930s as described in Gordon S. Brown, "Integration Versus Options in Electrical Engineering," *Electrical Engineering* 72, no. 7 (1953).
[42] Bruce Seely, "Research, Engineering, and Science in American Engineering Colleges: 1900-1960," *Technology and Culture* 34, no. 2 (1993).
[43] Ronald Kline, "The Paradox of "Engineering Science" - a Cold War Debated About Education in the U.S.," *IEEE Technology and Society Magazine* 19, no. 3 (2000). Of course, "engineering science" was a new concept itself.
[44] Kline, "World War II: A Watershed in Electrical Engineering Education."

engineers remained too practically oriented, their creativity may be limited by their less-than-thorough understanding of the physical structure of the problem at hand.[45] In the closing remarks of the same conference, attendees voiced their own opinions:

> From Dr. Bower… "I think the only real obstacles are going to remain in our own ignorance….The engineer…realizes now that he needs a terrific amount of mathematics to handle the automatic control problem adequately and I would like to vote for this idea of simplifying the access of the engineering student to mathematics."
>
> From Mr. Holzmann… "Sometimes mathematical analogy becomes a creative tool, suggesting new avenues of attack on a problem. But analysis is not the only pathway to progress. In fact, the analysis of any process control problem is liable to arrive at a point where further refinement pays diminishing returns. Beyond this point, one may find it more economical to shift the emphasis from desk to shop and laboratory."
>
> From Mr. West… "I feel that one of the obstacles to progress in nonlinear control is the lack of an adequate mathematical theory. While it is true that computers can be employed to predict the performance of a particular system, a better mathematical theory is required before the computer can be utilized effectively to synthesize a desired response."[46]

These same debates were also happening on college campuses. Gordon Brown, a member of Division 7 and MIT's electrical engineering department head in the early 1950s, published several papers on electrical engineering and feedback control education. Brown helped develop a new electrical engineering curriculum at MIT which would allow electrical engineers to learn "the science that would dominate the art of tomorrow."[47] In order to pull electrical engineers away from specific vocations, MIT's new curriculum placed a heavy emphasis on mathematics and the sciences with very little specialization as shown in Figure 3. Brown also published on the specific task of educating feedback control engineers, stating that:

> Adequate scholarly accomplishment in the field of feed-back control requires advanced work in the fields of mathematics, physics, chemistry, measurements, communications and electronics, servo-mechanisms, energy conversion, thermodynamics and computational techniques, in addition to undergraduate training in physics or engineering. Familiarity with mathematics of

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[45] "Open Panel Discussion," *IRE Transactions on Automatic Control* 5, no. 1 (1958): 67.

[46] "Closing Remarks," *IRE Transactions on Automatic Control* 5, no. 1 (1958): 70-71. It should be noted that the author decided that the study of control was not for her after taking her first class in nonlinear control. The math required to understand this is simply extraordinary (for her anyway).

[47] Gordon S. Brown, "Educating Electrical Engineers to Exploit Science," *Electrical Engineering* 74, no. 2 (1955): 111.

differential equations, functions of a complex variable, statistics and non-linear techniques…are basic to the program.[48]

As a leader in control engineering education, Brown believed that control engineers, as well as electrical engineers in general, required a solid background in mathematics and science in order to think creatively about future problems.

Table I. Electrical Engineering at MIT, 195–545

Freshman				
Physics	Chemistry	Mathematics	Elective	Humanities
Physics	Chemistry	Mathematics	Elective	Humanities
Sophomore				
Physics	Electric circuits, 6.00	Mathematics	Applied mechanics	Humanities
Physics	Electric circuits, 6.01	Mathematics	Applied mechanics	Humanities
Junior				
Electronic circuits 6.02	Fields, materials and components 6.03	Mathematics	Thermo	Humanities
Applied electronics 6.05	Elec. energy convertors, 6.04	2 Electives—both out of department		Humanities
Senior				
Energy transmission and radiation 6.07	Power modulators 6.06	2 Electives—inside or outside department		Humanities
Integration of above courses via free electives influenced by student's aptitudes and interests		Thesis		Humanities

Leads to commencement followed by

Graduate study and research, SM, EE, ScD

On-the-job training in industry, or self development by the graduate

Note: Subjects 6.00 through 6.07 include both classroom and laboratory. Both Junior and Senior subjects are influenced by research of faculty and graduates students,

Figure 3 MIT's new electrical engineering curriculum placed a heavy emphasis on mathematics, science, and basic theory.[49]

At the same time, former members of D-2 and Division 7 were publishing the first textbooks on automatic controls in order to pass new knowledge on to future generations of control engineers. Since the war had helped merge previous work specific to a variety of

[48] Gordon S. Brown, "Feed-Back System Engineering - a Challenging Educational Objective," in *Automatic and Manual Control Conference* (Cranfield, England: Butterworths Scientific Publications, 1951), 7.
[49] Brown, "Educating Electrical Engineers to Exploit Science," 112.

