Interview with Professor H.M. Paynter

Editor's note: The Magazine is proud to present a special feature this month. This chat with Professor H. M. Paynter of M.I.T. was constructed by Mark L. Nagurka, Associate Professor of Mechnical Engineering at Carnegie-Mellon University and graduate of M.I.T.

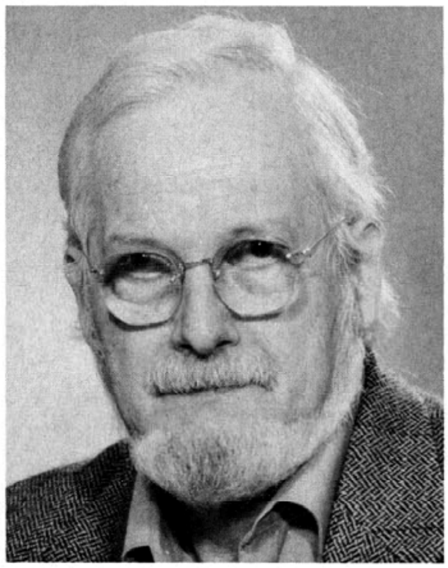
Professor Henry M. ("Hank") Paynter was born in Evanston, IL, in 1923 and received his S.B. (1944), S.M. (1949), and Sc.D. (1951) degrees, all from the Massachusetts Institute of Technology. From 1944-1946 he worked for Puget Power in Seattle, returning to M.I.T. for graduate study and teaching. He taught hydraulics, hydrology, and hydro power subjects in the Civil Engineering Department from 1946 to 1954. His research, which addressed fluid dynamics and control and power system governing, led to the formation with G.A. Philbrick of the Pi-Square Engineering Company. This company was devoted to electronic analog computing, and in his work Dr. Paynter collaborated closely with the Woodward Governor Company on hydro plant control.

In 1954, Dr. Paynter transferred to the Department of Mechanical Engineering at M.I.T., where he worked on a half-time basis until 1959, and then full time until his retirement in 1985. He is currently Professor of Mechanical Engineering Emeritus and Senior Lecturer at M.I.T.

Sometime Sigma Xi National Lecturer and an ASME Distinguished Lecturer, he has also received the Alfred Noble Prize of the Joint Engineering Societies (1953), the ASME Oldenburger Medal (1979), and the ACC Education Award (1984). He is a Fellow of ASME and a Life Member of ASCE.

Besides pioneering work in analog and digital computing, Dr. Paynter is known worldwide as the inventor of bond graphs. He has published on a wide variety of subjects in more than 100 papers, patents, articles, and book chapters, as well as several books.

In what follows, Prof. Paynter supplies insight on several topics for which he has become known throughout his career.



Professor Henry M. Paynter

CSM: When and how did you first become interested in computers?

Paynter: Upon graduating from M.I.T. in 1944, I went to work for Puget Power in Seattle. Many skilled people were absent in war-time service, so my responsibilities were unusually broad, simultaneously involving civil, mechanical, and electrical engineering. One day, my top boss, George Quinan, called me in to ask if I had ever noticed the Accounting Department's machines on the sixth floor of the Electric Building, two floors below where we worked. These were IBM Hollerith machines, capable of executing the four basic arithmetic operations (+, -, x, /) in four-digit decimal fields in IBM cards. He was convinced that these machines could solve some of our engineering problems, so I spent one year proving it. IBM technical people from New York came to visit to see what we were doing with digital computation, including complex number calculations. I then returned to M.I.T. in a euphoric state, hoping to build a Turing machine!

It is interesting to note in retrospect that my machine computations of load dispatching and network load flows led in turn to the pioneering applications of computers by the Northwest Power Pool and the Bonneville Power Administration.

CSM: How did you first get involved with analog computers ?

Paynter: Fortunately, my faculty advisors brought me down to earth. Back at Puget Power I had worked with hydroelectric plants, where I encountered fluid transients and speed governing problems [See Fig. 1]. Transients in this system involve a nonminimum phase system; upon opening the turbine wicket gates, the pressure drops. This results in a momentary decrease, rather than increase, in power. After an inertial time constant, the power ultimately increases. I set about to analyze the control problem under this critical adverse phasing.

