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Fitting Control Mathematics to Control Hardware: An Aspect of the 1968 IFAC Pulse-Symposium*

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(As indicated in the previous article, B. R. Gaines and R. A. Shemer participated directly in the computing systems discussions which were held at the Budapest Symposium, and they were asked to summarize the large number of papers devoted to control computers and components which were not written directly for inclusion in a control journal. As a consequence, they have provided an interesting orientation to this aspect of the symposium.—editor)

Summary—This brief review of some IFAC Budapest Symposium papers concentrates only on those papers in which novel approaches to data-processing were presented, and summarizes the wider implications of the recent developments in control hardware whose importance emerged from the discussion sessions. Some of the other papers concerning specific control applications will be published in this journal, and the conference proceedings themselves will eventually be available in book form as indicated in the previous article; a review of the Symposium has been published [1].

ONE DOES not expect to find a control conference with some 150 delegates and 63 technical papers devoted entirely, not to some aspect of control theory and associated mathematics, but instead to the design and application of control hardware, digital hardware at that. The IFAC Pulse-Symposium in Budapest was indeed a rare, possibly unique, event, and it is of interest to consider not only what was discussed there as well as why the conference took place. The reasons for the resurgence of interest in digital control systems using incremental, or counting, techniques actually have wider implications than those discussed at the Symposium, and are of general importance in determining the future directions of control techniques.

RISE AND FALL OF THE DDA

Incremental computing techniques, in which quantities are represented by pulse-rates, or counts in registers, are not new. The Digital Differential Analyser [2] (DDA) originated in concept from the mechanical ball-and-disc differential analyser developed by BUSH [3] in the early thirties, and used extensively in both Britain and the United States for the solution of ordnance problems during World War II.

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It is interesting to note that, sandwiched between the mechanical and electronic versions of the differential analyser, came the development of precursors to both modern analogue and digital computers, for the war itself stimulated construction of both high-gain DC operational amplifiers and the stored-program digital computer.

In 1949, about 5 years after von Neumann's step from the physical patching of ENIAC to the program-control of EDVAC, a digital version of the Bush differential analyser was developed, in which registers containing binary numbers interacting through digital adders replaced the mechanical system. Due to the cost, complexity and unreliability of vacuum-tube electronics at that time, these first DDAs used a magnetic drum for storage together with a simple arithmetic unit for up-dating each of the integrator registers in sequence. Some of the early disc files were, in fact, developed expressly for the DDA, and at one time Genesys Corporation offered a complete process control system based on a DDA with disc store.

A number of other manufacturers, including Litton industries, Solartron, Bendix, Wang Laboratories and IBM, developed DDA systems, and recent examples are to be found in various missile systems, Polaris submarines, and the ill-fated TSR2, a British aircraft similar in function to the American F111. Thus the present analog computer, digital computer and DDA, all developed at much the same time under the pressure for increased data processing power generated by the war, and with the same aim of exploiting the capabilities of the electronic vacuum tubes then becoming readily available.

The interest in DDAs showed a steady growth, matching that of general-purpose computers, until the late fifties. During this period high-speed parallel-processing DDAs were developed in which each integrator had its own arithmetic unit, the first operative example being the Packard Bell TRICE [4]. The binary-rate multiplier [5], a digital pulse-rate multiplier developed at MIT in 1949 for automatic machine-tool control, was used in the manufacture of low-cost, parallel DDAs [6] of limited accuracy. A number of more sophisticated DDAs have been developed in recent years,

incorporating features such as program control and variable increment size, which greatly increase the speed and computational power of the basic system [7–9].

After 1960, however, despite these many developments and favourable applications, interest in the DDA began to tail off, or at least become insignificant compared with the ever-increasing rate of growth in the development and application of general-purpose digital computers. This may be seen as part of the universal trend whereby the exploitation of the enormous potential of GP machines ousted all developments of special-purpose data processors tailored to specific problems.

The DDA can solve differential equations very well, but that is all. It had, and still has, useful application to problems involving the solution of complex differential equations at high data rates—for example, in inertial navigation systems. The GP machine can solve differential equations reasonably well, but can do a great deal more besides. For example, the differential equations for flight simulation are similar to those for inertial navigation, but the 'house-keeping' operations in a flight simulator so predominate over the solution of the flight equations that the use of a DDA gives no advantage—a GP machine can solve these equations, almost as a 'background' computation to its main tasks.