applications into a broader theoretical base, textbooks published shortly after the war tended to emphasize their generality as well as present these new theoretical approaches to automatic control. For example, in the book's foreword, Warren Weaver lauded LeRoy MacColl's Fundamental Theory of Servomechanisms for the beauty of the mathematical theory provided.[50] Another example was the Theory of Servomechanisms text produced as part of the Radiation Laboratory Series which emphasized its presentation of a theory general to servomechanisms and not specific to work done during the war.[51] However, not all textbooks expected readers to have the mathematical background required to study automatic control. While Ed Smith also emphasized the fundamental theory presented in his book, he included appendices amounting to approximately half of the book to provide enough background in mathematics for those who would read it.[52]

Even as universities were busy educating control engineers to think about the fundamental theory behind automatic control, universities were also building an environment for basic research in the subject. Before the war, most of the research in automatic control was done in industrial research labs with the notable exception of MIT's participation in developing servomechanisms. As discussed previously, new funding approaches developed during the war opened the door for supporting basic research not tied to particular applications at universities. In an attempt to find out where this funding was going, John Ward surveyed American universities in 1961 to determine the level of research activity in automatic control.[53] As seen in Figure 4, the survey divided research into a number of sub-topics and quantified the number of

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[50] MacColl, xiv-xv.

[51] Hubert M. James, Nathaniel B. Nichols, and Ralph S. Phillips, *Theory of Servomechanisms*, ed. Louis N. Ridenour, 28 vols., Massachusetts Institute of Technology Radiation Laboratory Series, vol. 25 (New York: McGraw-Hill Book Company, Inc., 1947), ix.

[52] Ed Sinclair Smith, *Automatic Control Engineering* (New York: McGraw-Hill Book Company, Inc., 1944), v.

[53] J. Ward, "A Survey of Control Research in U. S. Engineering Schools," *IRE Transactions on Automatic Control* 7, no. 5 (1962). This report contained more interesting information as well including information on annual budgets for controls research as well as the man-power and resulting number of theses involved in the research.

research groups studying these topics as well as the approximate classification of their work as theoretical or applied. In a telling statement of the shift towards theory in academic controls research, the three most actively studied topics were non-linear analysis, adaptive control, and feedback theory, all of which had a solid foundation in mathematics and theory. In addition, when Ward presented this information at a workshop in February 1962, many participants believed the survey was in fact skewed towards applied research since "the figures were heavily weighted by non-technical staff or students performing 'non-significant' research."[54]

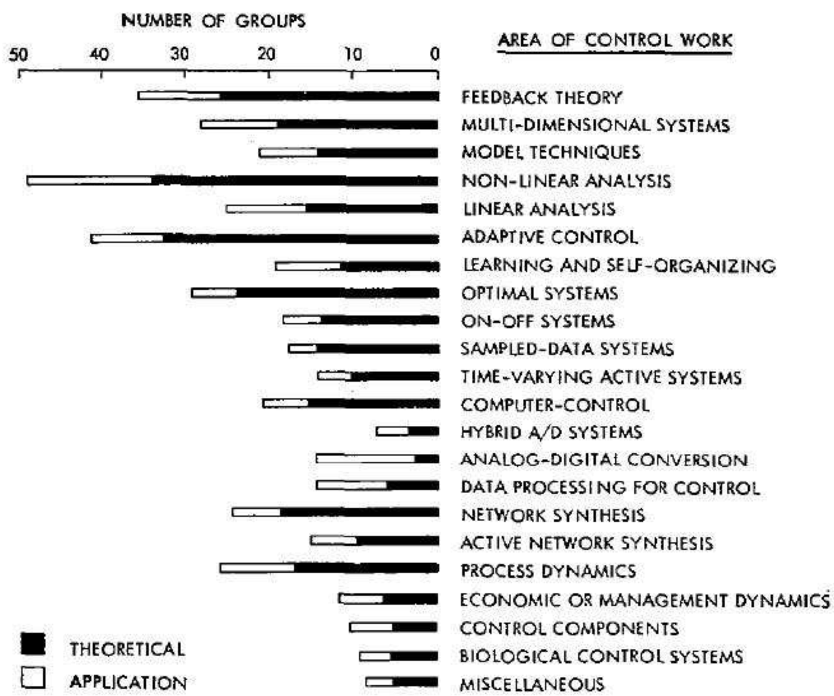

Figure 4 Control engineering research at universities in the United States as of 1962.[55]

Although universities provided much of the infrastructure and manpower for completing basic research in automatic control, new organizations were still required to provide a forum for presenting and distributing this research. During the war, D-2 and Division 7 accomplished this task by organizing diverse automatic control specialists. On the civilian front, the American

[54] Ibid.: 129.
[55] Ibid.: 128.

Society of Mechanical Engineers was the first to organize its control engineers by creating the Industrial Instruments and Regulators Committee, which became a division of the ASME in 1943. The same trend was also present in electrical engineering, although the society structures were a little more complex. After World War II, two separate organizations covered different topics in electrical engineering: the Institute of Radio Engineers (IRE) and the American Institute of Electrical Engineering (AIEE). In the AIEE, the structure was complicated at best, but an Industrial Control Devices committee was established in 1944.[56] A little later, the IRE created a Servomechanisms committee in 1951 which changed its name to the Feedback Control Systems committee in 1952. By 1955, a full fledged Professional Group on Automatic Control was created within the IRE, while the AIEE did not create the Technical Group on Automatic Control until 1961 when the IRE and AIEE merged.

