Keynote Address—Techniques for Reliability in Computers for Weapon Control

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THE RAPID advances made in computer developments during the past few years have had a profound effect upon the security and economy of the country and upon all our lives. Today, the influence of the high-speed, high-capacity computing machine is being felt throughout our total society: in industry, commerce, science, education, medicine, and in many other areas of human existence and progress. The most significant use of the computer, however, in this era of international instability, is its vital role in maintaining our national security.

Because of my association with the Department of Defense, I am naturally most interested in those computer applications which are of the greatest importance to our defense. I wish I could discuss in detail all the different ways in which various kinds of computing machines are being used throughout the military organization. Since that would not be appropriate here, I am going to limit my remarks to the types of computers used for the dynamic control of weapons and weapons systems.

Since the computer is now essential to the effective performance of all modern weapons and weapons systems, it is obvious that a very high level of reliability is essential. I can assure you that we in the Department of Defense consider that the theme "Techniques for Reliability" is completely appropriate for this Joint Computer Conference.

I shall begin my discussion by presenting a little more detail on the widespread usage of computers in weapon control, together with a few highlights of their developmental history. Perhaps I should make it clear at this point that I use the expression "weapons and weapons system control" to include all computers involved in direct control of weapons such as guns, missiles, torpedoes, rockets, bombs, or aircraft and those involved in such functions as tracking, threat evaluation, and weapon assignment.

Although computing machines have received much publicity over the past few years, I seriously doubt that the vital role they have played in the development of military weapons is generally appreciated.

It is probably not widely known that the fire of naval and army artillery was being controlled with computing devices even before World War I started. I doubt if many appreciate the fact that the precision and capabilities of these weapon control computers have advanced steadily since Hannibal Ford started development of his first computer for naval fire control in 1915, until today practically every offensive or defensive weapon depends for its effective operation upon one or more of these computing devices, some very simple and others even more complex than the largest machines in commercial use today.

On one end of the size-complexity scale is the tiny computer that is packed into the nose of a medium-caliber bullet to compute the point in space with respect to an air target at which detonation should occur. On the other end of this scale are the huge digital computers in the ground environment of the air defense system, which employ tens of thousands of electron tubes and occupy thousands of square feet of floor space. Between these two extremes of size and complexity are scores of different kinds and sizes of computers, each performing a specific function in the dynamic control of some weapon or weapons system. Although the performance, complexity, and packaging requirements of these many types of control computers differ widely, the need for a high degree of precision and operating reliability is common to all.

Until very recently, all these diversified weapon control computers were of the analog type. Although much development work has been done on digital weapon control computers, to my knowledge there is no digital weapon control computer in actual military service operation.

Because the history of weapon control is truly the history of analog computer development, it may be of interest to review very briefly some of the development highlights. As I mentioned before, the history of the fire-control computer in this country started in 1915 when Hannibal Ford began to develop the first computer to control naval surface-to-surface guns. His early computers, known as "rangekeepers," represented the first application of precision analog techniques to the solution of the gun fire-control problem.

At the conclusion of World War I, the need for control of surface guns against aircraft became apparent, and Ford again pioneered with the development of the first antiaircraft-gun fire-control system. This system, completed in 1926, was designed to handle aircraft having a maximum speed of 95 knots.

The computation in these early analog computers was performed entirely with mechanical cams, differentials, multipliers, component solvers, and integrators. With the exception of the electrical contact-type servos, the reliability of these mechanical analog computers was controlled almost entirely by the mechanical designer

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and the people in the machine shop. Improvements in the performance of these computers were obtained over the years through a better mathematical understanding of the dynamic fire-control problem and more precision in the design and production of the various mechanical components. In service, the reliability of these mechanical computers was very good.

Just prior to World War II, a basic advance was made in analog computer technology—the introduction of the electrical-electronic computer. These computers used electrical components such as shaped potentiometers, electrical resolvers and synchros, and the servomechanisms were electrically driven with vacuum-tube amplifiers. This new concept resulted in the more rapid solution of the fire-control problem and some reduction in size, weight, and manufacturing cost. Unfortunately, these computers were much less reliable than their mechanical predecessors, primarily because of the poor reliability of the amplifiers. The reasons for this are clear now, although they were not at that time. The problem was twofold. First, the amplifiers were designed by engineers with little background of experience in the design of electron-tube devices and, second, the pressure of war and the rapid changes in requirements did not permit redesign to improve reliability before attempting production. Some of these computers, extremely promising in concept and basic performance, never reached service use because their electronic amplifiers were so unreliable. I might add that even more developmental failures in fire-control computers occurred during World War II because of a reverse situation in which experienced electronics companies tried to design fire-control systems without the necessary background in the basic fire-control problem. The lessons learned were very expensive, but they helped to establish one of the fundamental principles of the modern reliability concept. We know now that to develop a satisfactory and reliable military device requires a thorough understanding of the operational area involved as well as experience in the design techniques employed.

