THE DIGITAC

SYSTEM

M - 73

RESEARCH AND DEVELOPMENT LABORATORIES

HUGHES AIRCRAFT COMPANY | *Culver City, California*

THE DIGITAC

SYSTEM

M - 73

15 May 1954

Papers presented at the 1954
National Convention of the
Institute of Radio Engineers

Introduction

The name Digitac (Digital Tactical Automatic Control) refers to a
fully automatic aerial navigation and weapon control system which has
been developed and successfully flight tested under a U.S.A.F. contract.
A noteworthy feature of the Digitac System is that it marks the first use
of an airborne digital computer to control an aircraft.

Flight testing of the Digitac System was completed in August 1953,
and those features of the system not under security classification were
discussed at the 1954 national convention of the Institute of Radio
Engineers in the following three papers:

> "Flight Testing of an Airborne Digital Computer," by E. M.
> Grabbe, D. W. Burbeck, and S. B. Neister

> "The Digitac Airborne Digital Computer," by E. E. Bolles

> "A Digital Autopilot Coupler," by W. L. Exner and A. D.
> Scarbrough

The texts of these three papers are reprinted herewith for the
convenience of those interested. These papers also appear in the official
I.R.E. Convention Record.

Four other papers dealing with various aspects of the Digitac System
have been presented at previous convention sessions. These papers are:

> D. W. Burbeck, E. E. Bolles, W. E. Frady, and E. M. Grabbe,
> "The Digitac Airborne Control System," Western Computer
> Conference, Los Angeles, California, February 1954.

> D. W. Burbeck and W. E. Frady, "Precision Automatic Time
> Measurement Equipment," 1952 IRE National Convention, New
> York, N. Y.

> A. D. Scarbrough, "An Analog to Digital Converter," 1953
> Western Electronic Show and Conference, San Francisco,
> California.

> A. S. Zukin, "Automatic Program Control Utilizing a Variable
> Reference for Addressing," Electronic Computer Symposium,
> 1952, at the University of California at Los Angeles.

FLIGHT TESTING of an AIRBORNE DIGITAL COMPUTER*

E. M. Grabbe

The Ramo-Wooldridge Corporation
Los Angeles, California

D. W. Burbeck

Hughes Aircraft Company
Culver City, California

and

S. B. Neister, Armament Laboratory

Wright Air Development Center
Dayton, Ohio

Introduction

Electronic digital computers have certain advantages, such as accuracy, flexibility, and versatility, which make them ideally suited for use in many military airborne control systems. However, for airborne use a digital computer must meet the additional stringent requirements, imposed by military aircraft, of size, weight, and facilities for cooling, beyond the requirements normally encountered in digital computer design. The past few years have seen many improvements in computer logic, circuitry, and packaging, so that compact, general-purpose airborne digital computers have now become a reality.[1] The Digitac System was the first in which an electronic digital computer was employed as an integral part of an airborne automatic control system. This paper contains a description of the evaluation tests of the Digitac System and reports certain unclassified results of these tests.

Digitac, standing for Digital Tactical Automatic Control, is a military system developed for completely automatic aircraft navigation and weapons control at line-of-sight ranges. This report of the Digitac flight tests will cover (a) a description of the system and the equipment developed for it, (b) the flight test objectives and details of the flight tests, and (c) a discussion of advantages of digital computation for future airborne control application. The weapons control part of the system has a security classification and, therefore, will not be discussed. A detailed description of the computer used in these flight tests is being presented in another paper at this convention.[2]

Description of System and Equipment

The Digitac Airborne Control System[3] was developed under contract with the Armament Laboratory, Wright Aeronautical Development Center. The objectives of the program were to develop a high-precision navigation system based on hyperbolic position determination. In a hyperbolic system two pairs of ground-based transmitter stations are required to establish the coordinate system. Usually, one of the stations is common so that three stations are sufficient: a master station and two slave stations. The master station alternately sends pulses to each of two slaves which relay the pulses to the aircraft, and measurements of the differences in time of arrival of pulses from the master station and the two slave stations define two hyperbolic lines of position so that a fix may be determined by the intersection. Hyperbolic systems have an inherent error factor, due to divergence of the coordinates, which increases with range from the ground stations. Hence, for precision navigation, high accuracy in both time measurement and computation is required.