In an international attempt to organize control engineers, Americans Rufus Oldenburger and Harold Chestnut participated in establishing the International Federation of Automatic Control (IFAC) in 1956.[57] IFAC was intended to have international representation much like the United Nations and an agreement was made for an American (Chestnut) to head the organization while the first major conference would be held in Moscow in 1960. Each country participating required a member organization for which the United States created the American Automatic Control Council in 1958.

At their roots, these new organizations did not dictate a preference of theory over practice. In fact, while the initial organizational structure for IFAC as seen in Figure 5 denoted 13 technical committees, only two might be considered theory-based in name: "Mathematics of

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[56] See Stuart Bennett, "The Emergence of a Discipline: Automatic Control 1940-1960," *Automatica* 12, no. 2 (1976). for more details on AIEE committees involving automatic control.

[57] Much more information may be found in R. Oldenburger, "IFAC, from Idea to Birth," *Automatica* 5, no. 6 (1969).

Control" and "Theory." Then again, that did not prevent the members of these organizations from preferring either theory or application. Oldenberger recalled:

> …I pictured the scope of IFAC as a very broad one. I further pictured a federation heavily weighted in the direction of the practical and fervently hoped that automatic control would not go the way of applied mechanics, which is no longer applied, but has become a mathematical discipline.[58]

However, when writing his paper in 1967, Oldenburger concluded:

> Contrary to what I anticipated, IFAC has become steadily more devoted to control theory. Papers tend now to be judged on the basis of mathematical elegance rather than industrial or other practical need. I have been forced to accept the fact that automatic control has become a mathematical discipline…[59]

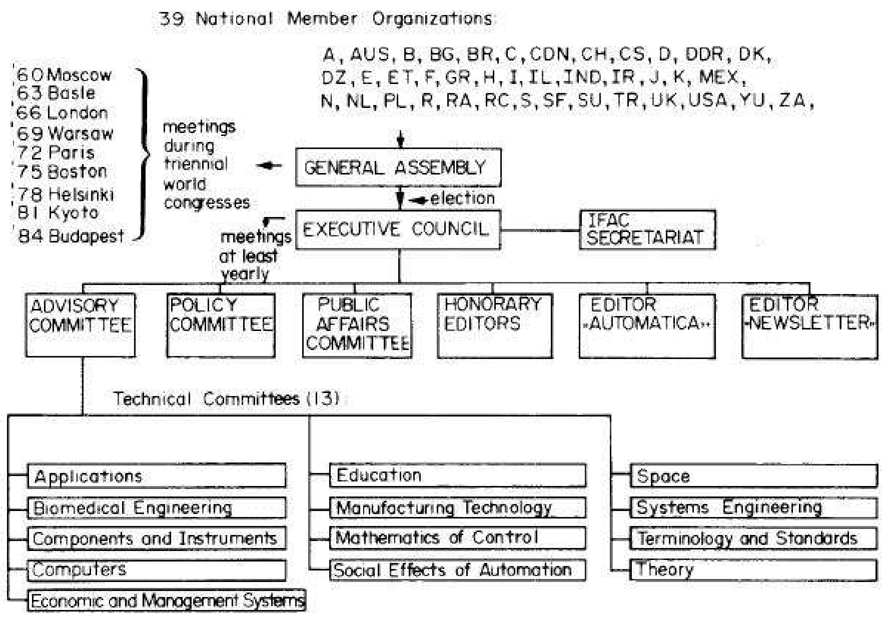

Figure 5 IFAC organizational structure.

Despite the preferences of individual members and the societies' original charters, conferences and journals proved to be more influential in directing automatic control societies away from practical pursuits. The primary purpose of these organizations was to serve their members by promoting the distribution of new ideas and techniques through conferences and

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[58] Ibid.: 699.
[59] Ibid.: 702.

journals, and in general, papers presented in these forums would dictate future papers submitted. Some of the earliest papers were presented at conferences offered in Britain, although prominent American control engineers also attended. Shortly after the war, these conferences still presented a significant number of papers on applied automatic control. For instance, the Convention on Automatic Regulators and Servo Mechanisms was held in 1947 with paper categories of Miscellaneous, Aeronautical Applications, Electronic Servo Systems, Industrial Applications, Military Applications, and Naval Applications.[60] However, by 1951 a small shift towards more mathematics was evident at the Conference on Automatic and Manual Control held in Cranfield, England. Topics at this conference included Educational Problems, General Theory, Process Control, Non-linear Problems, Systems Working on Intermittent Data, and Step-by-Step Servos, The Human Operator, and Particular Devices and Applications including Analogues. Due to the more mathematical nature of many of these subjects, the introduction to the conference proceedings contained a caveat on the mathematics involved in the presented papers and a short mathematics tutorial, "Mathematical note on the theory of the complex variable," was also included in the proceedings.[61]