After the basic electrical analog principles were first developed, improvements in analog computers for weapon control came about largely through improved reliability, reduced size, and increased precision of the computing components and, most significantly, as a result of a more sophisticated and scientific understanding and treatment of servomechanism design.

World War II and its forced-draft research and development effort, together with the development of fire-control radar and more advanced weapons, pushed computer development forward rapidly. Before the war was over, the control of guns, aircraft, bombs, torpedoes, mines, rockets, and even guided missiles was being accomplished with the aid of analog computers.

Near the close of the war, a most significant weapon control concept was developed—the integrated fire-control system. Prior to this development, it was the practice for military agencies to build up a fire-control system from various pieces procured separately from different companies. As the speed and maneuverability of targets increased, with a corresponding increase in the performance and complexity of a weapon control system, it became necessary to develop the entire system under one system engineering management. The integrated weapon control system, now a more or less uniformly accepted concept, resulted in improved performance and substantial savings in size and weight. This principle of integrated system design must be given careful consideration in all future weapon control developments.

Between World War II and the beginning of the Korean conflict in 1950, the Military Services embarked upon a new era of weapon development generally based upon the kind of war that might be fought in 1960. Development programs which offered only marginal improvement in performance over World War II devices were discontinued, and emphasis in air defense was placed on weapons capable of engaging targets of near-sonic or supersonic velocity in mass saturation attacks. Guns gave way to guided missiles; manual control of interceptor aircraft was considered obsolete and the lethality of nuclear weapons was multiplied many times over.

Requirements for computers for the dynamic control of these new warfare concepts advanced rapidly, and a new kind of computer emerged, one which had the functions of keeping track of a multiplicity of targets, evaluating their threat to certain defended areas, assigning defensive weapons to individual targets and, in some cases, controlling the weapons themselves. The successful instrumentation of a computer to perform this complex of operational functions indicated the desirability—if not the necessity—of going to digital techniques.

This was the beginning of the era of "push-button warfare," and with it began a rapid transition in engineering thinking from analog to digital computers for weapon control. There was a lot of opposition to this on the part of many knowledgeable people in the weapon control field, both in the military and outside, most strongly pressed by those involved in airborne weapon control. It was argued that a digital computer of the size and complexity of the then current general-purpose machines could not possibly be condensed into a size and weight that could go into any aircraft. Furthermore, it was argued, even if by some miracle of engineering it could be so compressed, such a machine would contain so many vacuum tubes and other electronic components that it would be completely unreliable in service. (I might add that some of these thoughts are still prevalent among military people.) However, with the promise of more reliable computer components, such as semiconductors and magnetic devices, this opposition gradually softened and a few visionary people throughout the military departments initiated experimental developments of weapon control systems around digital techniques.

Looking at the weapon control picture today, I believe that the change to digital computing techniques is desirable and inevitable. In view of the rapidly increasing complexity of weapons of all kinds, I am convinced that digital methods offer the greatest promise for solving the control problems. Furthermore, the state of the electronic component art justifies the development of digital devices for all new weapon control programs. I believe that, in the future, analog weapon control will play a minor role in the support of digital systems.

I doubt that it is fully appreciated in the weapon control field that the digital computer promises many advantages over the analog device in addition to its greater performance capabilities. By the very nature of its instrumentation, the digital computer has far greater flexibility than an analog device; as a result, a single basic computer design, with only minor modifications, can be applied to the solution of a number of different weapon control problems. This capability has very significant implications with regard to standardization of design, which would result in economy of engineering effort, improved reliability, and enhanced production and logistic posture.

Another advantage that is of some significance in these times of steadily increasing cost of national defense is the fact that a digital computer is considerably cheaper to manufacture and will require less skilled labor. Also, the lead time to get a newly developed digital computer into production should be much less than for an analog device.

To substantiate these advantages, I have some comparative information on an airborne digital computer which is now entering pilot production as a direct replacement for an analog computer in an existing bombing-navigation system. It is estimated that the quantity production cost of this digital computer will be about 40 to 50 per cent less than that of the analog computer it replaces. Capital equipment required for production of the digital computer is expected to be reduced by 70 per cent; the requirement for skilled manufacturing labor should be reduced by almost 70 per cent, and the lead time for new production is expected to be reduced by 60 to 70 per cent.

These many potential improvements in the digital weapon control computer are very attractive. But there is a matter of major concern to many military people and systems engineers, which could seriously delay the widespread application of digital computers in weapon systems; that is the fear that system reliability may be seriously decreased. The reliability of electronic devices has not acquired a good reputation among military people, and they know that digital computers are electronic equipments.

