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John Hugh Westcott was a leader in the revolution of the subject of automatic control that took place in the late 1950s and early 1960s. Appointed to a lectureship in the early 1950s, he rapidly created, and inspired, a group that successfully bridged the transition from classical to 'modern' control theory. He supported this activity via a large number of research grants garnered from industry by his persuasive advocacy of the benefits to be gained from modern developments. To encourage transfer of these developments to industry and elsewhere, he motivated and directed several large research projects in areas such as the cold rolling of steel and the control of the UK economy.

Early life

Westcott was born on 3 November 1920 in Chiswick, London W4, where his parents, John Stanley Westcott and Margaret Elizabeth Westcott (*née* Bass), both from Buckinghamshire, then lived. His only sibling was a younger sister, Margaret. The family moved to Southfields, London SW18, in 1930. Westcott's father was an inventive engineer and a member of the Institution of Mechanical Engineers; he specialized in refrigeration. A local friend, A. E. K. Morgan, an electrical engineer and the father of Westcott's future wife, constructed wireless sets in his home workshop; this enthused the teenaged Westcott, who subsequently, with Morgan's assistance, built many short-wave radios himself and, as a radio amateur, spent many nights communicating with similar enthusiasts, to the detriment of his school studies.

Westcott received his early education at Chiswick Primary School, Strand-on-the-Green, and moved to Wandsworth Secondary School in 1931. He was good at physics and, after a hiccup caused by his amateur radio activities, obtained a first-class matriculation pass. This gained him a scholarship from the London County Council to attend university. The

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scholarship was postponed for a year because his father believed in an apprenticeship for an engineer. Westcott was duly apprenticed to the British Thomson Houston (BTH) Company as a engineering apprentice with a starting wage of 2.55 pence an hour (a buying power of approximately £0.67 an hour in today's currency). A year later, in 1938, he took up his university scholarship and commenced a night-school course in electrical engineering at Battersea Polytechnic. After two years he was evacuated to Rugby, the location of the BTH factory, where he completed his final year of the degree course in 1941 as an external student of London University.

Westcott's subsequent work in BTH was influenced by the outbreak in 1939 of World War II. In 1942, after a stint in the research laboratories working on a temperamental magnetometer, devised by P. M. S. (later Lord) Blackett FRS (PRS 1965–70) for detecting submarines, Westcott was seconded, as a fully paid employee of BTH, to the Air Defence Research & Development Establishment (ARDE) in the south of England. Here he worked with a group adapting 10 cm radar for coastal gunnery, a particular concern being the fast and powerful German E-boats. Later that year, ARDE was transferred to Malvern to avoid the danger of attack. Westcott followed early in 1943, having obtained promotion to scientific staff. There he became one of a select group of three, all in their twenties, given full responsibility for the research, development and production of 3 cm radar that could direct coastal gun fire with finer discrimination, in range and azimuth, than that obtainable with the then widely employed 10 cm radar. One of the members of the team later became the founder of Tektronix. The project was highly successful and 3 cm radar was employed, *inter alia*, in June 1944 to count ships returning from the invasion beaches. After the surrender of Japan in September 1945, the establishment emptied with remarkable speed and, in October 1945, Westcott accepted a job with the control commission for Germany but found that the high-voltage direct-current transmission equipment that he was instructed to transfer to the UK had already been spirited away to the Soviet Union. His replacement job, participation in politico-economic negotiations between the four occupying powers, was not to his liking although he benefited from some educative discussions on the economic effects of reparations with Professor Alexander (later Sir Alec) Cairncross, who was then on the Reparations Commission. Westcott commented that these discussions 'represented a touch of sanity during a bizarre period'.