In the United States, early conferences also tended to focus on the practical application of automatic control, but theory was not neglected. In 1953, the Instruments and Regulators Division of the ASME offered a Frequency Response Symposium at the ASME Annual Meeting in New York City.[62] As evident by its name, this symposium focused on the techniques developed by Bode at Bell Labs to analyze feedback control systems. The 16 papers at this conference were relatively evenly split between application and theory with a few tutorial papers

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[60] "Proceedings at the Convention on Automatic Regulators and Servo Mechanisms," *The Journal of the Institution of Electrical Engineers, Part IIA* 94, no. 1 (1947).
[61] *Automatic and Manual Control: Papers Contributed to the Conference at Cranfield, 1951*, (London: Butterworths Scientific Publications, 1952), vii.
[62] *Frequency Response Symposium*, (New York City: The American Society of Mechanical Engineers, 1953).

thrown in for good measure. It is interesting to note, however, that all but one of the application papers were written by industrial members while only one of the theory papers was written by an engineer employed by a profit-seeking company.

In electrical engineering, the First Feedback Control Systems Conference hosted by the Feedback Control Systems Committee of the AIEE was held in Atlantic City, New Jersey in 1951. While the papers presented at this conference were never published, the preface to the proceedings of the second conference held in 1954 state that "developments in the *theory* of Feedback Control" were discussed.[63] While this may be true, the second conference was heavily skewed towards applications, and the conference even scheduled demonstrations for companies to show off their control-related products. All but one of the papers presented came from industry with the lone exception from the Lewis Flight Propulsion Laboratory (under the National Advisory Committee for Aeronautics). Conferences and their organizational sponsors still appeared to be heavily rooted in industry in the early 1950s.

The shift towards theory and mathematics in automatic control became more evident at the first IFAC conference held in Moscow in 1960. Papers presented at this conference were divided into three separate, and supposedly equal, categories – Theory, Components, and Applications. However, theory papers filled half of the resulting conference proceedings, and included Rudy Kalman's famous paper "On the General Theory of Control Systems." In his introduction, Kalman stated that he intended his paper to initiate "study of the pure theory of control…" and it is generally agreed that this paper began a revolution in the study of control theory versus application.[64] Kalman's paper, as well as many others presented at the Moscow

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[63] *The 2nd Feedback Control Systems Conference*, ed. G. S. Axelby (Atlantic City, New Jersey: American Institute of Electrical Engineers, 1954), 4.. Italics added by the author.

[64] R. E. Kalman, "On the General Theory of Control Systems," in *First International Congress of the International Federation of Automatic Control*, ed. J. F. Coales (Moscow: 1960), 481. Kalman goes so far as to compare his

conference, was a highly visible symbol of the shift in automatic controls research from practice to theory.

At the same time that conferences were beginning to focus on more mathematical subjects and less on application and components, journals were going through the same debate. In the mid-1950s, the first issue of the IRE Transactions on Automatic Control promised "attention will be given to any subject, abstract or practical, relating to automatic control within any of the system elements, simple or complex." Despite this promise though, that first issue contained only one paper on theory.[65] In the second issue, there were four papers on theory and two tutorial articles. This issue also included an editorial which asked the readers which proportion of papers on theory, practice, or instruction they would prefer.[66] Despite obvious attempts to include industrially-oriented papers, published papers continued to develop theory with less regard to physical systems. As stated previously, George Axelby, the editor of Transactions, calculated the percentage of "highly theoretical" papers in the first six years that the Transactions were published. From 1956 to 1961, he classified 57% of the two hundred published papers as theoretical. In the second three years from 1959 to 1961, 80% of papers focused on the theoretical aspects of automatic control.[67]

While papers presented at society conferences and published in society journals continued to trend away from practice and towards theory, it is not clear that academics completely displaced industrial members in the new control societies. Regardless, industry's presence in demanding and publishing more practically oriented papers was certainly not

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paper to Shannon's famous "A mathematical theory of communication" published in 1948. Shannon's paper is regarded as the origins of information theory and the communications revolution. The general agreement referred to here may be found in a number of references including Franklin, Powell, and Emami-Naeini, 13. and Bennett, *A History of Control Engineering 1930-1955*, 203-204.

[65] "Automatic Control and the IRE," *IRE Transactions on Automatic Control* 1, no. 1 (1956).

[66] "Theory, Practice or Instruction?," *IRE Transactions on Automatic Control* 2, no. 1 (1957).

[67] Axelby, "Image or Mirage?," 1.

evident. While it is likely, of course, that industrial members had less time and incentive to publish papers on their work, the fact that academia filled this void implied a greater focus on the academically important characteristics of originality and exactness in papers. As in any field, new developments build on top of previous work, and the society conferences and journals built a body of previous work that emphasized theory over practice early on.

Consequently, by the late 1950s, it was clear that education, research, and the early body of knowledge produced by the fledgling discipline of automatic control strongly emphasized theory over practice and mathematics over applied studies. Rapidly changing university curricula educated engineers with a deeper background in math and science, and a greater number of these engineers stayed in school creating an environment conducive to more basic research. Most importantly, the new societies developed to organize these researchers began to build a body of work where application and implementation were neglected in favor of advances in theory. By the early 1960s after the first IFAC conference, "the gap" was already becoming remarkably visible.