At this point, an EE pal (George King, who later went on to develop General Precision's kinescope) and I decided to build an electronic analog model of a complete hydro plant as a joint Masters thesis. This semipassive model used Dellenbaugh artificial transmission lines for both the fluid penstock and the electrical transmission line. The turbine and generator rotating machines, together with their controls, were constructed from vacuum-tube-driven active circuits. The alternator actually produced 60 Hz AC!

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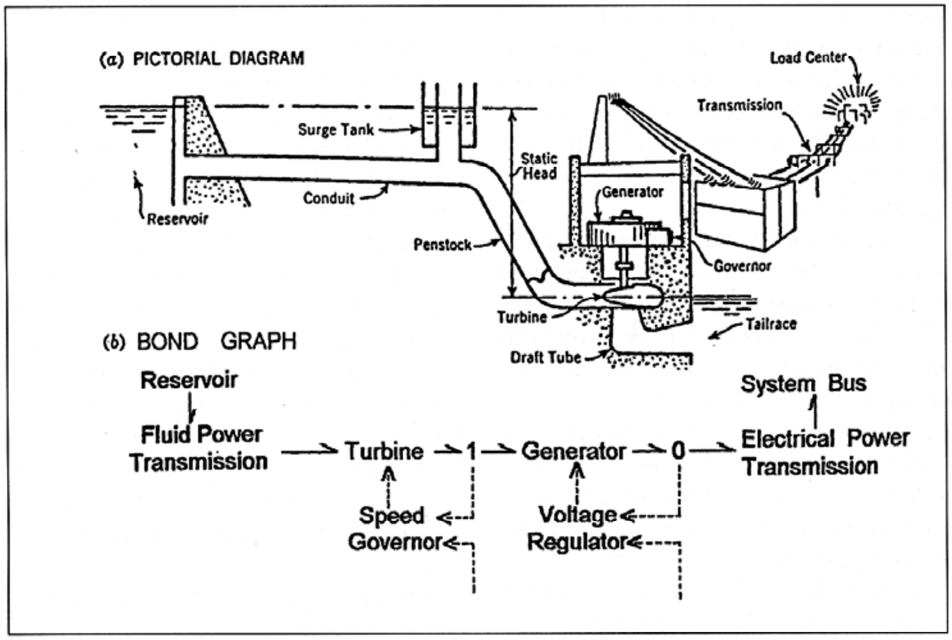


Fig. 1. Hydroelectric plant.

CSM: Could you tell us about your association with George Philbrick?

Paynter: This joint thesis I spoke of was stillborn, because in 1947 I was introduced to George Philbrick by John Hrones, who felt that as natural soul brothers we should join forces and that I shouldn't waste time by redoing what George had already done with his K3 "little black boxes," the veritable "Philbricks." Thus began a close association with George and his companies which lasted until his death in 1974. As a result, I early became the proud custodian of an assortment of linear (A, C, J, etc.) and nonlinear (B, Z, MU, etc.) GAP/R electronic analog computOr [sic] components. These were used artfully to complete a 1949 SM thesis ("The Stability of Surge Tanks") and a 1951 Sc.D. thesis ("Transient Analysis Of Certain Nonlinear Problems in Hydroelectric Plants").

CSM: This, then, was a "differential analyzer"?

Paynter: Yes, this electronic analog computer was also called an electronic differential analyzer [EDA], after its parent, the earlier mechanical differential analyzer [MDA] [See Fig. 2]. I have recounted the evolution of both these devices in an article published in this *Magazine* [vol. 9, pp. 3-8, Dec. 1989] which was based on a keynote address to the Pittsburgh 1989 ACC. That article made the point that an active mathematical instrument results from unloading the passive signal power elements through use of isolating power amplifiers [see Fig. 2].

I was initially exposed to the Bush MDA on my first visit to M.I.T. as a high school student in 1940; I only encountered the second-generation Rockefeller DA on my return to M.I.T. after the war. The cited *Control Systems Magazine* article does not explain my strong predisposition to Philbrickian ideas but my remarks above should make this plain.

CSM: What, in your opinion, is the future of computation (analog versus digital)?