Westcott's wartime experience in auto-following radar stirred his interest in automatic control and, in October 1946, he registered for a PhD at Imperial College, London, under Professor Willis (later Lord) Jackson (FRS 1953), aided by the award of a two-year Ferranti Scholarship of the Institution of Electrical Engineers. At that time there was no one at Imperial College qualified to supervise research in automatic control, so Jackson arranged for Westcott to spend three days a week at the GPO research station in Dollis Hill under H. J. Josephs, an expert in circuit analysis and Heaviside's operational calculus; during this period he became very familiar with the work of H. W. Bode, particularly his seminal book *Network analysis and feedback amplifier design* (Bode 1945), expertise that later stood him in good stead. Early in 1948, Westcott pursued a long-held aim to spend some time at the Massachusetts Institute of Technology (MIT) and was offered by MIT one year's guest facilities. Supported by a minimal £500 Commonwealth Scholarship, Westcott sailed to the USA in September 1948 to spend a highly profitable year at MIT, interacting with Norbert Wiener and following courses by E. A. Guillemin (on circuit theory), Y. W. Lee (on Wiener's celebrated filtering theory) and G. C. Newton (on servomechanism theory). Wiener gave Westcott a draft of his forthcoming book *Cybernetics* (Wiener 1948), which Westcott read with great interest. Guillemin arranged for Westcott to meet Bode and Sidney Darlington at the Bell Laboratories in Murray Hill; Westcott, because of his familiarity with Bode's book, found the discussion with Bode particularly rewarding. The year at MIT had enabled Westcott to meet outstanding leaders in the fields of automatic control and information theory. He returned to the UK in 1949 to complete his PhD supported by a research studentship from the Royal Commission for the Exhibition of 1851.

The Ratio Club

After his return, Westcott was invited to join the Ratio Club because of his 'many very distinguished contributions to control engineering, including some of the earliest work on control under noisy conditions'. The Ratio Club was a gathering of physicists, engineers and neuroscientists founded by John Bates, a neurologist, to explore cybernetics. Ross Ashby, a member of the club and the author of *Design for a brain* (Ashby 1960), commented 'we have formed a Cybernetics group for discussion—no professors, and only young people allowed in'. The purpose of the membership criterion was to avoid restriction of discussion because of the 'strongly hierarchical nature of professional relationships at that time'. The club met monthly of an evening between 1949 and 1953 and less frequently in 1953–55. Its 21 members included Ross Ashby, Horace Barlow (FRS 1969), I. J. Good, Donald Mackay, Alan Turing (FRS 1951), Grey Walter, John Westcott and Philip Woodward. Meetings consisted of a talk followed by discussion; Westcott gave, *inter alia*, a talk on 'The logic of discrimination' and Turing on 'The chemical origin of biological form', or why leopard spots are as they are, a theory recently validated by the discovery of chemicals that guide the migration of cells in developing organisms. An illuminating account of the Ratio Club, *The Ratio Club: a hub of British cybernetics*, by Phil Husbands and Owen Holland, may be accessed at http://www.sussex.ac.uk/Users/philh/pubs/Ratio2.pdf. Shortly after his return to the UK, Westcott arranged for Norbert Wiener to visit Imperial College to give a lecture on cybernetics and also to attend a meeting of the Ratio Club.

Creation of the Control Group

Westcott completed his thesis in 1950 and was appointed a lecturer in the Department of Electrical Engineering, Imperial College, in the autumn of that year. He started a postgraduate course on feedback systems, which won support from the Department of Scientific and Industrial Research in 1956; he gained space for a postgraduate laboratory, devised appropriate experiments and supervised the construction of appropriate equipment, the most well known being a position control servomechanism. To obtain support for his research students, Westcott then sought and acquired some 22 research grants, largely from industry and research institutions. He was promoted to Reader in 1956 and to Professor in 1961, by which time he had appointed four further lecturers in the Control Group. In 1963 the Electrical Engineering Department moved to a new building in which the Control Group had a whole floor for its teaching and research activities. Mainly as a result of his own efforts, Westcott secured recognition in 1965 of the Control Group by the Science Research Council

Figure 1. John and Fay Westcott at the 9th World Congress of the International Federation of Automatic Control, Budapest, 1984.

as one of three 'centres of excellence' for UK control research, the other two being Cambridge, under Professor J. F. Coales (FRS 1970), and the University of Manchester Institute of Science and Technology, under Professor H. H. Rosenbrock (FRS 1976); Westcott had laid a strong foundation for control research at Imperial College.