New Tools of the Trade

While life in academia had established automatic control as a theoretical discipline distinct from its origins as an applied engineering science, breakthroughs in theory did not come easily. To continue advances in theory, control engineers needed to develop a new set of mathematical and computational tools to help move theory forward without waiting to test new theories on a real system. It was not expected, for example, that new discoveries in the theory of guided missile control would need to be tested on a guided missile before others could improve on that theory to build an even better controller. Tackling and testing more complex problems like guided missile control required the ability to abstract a problem through modeling and system identification to make the problem more manageable. As yet another method of managing testing and complexity, analog and digital computers were being developed concurrently with post-war automatic controllers. These computers provided the perfect platform on which theories could be easily and cheaply tested without requiring implementation on the physical system in question. However, such abstractions would tend to promote the separation of theory from system implementation furthering the rift between practice and theory.

By the end of World War II control engineers had realized that automatic control could be viewed from a more general perspective than the hands-on approach practiced previously. Instead of fluid flows and motor torques, problems could be framed as signal manipulation within a generic dynamic system. Prior to this discovery, techniques to analyze control systems were highly application-specific. For example, process control engineers used terminology and diagrams specific to their field, referring to valves and tanks as shown in Figure 6.

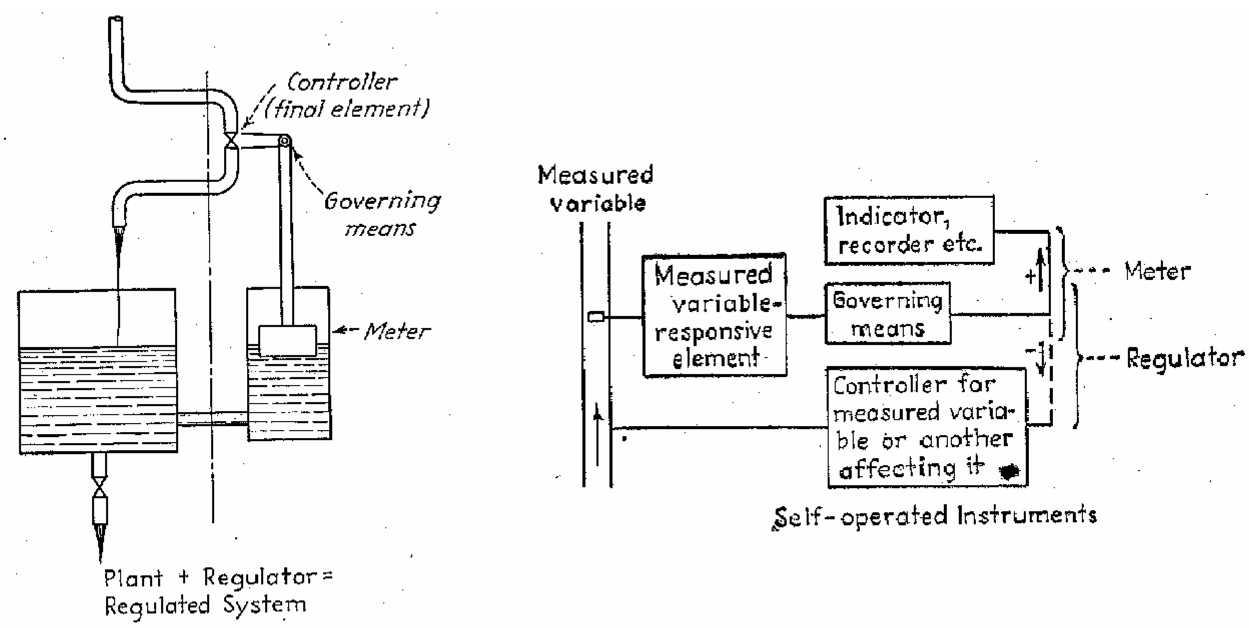

Figure 6 Generic regulated systems as described in Smith's 1944 textbook on automatic control.[68]

[68] Smith, 5-6.

Even the more generic block diagram at right still referenced the flow control seen in the more specific diagram at left by drawing the measured variable as a flow. In a move away from such practices, textbooks written during and after the war further abstracted systems by using equivalent circuits and block diagrams as seen in Figure 7. Equivalent circuits had been used previously in communication engineering to provide a more abstract means of designing filters. By associating each physical component with an electrical equivalent that behaved similarly, circuit tools (or the circuits themselves) could be used to analyze the system more simply than dealing with a more difficult mechanical model. Abstracting even further, block diagrams modeled each component by a mathematical input/output relationship. These diagrams could then be simplified by moving and merging the blocks in an algebraic manner.