Paynter: Historically, it was never analog versus digital, but rather analog-and-digital computations, as used in the hybrid computers of the 1960s. At M.I.T. we built hybrid computers, but by the end of the 1960s we recognized that these machines did not make sense. So now I do not see any reason for general-purpose analog computation to be revived. Of course the analog art, itself, remains immortalized in the modern solid-state OpAmp. But after 1974, with the introduction of the Intel 8088 and with logic burned into EPROMs, it finally became possible to do real-time digital simulation. Personally, I had a lot of experience with small DEC machines containing the LSI-11, an early microprocessor which was only bested by the later Intel 80286. It was very clear to some of us that a digital revolution had occurred in the 1970's leading to our modern personal computers. Apple II became Mac shortly after IBM launched the PC. Now with the advent of massive parallelism, it is possible with modern chips to do digitally anything that you could do with analog simulation. But it is interesting to note that with the Cray and the Thinking Machine, the disciplined approach of minimizing the number of computing operations has been totally supplanted; one can just buy more and more powerful computers and use brute force approaches. Yet many people today do not realize the speed and power we had using early analog computers. In the late 1950s and early 1960s we could do parametric optimization at 10^6 *solutions*/second. (This is much better than obtainable using an 486-class machine with efficient software.) Hybrid computers slowed the speed because of the interfacing problems. Yet in terms of future massive parallelism, the precision level will be much higher than anything we had in the analog world.

CSM: Could you now tell us about your involvement with bond graphs?

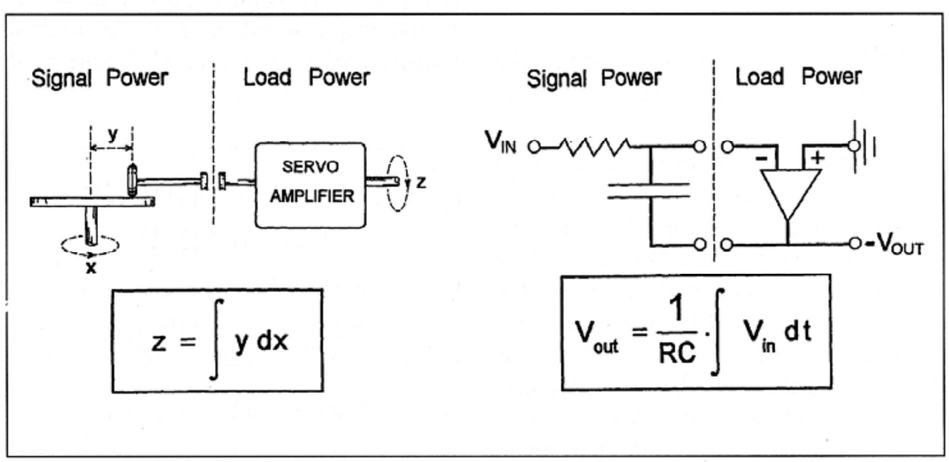


Fig. 2. DA integrators: MDA [left]; EDA [right].

Paynter: My special training and experience in hydroelectric power actually forced certain insights upon me [see Fig. 1], most particularly an awareness of the strong analogies existing between: transmission (fluid pipes and electric lines); transduction (turbines and generators); and control (speed governors and voltage regulators). When these analogous devices were reduced to equations for computer simulation, distinctions became completely blurred. Common sense dictated that such compelling analogies implied some underlying common generalization from which other beneficial specializations might ensue.

In the 1950s my professional focus spanned hydroelectric plants and industrial processes, analog and digital computing, and nonlinear dynamics and control. These activities embraced civil, mechanical, electrical, and electronic engineering. It was impossible for me to avoid becoming a systems engineer and practicing generalist. So after spending eight years, 1946 to 1954, in the M.I.T. Civil Engineering Dept., I then moved to Mechanical Engineering to establish the first systems engineering subjects at M.I.T. It was this specific task which five years later produced bond graphs, drawing naturally upon all the attitudes and experience indicated above.

On April 24, 1959, when I was about to give a seminar lecture at Case Institute (now Case Western) on "Interconnected Engineering Systems," the idea of 0, 1-junctions representing the two Kirchhoff laws was planted in my head. A hydro plant could now be represented by the bond graph [of Fig. 1]. Moreover, the very symbols (0,1) for KCL and KVL, respectively, were employed for these power-conserving multiports to make directly evident the correspondence between circuit duality and logical duality.

CSM: Could you describe further the other analogous components?

Paynter: The hydro+electric plant [of Fig. 1] necessarily requires the two energy-converting transduction multiports: the hydraulic turbine converting fluid power to rotary shaft power and the electrical generator which in turn converts this shaft power to polyphase AC power. It is noteworthy that the strict analogy between these two devices holds right down to the local field-continuum level. Thus the fluid vorticity corresponds precisely to the current density and the fluid circulation to the magnetizing current, so that even the turbine blades correspond to the generator pole pieces! In dynamic consequence, both these highly-efficient components become 2-port gyrators with parasitic losses.