Professional activities

Westcott was very active in professional societies. For a considerable period he was Chairman of the United Kingdom Automation Council, Vice-President of the Institute of Measurement and Control and Chairman of the Control and Automation Division of the Institute of Electrical Engineers. He was a founding father of the International Federation of Automatic Control (IFAC) in that he was one of the signatories, in Heidelberg, of the celebrated 'resolution for IFAC' that led shortly afterwards to the birth of this organization; he was subsequently a member of IFAC's executive council from 1969 until 1975 and Chairman of its Theory Committee; he participated in many of its subsequent activities (see figure 1). An IFAC colleague commented, 'In his talk [at an anniversary of the Heidelberg meeting] John recalled how the first personal contacts with Soviet Scientists helped develop mutual understanding. He modestly avoided mentioning how much he contributed to this understanding and, hence, to IFAC.'

During his early career as an academic, Westcott consulted extensively on such topics as dynamic positioning of a drill ship, process control, control of a superconducting homopolar motor, control of a radio telescope, control of distillation columns, analysis of seismic signals, control of drives for cold rolling of steel, an on-line real-time programming language, and dynamic optimization; these consultancies focused his attention on important industrial problems that later influenced research directions of the Control Group. One of his earliest consultancies, and perhaps the most formative, was for Royal Dutch Shell together with Dr Ing. J. M. L. Janssen.

In 1958 Westcott directed some of his considerable entrepreneurial energy to the creation of a commercial company, Feedback Limited, that in its early years exploited the excellent teaching experiments that Westcott and his colleague Dr Peter Blackman had developed for the control teaching laboratories. This company was successful and sold teaching equipment to universities and colleges worldwide. It grew to manufacture a wide range of products such as laboratory test instruments, computer peripherals and communications equipment. A reduced form of the company still exists. Westcott was also the founder chairman of a second company that supplied a wide range of equipment for fluid measurement, telemetry and control from 1974 to 1994.

Computing at Imperial College

Computing got off to a slow start at Imperial College. A major setback was the departure, because of lack of support, of the college's computing pioneers, Sidney Michaelson, Tony Brooker and Keith Tocher, in the Department of Mathematics, who, among other major contributions, had constructed the first Imperial College Computing Engine, ICCE 1, in the late 1940s and early 1950s; ICCE 1 was a relay-based machine that was slow but reliable. When IBM offered Imperial College a valve-based computer in 1960, Westcott was involved because, if accepted, the computer would be housed in the Department of Electrical Engineering. The offer was refused because of the inferior reliability of this type of computer. IBM later approached Westcott, in 1962, with an improved offer of the solid-state 7090. This offer was finally accepted by the college in 1964 and Stanley Gill was appointed director of the college's new Computer Unit (see figure 2). Westcott's role in this development had ensured the re-creation of a computing group at Imperial College. In 1966, the college created the postgraduate Centre for Computing and Automation, headed by Gill (computing) and Westcott (automation); most members of the Control Group in Electrical Engineering migrated with Westcott to the new centre, where its research flourished. After Gill's departure to industry in 1970, Westcott encouraged the conversion of the postgraduate diploma in computing into an MSc course and successfully lobbied for the centre to become a new department that would plan and develop an undergraduate engineering course in computing. The first BSc (Eng.) students graduated from the course in 1976. Westcott steered the new department as its head until 1979. Westcott, together with the Control Group, migrated back to the Department of Electrical Engineering shortly afterwards. Westcott's role in the acquisition of the IBM 7090 computer and associated Computer Centre, and in the later creation of the Department of Computing and its undergraduate course, were major contributions to the college.