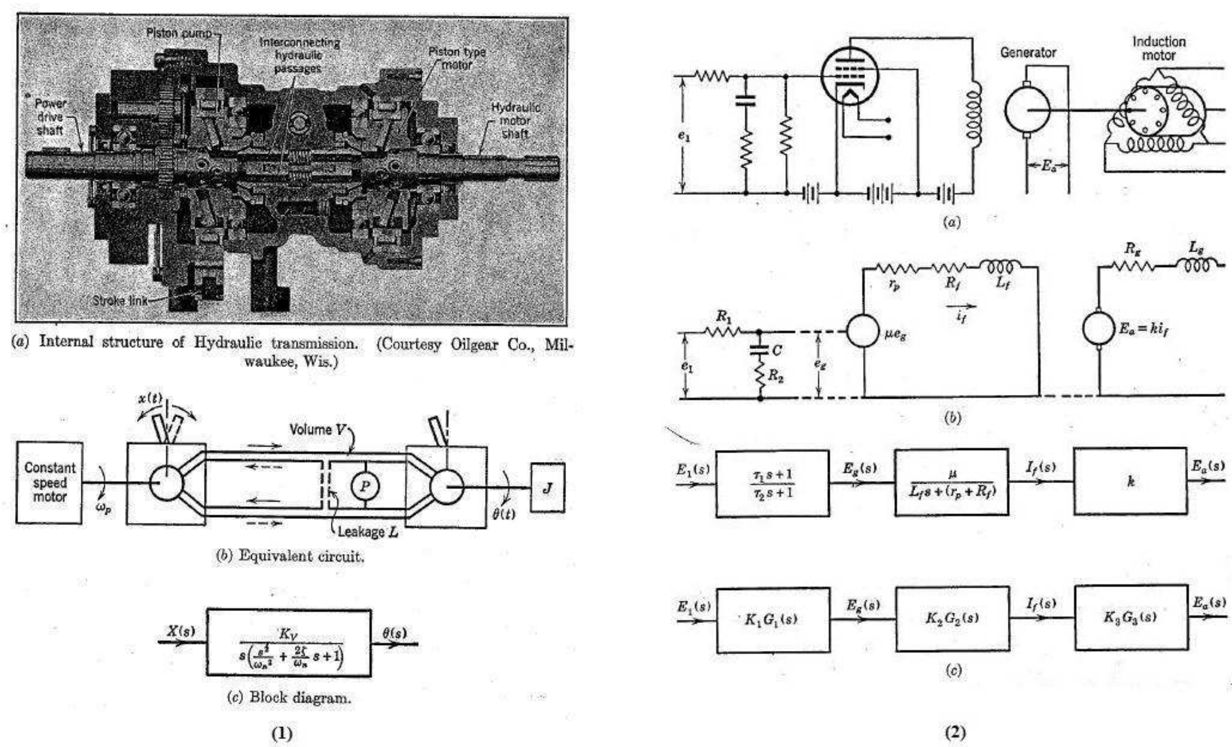

Figure 7 Equivalent circuit and block diagram methods from Brown and Campbell in 1948.[69]

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[69] Gordon S. Brown and Donald P. Campbell, *Principles of Servomechanisms: Dynamics and Synthesis of Closed-Loop Control Systems* (New York: John Wiley & Sons, Inc., 1948), 112,137.

The language and diagrams used to analyze automatic control systems were moving the subject away from physical systems and towards systems simply described by an evolving meta-language. Mr. W. H. P. Leslie summed up this new language while discussing the difficulties in reading papers from different branches of automatic control:

> I disagree with certain speakers about terminology being a difficulty when reading papers on other branches of this subject. Where a paper is properly illustrated by the universal language of diagrams and mathematics, the terminology used is obvious and does not cause difficulty.[70]

But block diagrams and mathematical abstractions allowed more than simple aids in communication. Bissell argues that modeling made automatic control more accessible by hiding the more complex mathematics.[71] However, perhaps more importantly, automatic control was made more accessible in that it was now a problem which could be solved on paper instead of in the laboratory. Through abstract modeling, automatic control no longer required a physical system to study new developments in stability, optimization, robustness, adaptability, among other properties of control systems.

While mathematical modeling abstracted problems away from their physical representation, modern computing would take the story the rest of the way. Many histories have been written on the evolution of computing, but for the purposes of automatic control, modern computing originated with Charles Babbage in the 19th century and his description of an "analytical machine" capable of performing any calculation a user required.[72] This description was first realized by the Harvard Mark I, and more importantly the Electronic Numerical Integrator and Computer (ENIAC) during World War II. In an interesting parallel to the work on automatic control during the war, the ENIAC was built to help solve fire control problems by

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70 "Proceedings at the Convention on Automatic Regulators and Servo Mechanisms."
71 C. C. Bissell, "Models and Black Boxes: Mathematics as an Enabling Technology in the History of Communication and Control Engineering," *Revue d'Histoire des Sciences* (forthcoming).
72 See Martin Campbell-Kelly and William Aspray, *Computer: A History of the Information Machine*, 2nd ed., The Sloan Technology Series (Boulder, Colo.: Westview Press, 2004). and Paul E. Ceruzzi, *A History of Modern Computing*, 2nd ed. (Cambridge, Mass.: The MIT Press, 2003). for a more detailed history of modern computing.

computing targeting trajectories. Similar to automatic control, automatic computing removed humans from the loop in order to improve accuracy, time to completion, and cost.