Equipment developed for the Digitac System consisted of one set of three ground stations and two models of the airborne system. Figure 1 shows a block diagram of the airborne system. The airborne equipment
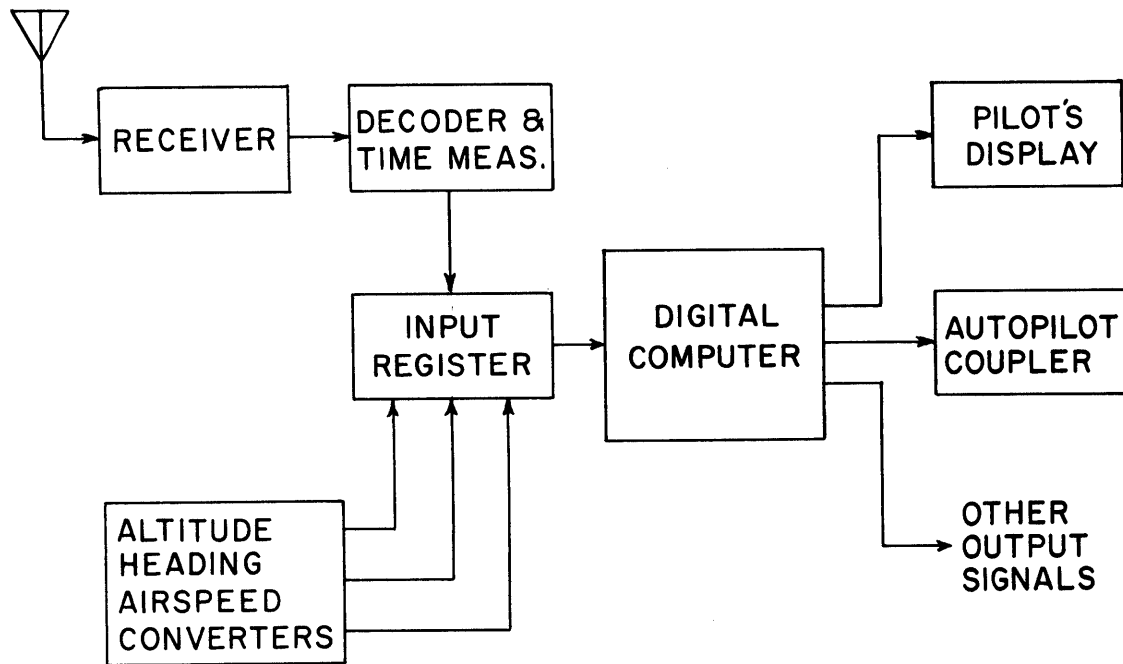

Figure 1

Airborne Digitac System

as shown in Figure 1 was made up of a receiver, decoder and time measurement equipment, instrument analogue-to-digital conversion units, an input register, a digital computer, and outputs. The time measurement part of the system was designed to measure time auto- matically in digital form with an over-all accuracy of one part in 30,000 or about 0.02 microsecond.[4] The aircraft instrument inputs to the system consisted of altitude, air speed, and compass heading, and a counter-type shaft-to-digital converter was used for each of these instruments' inputs.[5] The outputs consisted of a steering signal, a pilot's display and certain weapon control signals.

Figure 2 shows the computer model which was flight tested. The general-purpose computer is a serial magnetic drum machine with a word length of 16 binary digits plus sign and a digit frequency of 100 kc. Figure 3 is the input-output equipment including the input register, time
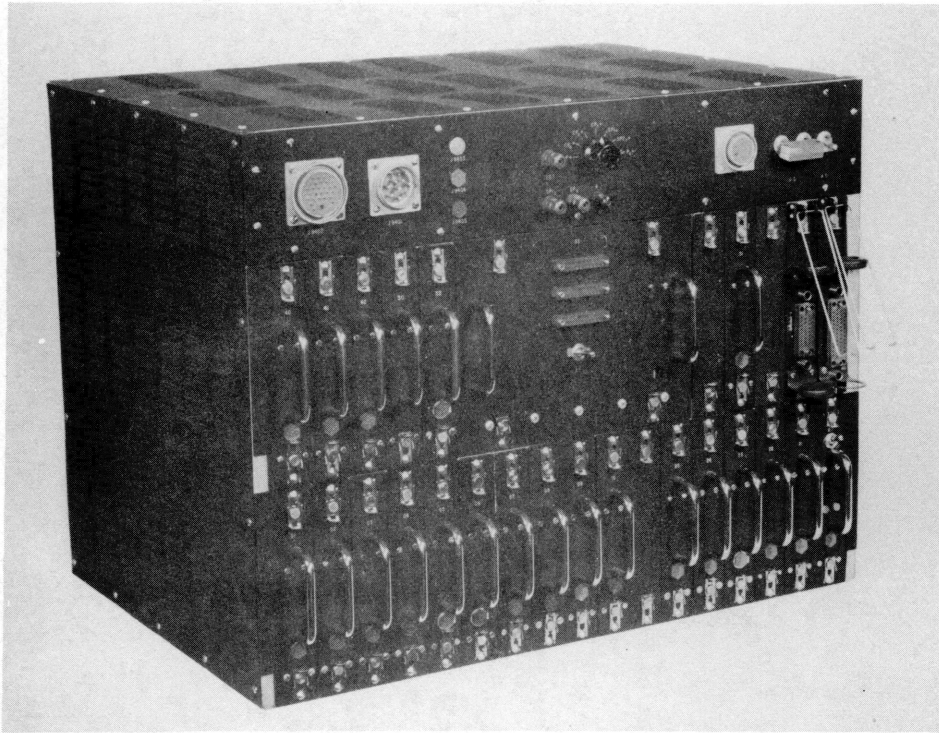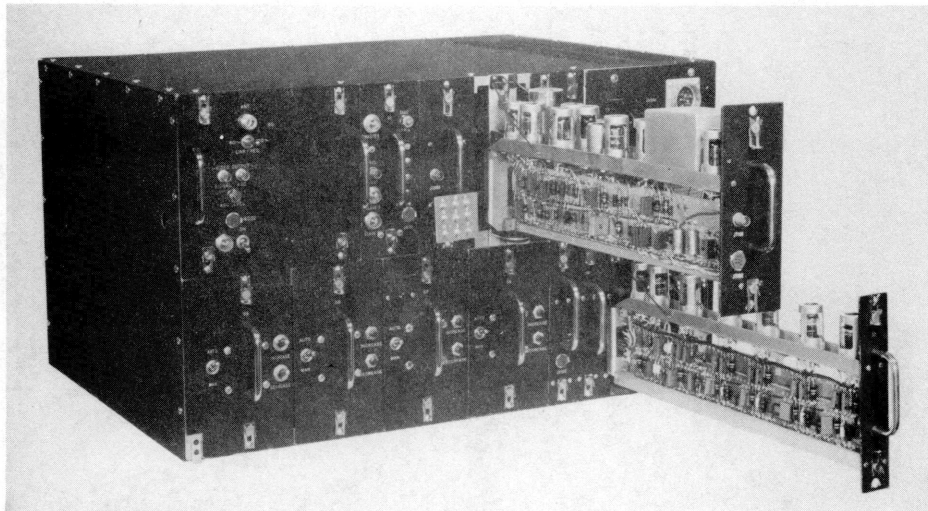
Figure 2