Thus, if there was ever any battle between incremental computers of the DDA-type and stored-program general-purpose machines, it would seem that the GP machine won some years ago, and that the DDA is now a computational curiosity. The interest demonstrated by the IFAC Pulse-Symposium shows that this is not so, and the following section discusses the reasons why.

INTEGRATED CIRCUITS AND LARGE-SCALE INTEGRATION

The re-awakening of interest in the DDA by control engineers is part of a general tendency to take a new look at special-purpose computer techniques, generated by the decreasing cost of modern integrated circuits and the promise of much lower cost and higher packing density through the coming of large-scale integration (LSI). Although these circuits are also having a tremendous impact on the economics of conventional digital computers, and their genesis is largely a result of the demands of the computer industry, their relative effect on the economics of special-purpose machines is rather greater because the ratio of hardware to software/peripheral costs in these machines is so much higher.

Conventional general-purpose machines have a comparatively simple arithmetic unit coupled to a massive store of simple and uniform construction, and require a profound re-organization to utilize an increased hardware content, such as would result from multi-processing. Thus interest in special-purpose machines has arisen together with attempts to re-structure general purpose machines. In particular, component manufacturers already capable of large scale integration using MOS integrated circuits have commenced studies of the application of DDAs in navigation and control systems.

The impact of LSI on computer structures, and the development of modular, programmable, DDA-like computers, were discussed at the Symposium in three papers by HATVANY [10] and the present authors [11, 12]. All three papers are very much more concerned with computers than control and assume that the main capability required in a process-controller is the solution of differential equations: many of their arguments about hardware/software and sequential/parallel tradeoffs apply, however, if this assumption is not justified.

Hatvany considers the DDA in the context of previous studies of iterative parallel-processing and variable structure machines. He concludes that the next generation of process control computers will have a parallel organization of iterative modules, to give it higher speed, easier manufacture, better maintainability, and higher operating reliability. Pulse trains will be used for internal information interchange, because of the fewer leads and interconnections required, and the higher reliability and better diagnostic facilities they afford. The computer will use DDA techniques in order to take advantage of their greater processing efficiency, particularly with respect to systems of differential equations.

COMPUTING SYSTEMS OF THE FUTURE

The discussion session on, "The Place of Incremental Techniques in the Computing Systems of the Future", brought into the open many doubts about the reality of the role proposed for DDAs in future control systems. Despite the eloquence of proponents of the DDA, it is clear that all operative direct digital control (DDC) systems are based on general-purpose machines, and there is no indication of any major changes in this approach. One plausible reason for this is that DDC is in its infancy, and at the development stage there is strong pressure to use the more flexible hardware for its implementation, on the grounds that this will be changing as more experience is gained. When, eventually, the control system is engineered for production the same general-purpose machine is naturally used.

It is possible that this is an adequate explanation of the general tendency to use general-purpose machines, and certainly any special-purpose

machine has to compete in a very tight market against the low, and decreasing, cost of small, conventional digital computers. The DDA, like the analog computer, is naturally suited to the solution of differential equations, and has the advantage over the conventional analog machine that its integrations are with respect to arbitrary variables, not necessarily time. However, how much of process control is the solution of differential equations, and how much is the sheer 'house-keeping' of run-up and run-down sequencing, product monitoring, alarm generation, and so on, was not really discussed; it is clearly of vital importance to the arguments put forward at the Symposium.

It would have been interesting to have heard the viewpoints of those responsible for implementing DDC with conventional machines. It is probably a good thing for any highly specialist conference to include a few "generalist" papers in related fields, particularly if they are opposed to the general theme of the conference. It is clear that neither general-purpose machines nor the DDA provide the ideal and ultimate hardware for control systems—a comparison of their relative advantages and disadvantages, not neglecting analog techniques, which are also favourally affected by LSI, would be very useful.

APPLICATION OF INCREMENTAL MACHINES IN THE INTERFACE

Whilst the grander schemes for large DDA systems were of doubtful application, and the DDA did not appear to be a contender for use in the multi-loop, time-shared control systems, where the small GP machine is being widely applied, its advantages in single-loop controllers for specific purposes, such as driving positional actuators, were very clear. For example, a stepping motor can provide far higher torques when used in a closed-loop mode, and a pulse-counting digital servo forms a natural interface between a digital computer output bus and a stepping motor. FREDRIKSEN [13], described such a system in which various modes of operation, fast-response, constant speed, etc. are available in the actuator and may be commanded by the main computer.