While digital computers such as the ENIAC were first built during World War II to perform tedious calculations, analog computers had an early history in automatic control as simulators. As a precursor to the analog computer, George Philbrick built hardware equivalent circuits of processes in the 1930s to simulate and test process controllers.[73] Additionally, servomechanisms were used in some of the earliest analog computers such as Vannevar Bush's differential analyzer which were later used to test fire control algorithms during the war. By the late 1950s digital computing was becoming more popular and finding uses other than simply crunching numbers. George West advocated using digital computers as an integral part in the design process of control systems to reduce design cost.

> Instead of building system hardware and modifying it, he [the control engineer] conducts his experiment on a computational model of the system. The computational model is usually much cheaper to modify than actual hardware.[74]

Computers were an obvious choice as a simple platform on which to test new control systems. By programming the computer with the system model, which could be made as simple or complex as required, the computer became the system implementation and therefore the end-point of theory development.

Thus, the development of new tools such as modeling and computers widened "the gap" by removing a need for practical implementations on real equipment. At the first IFAC conference in 1960, Rudy Kalman stated in his paper "On the General Theory of Control Systems":

> …In its methodology the pure theory of communication and control closely resembles mathematics, rather than physics; however, it is not a branch of mathematics because at present

[73] Bennett, *A History of Control Engineering 1930-1955*, 55.
[74] George P. West, "The Role of Computers in Analysis and Design of Control Systems," *IRE Transactions on Automatic Control* 5, no. 1 (1958): 65.

> we cannot (yet?) disregard questions of physical realizability in the study of mathematical models.[75]

Kalman certainly pictured a day where the study of automatic control became completely separated from the physical systems being controlled.

Despite automatic control's strong foothold in practice during the 1930s, theory had become the primary research effort in automatic control by the early 1960s. Certainly, the individuals involved in D-2 and Division 7 during World War II prompted some of this change by approaching their task of fire control from a mathematical perspective for the first time. However, most of the emphasis on theory came after the war. Researchers built a base of knowledge in automatic control from their textbooks and papers, many of which presented the design of theories instead of mechanisms. In addition, educators prompted the study of more mathematics and science so that students could take new and more creative directions in research through a more thorough understanding of the fundamentals. But this shift was not without its critics. In fact, great efforts were made to appeal to industrial members in large control societies and many early researchers expressed a desire for the field to remain connected to its roots in practice. Unfortunately for many of these critics, theory had become more important in developing techniques to manage the more complex systems that were being studied after the war. Additionally, modeling and computing allowed researchers to avoid the laboratory entirely by testing their theories on a model instead of a real system. Indeed, while this progression of events defined "the gap" in automatic control, it was the researchers themselves who influenced the shift of their subject from practice to theory.

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[75] Kalman, 481. It is quite interesting to note George Axelby's recollection of a letter written to him by Rudy Kalman in Abramovitch and Franklin: 34. Kalman congratulated Axelby for writing an editorial exposing "the gap" between theory and practice in automatic control.

Works Cited

The 2nd Feedback Control Systems Conference. ed. G. S. Axelby. Atlantic City, New Jersey: American Institute of Electrical Engineers, 1954.

Abramovitch, Daniel Y., and Gene F. Franklin. "Fifty Years in Control: The Story of the IEEE Control Systems Society." *IEEE Control Systems Magazine* 24, no. 6 (2004): 19-36.

American Control Conference 2004. 2004. Accessed. Available from http://www.mie.uiuc.edu/acc2004/.

Astrom, K. J., and T. Hagglund. "PID Control." In *The Control Handbook*, ed. W. S. Levine. Boca Raton, Florida: CRC Press, 1996.

Automatic and Manual Control: Papers Contributed to the Conference at Cranfield, 1951. London: Butterworths Scientific Publications, 1952.

"Automatic Control and the IRE." *IRE Transactions on Automatic Control* 1, no. 1 (1956): 1-2.

"Automatic-Control Terms." *Mechanical Engineering* 68, no. 2 (1946): 134-138.

Axelby, George. "Image or Mirage?" *IRE Transactions on Automatic Control* 7, no. 4 (1962): 1.

________. "The Gap - Form and Future." *IEEE Transactions on Automatic Control* 9, no. 2 (1964): 125-6.

Bennett, Stuart. "The Emergence of a Discipline: Automatic Control 1940-1960." *Automatica* 12, no. 2 (1976): 113-121.

________. "Nicolas Minorsky and the Automatic Steering of Ships." *IEEE Control Systems Magazine* 4, no. 4 (1984): 10-15.

________. "Development of the PID Controller." *IEEE Control Systems Magazine* 13, no. 6 (1993): 58-62,64-5.

________. *A History of Control Engineering 1930-1955*. Vol. 47. 47 vols. IEE Control Engineering Series, ed. P. J. Antsaklis, D. P. Atherton and K. Warwick. London: Peter Peregrinus Ltd, 1993.

Bissell, C. C. "Spreading the Word: Aspects of the Evolution of the Language of Measurement and Control." *Measurement and Control* 27, no. 5 (1994): 149-155.

________. "Models and Black Boxes: Mathematics as an Enabling Technology in the History of Communication and Control Engineering." *Revue d'Histoire des Sciences* (forthcoming).