Also, as I mentioned, the hydro plant requires efficient fluid and electrical power transmission elements. These wavelike distributed lines are best analyzed and simulated in terms of wave-scattering variables, whose forewaves and backwaves go back to the Bernoullis. But when coupled to the other components, the need to represent such differential-difference equations requires creative approaches to analysis and simulation.

Finally, the turbine and generator each require highly-reliable regulation and control components. The differential surge tank shown serves as a passive pressure regulator, while the speed governor and voltage regulator are required to start up and shut down the units, as well as to synchronize them with the system and to help control the frequency and real/reactive power flows throughout the interconnected system.

CSM: How do the wave-scattering variables relate to electric circuitry and to bond graphs?

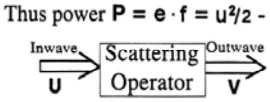
Paynter: Scattering matrices and their variables entered circuit theory primarily as a result of the forced and rapid development of microwaves and radar during World War II, when physicists worked closely with electrical and electronic engineers. But in both acoustics and optics such variables had already been in use for at least two centuries.

These alternative power pairs may be quite simply related to the more familiar (e,f) pairs (e.g., voltage-current; force-velocity; torque-speed; etc.) by a linear dual transformation [see Fig. 3]. These dual transforms simply reflect the familiar two descriptions of an hyperbola.

$$\begin{bmatrix} e \\ f \end{bmatrix} = \mathbb{H}\begin{bmatrix} u \\ v \end{bmatrix}; \quad \begin{bmatrix} u \\ v \end{bmatrix} = \mathbb{H}\begin{bmatrix} e \\ f \end{bmatrix};$$

with $\mathbb{H} \equiv (1/\sqrt{2})\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$

Thus power $\mathbf{P} = \mathbf{e} \cdot \mathbf{f} = \mathbf{u}^2/2 - \mathbf{v}^2/2$



$$q * X = \mathbf{F}(X,U); \quad V = \mathbf{G}(X,U)$$

Fig. 3. Wave-scatter operators.

The state-equations for any given multiport element or system are written as indicated to account for the fact that both lumped and distributed components may be incorporated in the model. Thus q represents at the same time both s corresponding to the time derivative operator and $z = \exp(Ts)$ corresponding to the time advance operator. My own use of wave-scattering methods came via the transmission line problems mentioned previously. Thus the relation to conservation laws and scattering techniques was quite natural while the connection with causality became readily apparent through analog computation.

CSM: Should such modeling be taught, and if so how, in the undergraduate controls courses?

Paynter: Modeling should definitely be taught, and taught early, not necessarily in the context of controls. Yet it is extremely important for students to see that theory actually works! Laboratory experiences and physical demonstrations give explicit confirmation of the value of modeling, but much of the educational process today does not involve the student in personally "closing the loop." Each student needs to make manipulative experiments as necessary reinforcement. In electrical engineering programs this often occurs in the sophomore level circuits lab but in many mechanical engineering programs, this vital experience is postponed until the junior and/or senior years. In my opinion, this is too late; the experience should occur in the freshman and sophomore years. It does not matter in what subject; it only matters that models be made, and then confirmed or invalidated, all based on actual personal experience.

CSM: Where do you see the next big push in sensors and actuators?

Paynter: I see a push toward ever-smarter instruments and sensors, with more and more of the intelligence built right into the "front end." But just as the MDA and EDA [of Fig. 2], when treated as active instruments, required the isolation of the primary sensors from the driven load through appropriate power amplifiers, the relations between information-bearing signals and the power-level variables must become better understood.

The analogy between Heisenberg uncertainty in quantum physics and finite word length in digital computation can even now be appreciated in terms of the directly corresponding Fourier transform properties. Yet adequate attention must be paid to the "stochastic-skew" engendered by the least-significant-bits (LSBs) which must necessarily circulate in all such nonanalytic computer models as well as in physical plants under digital control. Furthermore, any attempt to enforce known symmetry-conservation constraints must necessarily "melt" the canonical conjugate, just as "freezing" energy or momentum "melts" time or position, respectively.

CSM: In conclusion, is there anything else you would like to say to the controls community ?