This is a typical example of the use of special-purpose digital computing techniques to make a peripheral with an optimal relationship to the main machine. The ease of interfacing to transducers and actuators was universally proposed as an important advantage of incremental digital techniques, and the equal ease of interfacing from the digital registers of the DDA to the I/O bus of a conventional computer, makes the use of DDAs for peripheral data-processing very attractive.

A futher example of this was the use of DDA techniques in graphic displays described by BERNAT and LADANYI [14]. Some of the earliest examples of the use of the DDA are to be found in displays, since the binary rate multiplier was applied to vector generation at MIT, and is incorporated in Digital Equipment Corporation's Type 340 display.

Several papers described single-loop Proportional-Integral (PI) or Proportional, Integral, Differential (PID), controllers using incremental computing and digital counters as integrators. All of these controllers achieved a low cost, comparable to that of analog systems, by use of binary rate multipliers rather than true DDA integrators to generate pulse sequences, and the inaccuracies of this form of rate multiplier, and its effect on the controller, were extensively discussed. In the discussion session on single-loop controllers it was generally agreed that PI and PID algorithms were the only ones of practical utility at present, although they take little advantage of the capabilities of all-digital controllers.

CONCLUSIONS

Whatever the state of the special-purpose/general-purpose controversy, it is clear from the Symposium that the advent of low-cost integrated circuits has opened up a tremendous range of possibilities for new developments in control hardware; the re-development of DDA-like incremental computing techniques is one of the more attractive possibilities which is likely to lead to practical applications. Other effects of decreasing hardware costs will be of equal, if not greater, importance, however, including those on conventional digital and analog machines, and it would be interesting to have some future symposium concerned with the general impact of integrated circuits and LSI on control systems. In particular, the emphasis on the ease of solution of differential equations with the DDA demonstrated the practical importance of fitting control mathematics to control hardware. There is, however, a far wider range of computational requirements peculiar to control systems, particularly in the context of the modern state-space approach, and it is a research problem in its own right to specify these and determine how they may best be implemented.

Arguments over merits and demerits of specific approaches obscure the point that there is a great variety of data-processing techniques and associated hardware available to the engineer, and, for the optimum solution to any particular problem, it is important that the latest information on techniques and products is at hand. Although analogue and parallel-digital data processing techniques are widely appreciated and understood, DDA techniques have been neglected, and the most important function of this symposium was to disseminate information about them more widely.

The organizers are to be congratulated for having the foresight to realize the great, but widespread, interest which is growing in incremental digital techniques. Their excellent organization, coupled with traditional Hungarian hospitality, made this a pleasurable and stimulating occasion for all.

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Résumé—Ce bref résumé de quelques communications du Symposium IFAC à Budapest couvre les seules communications contenant de nouvelles methodes de traitement de l'information et fait la somme des aspects plus larges des developpements récents du matériel automatique dont l'importance à été mise en évidence par les séances de discussion. Certaines des autres communications relatives à des applications spécifiques de l'Automatique seront publiées dans ce journal et les actes de la conférence eux-mêmes seront éventuellement disponibles sous la forme d'un livre, ainsi qu'il est indiqué dans l'article précédent; un rapport sur le Symposium a été publié [1].

Zusammenfassung—Dieser kurze Bericht über einige Vorträge des IFAC-Symposiums in Budapest konzentriert sich auf solche Vorträge, in denen neuartige Vorgehensweisen zur Datenverarbeitung dargestellt wurden und faßt die breiteren Verflechtungen bei den neueren Entwicklungen in Kontroll-"Hartware" zusammen, deren Wichtigkeit auf den Diskussionssitzungen offenbar wurde. Einige andere Vorträge, die spezifische Anwendungen der Regelung betreffen, werden noch in dieser Zeitschrift veröffentlicht und die Konferenzberichte werden, wie im vorangegangenen Artikel angekündigt, ggf. in Buchform verfügbar sein. Ein Überblick über das Symposium wurde bereits veröffentlicht [1].

Резюме—Это краткое обозрение некоторых сообщений на Симпозиуме ИФАК'а в Ъудапеште ограничивается сообщениями в которых были указаны новые подходы к обработке информации и подводит итог более широких аспектов последних развитий автоматического оборудования важность которых была выявлена на дискуссионных сессиях. Некоторые из других сообщенй относящихся к специфическим применениям Автоматики будут опубликованы в этом журнале и сами акты конференции будут возможно достижимы в книжной форме, как было указано в предыдущей статье; обзор Симпозиума был опубликован [1].