Bode, Hendrick W. *Network Analysis and Feedback Amplifier Design* The Bell Telephone Laboratories Series. Princeton, New Jersey: D. Van Nostrand Company, Inc., 1945.

Brown, Gordon S. "Feed-Back System Engineering - a Challenging Educational Objective." In *Automatic and Manual Control Conference*, 5-12. Cranfield, England: Butterworths Scientific Publications, 1951.

________. "Integration Versus Options in Electrical Engineering." *Electrical Engineering* 72, no. 7 (1953): 595-597.

________. "Educating Electrical Engineers to Exploit Science." *Electrical Engineering* 74, no. 2 (1955): 110-115.

Brown, Gordon S., and Donald P. Campbell. *Principles of Servomechanisms: Dynamics and Synthesis of Closed-Loop Control Systems*. New York: John Wiley & Sons, Inc., 1948.

Bush, Vannevar. *Science: The Endless Frontier*. Washington, DC: United States Government Printing Office, 1945.

Campbell-Kelly, Martin, and William Aspray. *Computer: A History of the Information Machine*. 2nd ed. The Sloan Technology Series. Boulder, Colo.: Westview Press, 2004.

Ceruzzi, Paul E. *A History of Modern Computing*. 2nd ed. Cambridge, Mass.: The MIT Press, 2003.

Chestnut, Harold. "Bridging the Gap in Control - Status 1965." *IEEE Transactions on Automatic Control* 10, no. 2 (1965): 125-126.

"Closing Remarks." *IRE Transactions on Automatic Control* 5, no. 1 (1958): 70-72.

Franklin, Gene F., J. David Powell, and Abbas Emami-Naeini. *Feedback Control of Dynamic Systems*. 3rd ed. Reading, Massachusetts: Addison-Wesley Publishing Company, 1994.

Frequency Response Symposium. New York City: The American Society of Mechanical Engineers, 1953.

Hazen, H. L. "Design and Test of High-Performance Servo-Mechanism." *Journal of The Franklin Institute* 218, no. 5 (1934): 543-580.

________. "Theory of Servo-Mechanisms." *Journal of The Franklin Institute* 218, no. 3 (1934): 279-331.

Ivanoff, A. "Theoretical Foundations of the Automatic Regulation of Temperature." *Institute of Fuel -- Journal* 7, no. 33 (1934): 117-130.

James, Hubert M., Nathaniel B. Nichols, and Ralph S. Phillips. *Theory of Servomechanisms*. Vol. 25. 28 vols. Massachusetts Institute of Technology Radiation Laboratory Series, ed. Louis N. Ridenour. New York: McGraw-Hill Book Company, Inc., 1947.

Kalman, R. E. "On the General Theory of Control Systems." In *First International Congress of the International Federation of Automatic Control*, ed. J. F. Coales, 1, 481-92. Moscow, 1960.

Kline, Ronald. "World War II: A Watershed in Electrical Engineering Education." *IEEE Technology and Society Magazine* 13, no. 2 (1994): 17-23.

________. "The Paradox of "Engineering Science" - a Cold War Debated About Education in the U.S." *IEEE Technology and Society Magazine* 19, no. 3 (2000): 19-25.

MacColl, LeRoy A. *Fundamental Theory of Servomechanisms*. New York: D. Van Nostrand Company, Inc., 1945.

Mindell, David A. "Engineers, Psychologists, and Administrators: Control Systems Research in Wartime, 1940-45." *IEEE Control Systems Magazine* 15, no. 4 (1995): 91-99.

________. "Opening Black's Box: Rethinking Feedback's Myth of Origin." *Technology and Culture* 41, no. 3 (2000): 405-34.

________. *Between Human and Machine: Feedback, Control, and Computing before Cybernetics*. Baltimore, Maryland: The Johns Hopkins University Press, 2002.

Oldenburger, R. "IFAC, from Idea to Birth." *Automatica* 5, no. 6 (1969): 697-703.

"Open Panel Discussion." *IRE Transactions on Automatic Control* 5, no. 1 (1958): 67-70.

Ott, P. W. "Usefulness of Mathematics to Engineers." *General Electric Review* 38, no. 3 (1935): 135-140.

"Proceedings at the Convention on Automatic Regulators and Servo Mechanisms." *The Journal of the Institution of Electrical Engineers, Part IIA* 94, no. 1 (1947).

Seely, Bruce. "Research, Engineering, and Science in American Engineering Colleges: 1900-1960." *Technology and Culture* 34, no. 2 (1993): 344-386.

Smith, Ed Sinclair. *Automatic Control Engineering*. New York: McGraw-Hill Book Company, Inc., 1944.

"Theory, Practice or Instruction?" *IRE Transactions on Automatic Control* 2, no. 1 (1957): 2.

Ward, J. "A Survey of Control Research in U. S. Engineering Schools." *IRE Transactions on Automatic Control* 7, no. 5 (1962): 126-129.

West, George P. "The Role of Computers in Analysis and Design of Control Systems." *IRE Transactions on Automatic Control* 5, no. 1 (1958): 65.