Figure 2. Westcott and Gill at the inauguration of the Imperial College Computer Unit, May 1965. Standing, from left to right: Westcott, Gill, Sir Patrick Linstead (Rector of Imperial College), Tom Hudson (Managing Director, IBM UK), Lord Sherfield. Seated: Lord Halsbury. (Reproduced by permission of the College Archives, Imperial College London)

Research

Westcott straddled the major revolution in the development of the theory of control that took place in the late 1950s with the almost simultaneous arrival of Lev Pontryagin's maximum principle, a necessary condition for the optimality of a control (Pontryagin 1962), Richard Bellman's dynamic programming (Bellman 1957) and Rudolf Kálmán's filtering theory (Kalman 1960). His initial research was conducted in the earlier period during which the main tools for feedback design were those due to Harry Nyquist (Nyquist 1932) and Bode (Bode 1945); these tools provided a simple but powerful method for the design of single-input single-output linear feedback systems whose frequency response could be easily determined, either analytically or experimentally. Westcott was familiar with Bode's work and in (1)* he noted, before its relatively recent rediscovery in the control literature, an important consequence that limits performance of linear control systems, namely that the sensitivity function $S(s)$ (the transfer function from disturbance to output), satisfies $\int_0^\infty \log|S(i\omega)|d\omega = c$, so that making the sensitivity $S(i\omega)$ smaller in the frequency range $[0, \omega_c]$ results in an increase in the sensitivity in the range (ω_c, ∞) (the 'waterbed effect'). In this early period, linear stochastic control problems were recast as linear filtering problems so that Wiener's theory of optimal filtering

* Numbers in this form refer to the bibliography at the end of the text.

Figure 3. Westcott and George Burt testing control equipment for a marine application, 1976.

(Wiener 1949) could be employed; Westcott proposed in (2) a modification that ensured that the resultant control power was not excessive. He also proposed a new performance criterion for servomechanism design (3) and wrote papers on circuit synthesis (4), the design of optimal multivariable filters (5), the determination of process dynamics from normal disturbance records of the process being controlled (7), the design of sampled-date control systems (6), and parameter estimation (8).

To build up and support a research group, Westcott actively sought, early in his academic career, research grants from industry and research institutions; at one stage he was administering 22 grants (see figure 3). Although during this early period Westcott wrote more papers on, for example, the human operator in a control loop, his most important contributions resulted from his rapid appreciation of the significant developments in the late 1950s. He returned from the first World Congress of the International Federation of Automatic Control, where he presented a paper (3) on parameter estimation, bringing with him seminal papers by Pontryagin, Bellman and Kalman. He encouraged his colleagues and students to pursue the new and important research areas revealed by these papers and generated a very exciting research atmosphere that stimulated many contributions from his students during the 1960s and 1970s. Thus John Florentin, one of his early students and later Professor of Computing at Birkbeck College, made influential contributions to optimal control of Markov systems (Florentin 1961), partial observability and optimal control (Florentin 1962*a*), optimal, probing, adaptive control of a simple Bayesian system (Florentin 1962*b*) and optimal control of systems with Poisson inputs (Florentin 1963), pursuing the two themes—optimal and adaptive control—that Westcott had previously identified as priorities. To make implementation of the relatively sophisticated theories of optimal and adaptive control, Westcott encouraged the development of approximate methods (9). Sanjoy Mitter, another former student, now a professor at MIT, gave the first rigorous convergence proof (Mitter 1966) for a second-order variational method for solving nonlinear optimal control problems. A third student, Martin Clark, now Emeritus Reader at Imperial College, made some fundamental contributions (Clark 1970, 1978) to the theory of stochastic processes and nonlinear filtering. Many other contributions were made during this effervescent period; examples include pioneering papers on dynamic optimization (11) and particle filtering (Handschin & Mayne 1969). While Westcott was not a co-author of all the papers published by the Control Group during this period, he certainly provided the necessary support and created the environment and the atmosphere in which this research flourished; the intellectual atmosphere at this time was the most exciting I have ever experienced.

Early in the 1960s Westcott decided to focus research on optimal and adaptive control. He was strongly motivated to ensure the industrial relevance of his group's research and knew that computer control was necessary. The University of London's Mercury Computer (with paper-tape input and 4 kilobytes of random-access memory) was clearly inadequate. When the University of London acquired an Atlas Computer, Westcott obtained support for a high-speed link from Imperial College that he hoped to employ to implement the theory then being developed by his group and elsewhere for computer control of industrial processes. He envisaged a form of adaptive control (10) in which optimal control, computed on the basis of a simple model of the plant, was employed; using plant input–output data, the simple model was periodically updated by comparison with an accurate model. An outline of the hardware and software that was developed for this project and the difficulty in employing the Atlas computer for on-line experiments are given in (12). The delay in persuading the Atlas engineers to modify the supervisor to permit interrupts, the complexity of the hardware required and the lack at the time of a real-time language led to the abandonment of this early and ambitious attempt at 'modern' computer control. The high-speed link was subsequently used by Imperial College for conventional batch processing.