I also share this concern, not because the reliability of digital computers cannot be made as good as, or better than, the best analog device now in service, but because, in entering this new field of digital technology, we may not fully use the knowledge of weapon control systems engineering and equipment reliability which has been developing in the electronics and weapons system industry.

The relatively new field of digital computers has been built up primarily around the requirements of the general-purpose machine. As in any new and highly specialized branch of engineering, there is a tendency here that a tightly bound group of specialists may develop, speaking its own language and tending to some extent to break away from other branches of the electronics industry. This has the effect of decreasing the interchange of technical experience—a potentially serious deterrent to both the reliability and systems performance of digital computers in weapon control systems.

As weapon and target capabilities have increased, the basic weapon control problem has changed little. The problem has become more complex and the requirements for solution more exacting, but the fundamental principles are the same. The only thing we are doing differently with digital techniques is to solve an old problem with new mechanization. We can waste a lot of time and engineering resources in this inevitable transition from analog to digital computing techniques if we do not make maximum and continued use of the weapon control know-how that has been built up in this country over the past quarter of a century.

We can suffer even greater losses if the proven reliability concepts and techniques established through years of hard work and cooperative effort on the part of industry and the military departments are not applied to the fullest extent in the military digital-computer field. After all, to obtain reliability, the techniques which must be applied in design, test, manufacture, operation, and maintenance are no different for a digital computer than for any other military electronic device of comparable complexity. Unquestionably, such methods as self-checking, which can be applied so readily to digital computers, will greatly assist in service maintenance, but they will not improve the operational reliability of a weapon system such as a guided missile or a high-performance interceptor aircraft.

With present techniques and components, I am convinced that we can design digital weapon system computers which will be more reliable than the best electronic equipment now in service. In a progress report on reliability of military electronic equipment, given before the Third National Symposium on Reliability and Quality Control on January 14, 1957, I used data on a digital bombing computer as an example of reliability improvement made over the past year. This kind of reliability can be achieved, however, only when the basic design of a device is thoroughly engineered for reliability and adequately tested before production is initiated.

Many times in the past two years I have discussed the basic steps in design, testing, production, procurement, maintenance, and use that are required to obtain a highly reliable military electronic device. I need not repeat these in detail here since they have been published widely in the technical press. But I do want to emphasize that the reliability of any electronic equipment is critically dependent upon the design engineer. If computer designers do not take into proper account the engineering principles controlling reliability, which are now well known, designs will very likely be unreliable in service, regardless of how sophisticated the logic may be and in spite of anything that can be done in the production line or by maintenance. Reliability can be controlled in manufacture and it can be maintained in service, but it can be established only by sound basic engineering in design.

One of the most promising techniques for obtaining reliability in digital computers appears to be the exploitation of their basic inherent flexibility to develop standardized designs of system building blocks. The basic geometry of many weapon control problems is quite similar and can be solved by proper system grouping of similar computer elements. Such a standardized design would make it unnecessary to develop a completely original computer for every new weapon system project and would permit the use of standard computer elements of proven reliability—reliability which could be brought to a very high level through extensive engineering, testing, reengineering, and continued production.

It may be argued that such a philosophy would seriously impede the advancement of digital computer technology. I do not agree. The real advance of digital computers in the weapon control field is going to result from more sophisticated weapon system engineering, advances in logic and improved component parts, not from a continued redesign of circuits and packaging.

At any given time, the same component parts are available to all computer designers—or, at least, they should be. Once circuits and packaging techniques, developed around these components to perform a particular computer function, have demonstrated a high degree of reliability, these circuits and packaging designs should be standardized and used in all applications to weapon control computers where an unacceptable compromise of weapon system performance would not result. Obviously, as new and improved components or techniques become available, new standardized designs should be developed around them. These designs, when proved to be better than those already in existence, should be adopted immediately.

In summarizing the advantages that can accrue to the military users from a design standardization program (some of which I have already mentioned), these factors are significant. The amount of engineering effort, cost and time required to develop a new weapon system would be substantially lessened. Also, the cost of production could be reduced because larger quantities of similar items could be manufactured, thus permitting the utilization of more economical manufacturing processes such as automatic assembly. Furthermore, the lead time required to get a newly designed weapon control system into production would be shorter. Another advantage to be gained from such a standardization program would, of course, consist of improvements in logistics, supply, and service maintenance.

I urge that those who are engaged in the development of digital computers for military weapons systems give careful consideration to this challenging problem of establishing and maintaining design standardization in this field. I can assure you that my office will make every effort to assist in bringing such a standardization philosophy into being as early as possible.