Paynter: For two decades I have been obsessed by the notion that the next century will become the Chemical Century, just as our own 1900s have been the Electronic Century. People will ultimately comprehend and understand that the living-state involves a richly-structured integrated dynamic system. For even the very simplest unicellular organism contains material and energetic control mechanisms vastly more complex and elaborate than humankind has yet designed or even imagined.

But future knowledge must — and will — build upon already existing engineering concepts, like amplification, feedback, control, information, etc., at least as much as upon the more traditional concepts of physics and chemistry. Indeed, because "Nature knows no names" or "*la naturalesa no nota nombres*," such historical nominalism has stood directly athwart more complete understanding. Yet, in fairness, as long as wave mechanics, electrochemistry, and biochemistry lie outside the conventional engineering purview, progress here will be unduly slowed.

Calendar

(continued from page 66)

1994. Contact: Prof. Y. Sunahara, The Mita Press, Kyota Annex, Asahi Karasuma Building-4F 381, Shimizu-cho, Karasuma-East, Takeya, Nakagyo-ku, Kyoto 604, Japan. Phone: (+81)+75-211-1055. Fax: (+81) +75-211-1135.

Third International Conference on Automation, Robotics, and Computer Vision, November 8-11, 1994, Singapore. Contact: Prof. N. Sundararajan, c/o UCARCV'94 Conference Secretariat, Institution of Engineers, Singapore, 70 Bukit Tinggi Road, Singapore 1128, Republic of Singapore. Phone: (65) 469 5000. Fax: (65) 467 1108. Telex: RS 22992 IESIN. Email: ensundara@ntu-vax.ntu.ac.sg.

1994 Conference on Decision and Control, December 14-16, 1994, Buena Vista Palace, Orlando, FL. Contact: Dr.Michael K. Masten, 33rd CDC, Texas Instruments, 2309 Northcrest Plano, TX 75075. Phone: (214) 462-3433. Fax: (214) 462-3126. Email: m.masten @ieee.org.

NAFIPS/IFIS/NASA '94: International Joint Conference of The North American Fuzzy Information Processing Society Biannual Conference, The Industrial Fuzzy Control and Intelligent Systems Conference, and The NASA Joint Technology Workshop on Neural Networks and Fuzzy Logic, San Antonio, TX, December 18-20, 1994. Contact: Uthra Venkatraman, CFLISR, Texas A&M University, College Station, TS 77843-3112. Phone: (409) 845-1870. Fax: (409) 847-8578. Email: nafips94@cs.tamu.edu.

First International Conference on Electronics, Circuits and Systems ICECSS '94, Nile Hilton, Cairo, Egypt, December 19-22, 1994. General Chair, Dr. Esmat A. Abdallah. Contact: Technical Program Chair Dr. Mohammed Ismail, Dept. of Electrical Engineering, The Ohio State University, 2015 Neil Ave., Columbus, OH 43210-1272, USA. Phone: (614) 292-2572; fax: (614) 292-7596.

1995 Listings

9th Power Plant Dynamics, Control, and Testing Symposium, Knoxville, TN, May 24-26, 1995. Submit 3 copies of 600 word summary (+1 page allowed for illustrations) by Sept. 2, 1994, to: B.R. Upadhyaya, Nuclear Engineering Dept., Pasqua Engineering Building, The University of Tennessee, 1004 Estabrook Road, Knoxville, TN 37996-2300. Phone: (615) 974-5048. Fax: (615)974-0668.

1995 IEEE Singapore International Conference on Intelligent Control and Instrumentation, Singapore, July 3-7, 1995. Contact: General Chair, Shawn Toumodge, email: eshawn@ntu-vax.ntu.ac.sg or Technical Chairmen: T.H. Lee, email: eleleth@nusvm.bitnet or N. Sundararajan, email: ensundara@ntu-vax.ntu.ac.sg, or SICICI'95 Secretary, IEEE Singapore Section, #59D Science Park Drive, Fleming, Singapore 0511. Fax: (65) 773-1142.

Third European Control Conference (ECC '95), Rome, Italy, September 5-8, 1995. Manuscript submission deadline: October 1, 1994. Submit 4 copies with address, email, fax, and phone of corresponding author to: ECC 95 Secretariat, Prof. Alessandro De Luca, Dipartimento di Informatica e Sistemistica, Universita egli Studi di Roma "La Sapienza," Via Eudossiana 18, 00184 Roma, Italy. Email: ecc95@itcaspur.caspur.it.