Undaunted by this setback, Westcott sought another area for industrial control. He was aware that successful implementation of modern control on a significant industrial process required, in addition to the user and an automation company, external funding because the amount of work involved could not be justified for an untried system unless a reasonable number of similar jobs could be guaranteed. Finding a suitable application proved very arduous. Five possibilities were explored but eventually discarded. After a short collaboration with the British Iron and Steel Association (BISRA), Westcott appointed G. F. Bryant, then a research engineer at BISRA (now Professor Emeritus) as a research fellow. In response to a funding opportunity, Bryant, under Westcott's tutelage, formulated a comprehensive research proposal for the development of an advanced system for tandem mill automation that would integrate mill set-up and threading as well as dynamic control of gauge, tension and shape. The control problem was complex and nonlinear, involving time delays, significant schedule changes and disturbances. Negotiations during 1966 and 1967 were arduous and protracted and were not helped by the fact that the steel industry was about to be nationalized. Five parties were involved: the Abbey works of the Steel Company of Wales to provide guidance, the automation company GEC–Elliot to implement the scheme, Imperial College to provide modelling, multivariable analysis and dynamic design, the Science Research Council to support the necessary research, and the Ministry of Technology for industrial funds. Westcott's expertise and reputation were an important factor in obtaining agreement from such a disparate group. But there was one more significant hurdle: because of the size of the project, Her Majesty's Treasury baulked at the cost. Jeremy Bray, who was then an MP and who, exceptionally for an MP, had appropriate scientific expertise, carried the day at an extraordinary meeting in September 1967 of 20 principal actors, mainly civil servants, at the House of Commons, where the project was finally approved. A team of 15 was soon assembled, six from GEC to ensure, *inter alia*, transfer of know-how to industry, five appointed by Bryant from the research community, and four from Imperial College support staff. Within four years a working scheme had been developed and accepted by the British Steel Corporation for implementation on all their main tandem mills. Regretfully this success was not followed up in the UK, perhaps because of financial difficulties of British Steel and a lack of interest by GEC, so permission was granted to publish the research in full in book form (Bryant 1973) and in two papers (14, 15). Further applications took place overseas with substantial impact on aluminium tandem rolling in Alcao; the research also stimulated new approaches to process and business control in several countries.

In 1965 Westcott became aware of another promising project, development of a compiler-compiler. The proposal for this project was formulated by Roy Francis, then a lecturer in the Centre, who was familiar with previous work done by Brooker and Derrick Morris for the Atlas Computer. Francis proposed the development of a compiler-compiler that could generate a compiler for a given language (that used standard syntax and data structures) and for a given machine (that had a standard description). A feature of the proposed technique was the attachment of a 'cost' to the set of transformations required for a particular program to ensure that efficient transformations were selected for compilation of a specific program for a specific machine. Expert advice suggested the proposal was worth pursuing; Gill assessed the probability of failure to be 1 in 5. After a period of intense negotiation, Westcott obtained funding from the Ministry of Technology and acted as contract supervisor for a team that at its peak had 15 members. Two processing stages were successfully developed: the first, which was named 'Source to Intermediate Language' (SIL), transformed the input program into an intermediate language; the second transformed the SIL version into object code for the particular machine. However, the excessive computation that might be required was the Achilles' heel for the project and so it was quietly abandoned after three years when the funding ran out.