Another important need in connection with reliability in weapon systems employing digital computers is for increased emphasis on systems engineering. At present, digital computers are being developed to work in weapons systems in which other major system components were designed to function with analog computers. The input and output elements of these systems are analog and must be converted to operate with a digital computer. These conversions are costly in equipment complexity and they penalize over-all system reliability. Much more emphasis is needed on the development of various weapon system elements specifically designed to operate in a digital environment so that these costly conversions will not be necessary.

The last technique for reliability that I will present is simplicity. This, again, is a reliability axiom which is not unique to the digital computer field—but I suspect that it may be more difficult to achieve in this field than in other areas of military electronics. By careful design of logic and programming, much can be done to simplify the computer instrumentation in a weapon control system. We must have very careful systems engineering to make certain that we have the simplest system possible and that some of the solutions in the over-all weapon control problem cannot be obtained satisfactorily with less complexity and more reliability by using analog techniques.

In summarizing I would like to present these pertinent conclusions.

1) Because computers are vital to the operation of every modern weapon and weapons system, an extremely high level of operational reliability in these devices is absolutely mandatory.

2) The trend in weapon control is definitely toward the digital computer, because of its greater flexibility and higher accuracy and its advantages of lower cost, better producibility, shorter lead time, and lower requirements for skilled manufacturing labor.

3) The cooperative effort of the military departments and industry must be directed toward the immediate goal of standardizing the design of digital computer functional building blocks for application to weapon systems.

4) The successful use of digital techniques in weapon control will depend to a large extent upon the applica-

tion of combined experience in weapon control and digital technology.

5) The techniques for obtaining reliability in a digital computer are fundamentally the same as for any other electronic equipment of similar complexity. The principles for obtaining reliability of military electronics equipment through sound design, testing, and production controls are now fairly well established and should be applied to the fullest extent in new computer designs.

6) Careful attention should be given to systems engineering in the development of a weapon system employing digital computers to ensure that all system components are designed so as to minimize conversion of information between analog and digital forms.

7) Careful consideration should be given to logical design to obtain optimum simplicity of equipment design. Analog techniques should be employed for mechanizing functions where they are best for the purpose.

In closing, I would like to emphasize that they who are working in this relatively new field of digital computers have a great obligation in the defense of the country.

Many of the computing devices which are being designed are absolutely essential to military weapons and weapons systems, and they will become progressively more important as the capability and complexity of these systems continue to advance.

Although the challenge of making these new devices sufficiently reliable to be acceptable for military applications is great, there is a substantial background of knowledge and experience in reliability engineering to draw upon.

I see no reason why these new devices should not be completely reliable as they first become available to the using military services. If they are not, the future of digital computers for the dynamic control of weapons may be seriously affected.

Computers with European Accents

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AS THIS is a luncheon talk, it should contain some humor but there is really nothing very funny about some of the European computer developments which are offering competition to certain unnamed American firms that are trying to peddle their wares in Europe. One of these competing computers, known as the GAMMA 3, is manufactured in France by an organization known as Compagnie des Machines Bull. Compagnie Bull has some 350 of the GAMMA 3 machines in the field. It is primarily a plugboard machine with 64 single-address instructions and can be compared in a general way with the IBM 604, although, more strictly speaking, it occupies a position intermediate between the 604 and the 650, particularly when an 8000-word drum extension unt is attached. The interesting features of this machine are not, however, the size, speed, or relative cost, which after all are quite comparable with American developments, but rather the extensive use of techniques which have never found wide acceptance in the United States. This refers particularly to the use of electromagnetic delay lines as storage elements, and a number of other techniques, the use of which has enabled this moderately small organization to compete with organizations many times its size. This is a virility which belies the all-too-prevalent impression of French decadence.

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The same company has recently announced a complete data processing system called the GAMMA 60 which includes a central processing unit with magnetic corestorage. The peripheral equipment includes magnetic drums, magnetic tape units, both card and paper tape readers and punches, lined printers, etc., all under internal stored program control.

Professor F. C. Williams of Manchester University has made many contributions to the computing art, perhaps the most well-known being the cathode-ray storage system to which his name is customarily attached. He has gathered around him at the University a small group of very competent men who have made and are continuing to make substantial contributions. The main location of the Ferranti Company happens to be in Manchester, and, as one might expect, a cooperative arrangement has developed in which Ferranti contributes to the support of a computer project at the University. It profits, in turn, by the developments made there, and manufactures commercial computers embodying some of the University's developments. Several machines of a first design, known as the MARK I, have been made and are in operation at such diverse places as Toronto, Canada, and Rome, Italy. This computer was followed by the MARK I STAR, and more recently the Ferranti Company has announced a new large-scale computer known as the Ferranti MERCURY Computer. This is a high-speed computer, using floating point, with a