Westcott's last and longest-lasting research project was initiated by Jeremy Bray, his old ally on the Tandem Mill Project. Bray, a junior minister in the Labour government in 1971, was sacked by Harold Wilson because he had written a book, *Decision in government* (Bray 1970), to which Wilson took exception; Bray thus had time for a new initiative. He had previous experience in identification and control of complex chemical processes, so he invited Maurice (later Lord) Peston, then a Professor of Economics at Queen Mary College, and Westcott to undertake a joint research project of the use of modern control theory to control the UK economy. Westcott, influenced perhaps by the earlier interest of Arnold Tustin, his one-time head of department, in this topic (Tustin 1957) readily accepted, as did Peston. Bray obtained funding from the Social Science Research Council for the project, called 'Programme for Research into Economic Methods' (PREM), with Bray, Westcott and Peston as Principal Investigators. Three researchers were recruited, two with control and one with economic expertise. For control purposes (18), a relatively small linear model (state dimension 20) was estimated by using differenced data because the economy was growing at the time. This model was employed, using linear quadratic control, to control the London Business School model (19) that had 350 nonlinear equations, 50 control variables and 150 outputs. Linear quadratic optimal control was employed; this required specification of the parameters of a quadratic performance index. To assist this choice, a procedure for iteratively changing the performance index to move the controlled trajectories of the system closer to their desired values (17) was devised. In a further phase of this project, called 'Programme of Research into Policy Optimization' (PROPE), with Westcott as Principal Investigator, the use of nonlinear optimal control was investigated. Unlike the earlier phase, in which linear quadratic control based on a relatively simple linear stochastic model, separately estimated, was employed, this phase focused on direct determination of optimal control for the large nonlinear London Business School model. A simple, linear control law that could be comprehended by politicians was specified and optimization was employed (on the large nonlinear model) to determine optimal values for its parameters (16). These feedback laws aroused political interest, and discussion of their use formed part of the evidence submitted to the House of Commons Select Committee on Treasury and Civil Service in the early 1980s (20). Because complexity made direct consideration of stochastic disturbances impossible, the sensitivity of the resultant control to random shocks was reduced by adding terms to the objective function that represented sensitivity to various types of uncertainty. Similar studies on other nonlinear models (Treasury and National Institute of Economic and Social Research) yielded surprising differences. This problem was addressed by using discrete time minimax optimization to determine the worst-case robust policy. Further research investigated the incorporation of rational expectations and, using game theory, the influence of organized lobbies. Research ceased in 1991, 20 years after its commencement. Although this research was considered, in its early stages, to be potentially very valuable and was supported by the Economic and Social Research Council, the Engineering and Physical Sciences Research Council and the Treasury, in later years it faced conceptual opposition due to two problems: the continuing difficulty in modelling the macroeconomic system sufficiently accurately, and the limits, revealed in the research on rational expectations, to effective control. Central banks throughout the world still use economic models to assess the effect of control via monetary and fiscal policy, but research interest has waned over the years. Nevertheless, Westcott's research contributed to the ongoing macroeconomic policy debate at the Treasury and in the House of Commons Select Committee in the 1970s, 1980s and 1990s and influenced later approaches to uncertainty and robustness.

Westcott's early research took place well before the control 'revolution' in the late 1950s and early 1960s, so his university education did not provide him with the skills necessary to engage with ease in the new developments that were highly mathematical. It is to his credit that, despite this, he appreciated so early the potential of the new theory and moved so vigorously to create a group capable of contributing to these developments. His expertise, acquired in part from his wartime experience and his extensive consulting, his desire for putting the advances in control theory to good use in important applications, and his skill in communicating to potential users the advantages that could be obtained from recent developments, enabled him to support talented teams of researchers to realize his vision of advancing automatic control in the UK.

Family

In 1950 Westcott married Helen Fay Morgan, a marriage that lasted happily for 64 years. He was a devoted father to his three children, Gillian, Thomas and Nicholas, and took a lively interest in the development of his four grandchildren. In retirement, he and Fay enjoyed travelling, music, reading and gardening.

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I am grateful to Westcott's family, Fay, Gillian, Thomas and Nicholas, for their help. I am also very appreciative of the specialist advice given by Greyham Bryant, Martin Clark, Jim Cunningham and Berç Rüstem.

The frontispiece photograph was taken in 1969 by Fox-Waterman Photography Ltd.

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