Digitac Computer

Figure 3

Input and Output Equipment

measurements circuits, instrument input converters and output units.

The aircraft used in these flight tests was a cargo type C-47 in which an E-6 autopilot was installed. A vertically stabilized camera was used in the aircraft to determine position so that the accuracy of flight control could be determined.

Objectives

The objectives of the flight test program were to evaluate the flight performance of this navigational system, including the digital computer. Considerable care was taken to lay out a test program that would provide the maximum operational data on the system. It should be pointed out that this constituted the first flight test of an airborne digital computer and the program was approached with the usual concern which accompanies the first trial of something completely new.

The following specific objectives were established for the flight test program:

> (1) To determine the accuracy of the position determination of the system by making measurements on the ground;
>
> (2) To determine the accuracy of position determination in flight using the vertically stabilized camera in the aircraft;
>
> (3) To carry out navigation through a series of way points, first (a) by pilot operation from PDI signals, and second (b) by automatic control of the aircraft through a digital auto-pilot coupler;
>
> (4) To determine the system accuracy of automatic navigation and dead reckoning.

Flight Tests

The three ground stations required for the system tests were located on hilltops in the West Los Angeles area and formed two base-lines five to six miles in length. This setup provided a sizable test area in the neighborhood of metropolitan Los Angeles where there are excellent check points for both ground and air tests, since many street-corner locations are known to first-order survey accuracy.

The first objective of determining the accuracy of fix on the ground was accomplished by mounting the receiver and time measurements

equipment without the computer in a two-ton van. Digital time measurements were recorded and position was computed to compare with geodetic coordinates. It should be noted that, while most of the data concerning these flight tests have been declassified, the operational data involving accuracies of the system still have a security classification.

The flight test program for completing the other three objectives was carried out over a period of 14 months; 59 flights were made for a total of 92 hours of flight time. This amounted to about one and one-half hours of flying time per week during the period of the test program. Of these flights, approximately three-quarters were made using the airborne digital computer.

Part of the test equipment developed for the flight test program was a digital data recorder. Fifteen digital quantities consisting of input data and results of computation could be extracted from the computer on call, displayed on a cathode-ray tube and photographed. Data could be recorded at the rate of about two sets per second automatically, or at longer intervals, under manual control. At 150 mph, a reasonable cruising speed for the C-47, the aircraft travels about 220 feet per second; hence, data could be recorded about every 100 feet. This test equipment proved very valuable in trouble-shooting and checking out of components as well as in evaluating the performance of the complete system.

In carrying out the second objective of determining accuracy of position in the air, flights were made over well-defined locations close to first-order survey points in the area; for example, the Santa Monica water tower is near a first-order survey point and has the advantage that the diameter of the water tank gives an additional yardstick for measurements in the photographs. The computer was programed for coordinate transformation from hyperbolic to rectangular coordinates, and the position data were recorded when the aircraft was directly over the selected point. Simultaneously, a photograph was taken by the vertically stabilized camera and then the accuracy of fix could be determined by comparing these two records. After the accuracy of the time measurements had been established from the vertical photographs, the position of the aircraft in later flights was determined mainly from the recorded time measurements data.

For completing the last two objectives of the system, a complete programing of the system equations for navigation was required. A flow chart of the computer program is shown in Figure 4. From the time measurements and instruments data, position is determined in
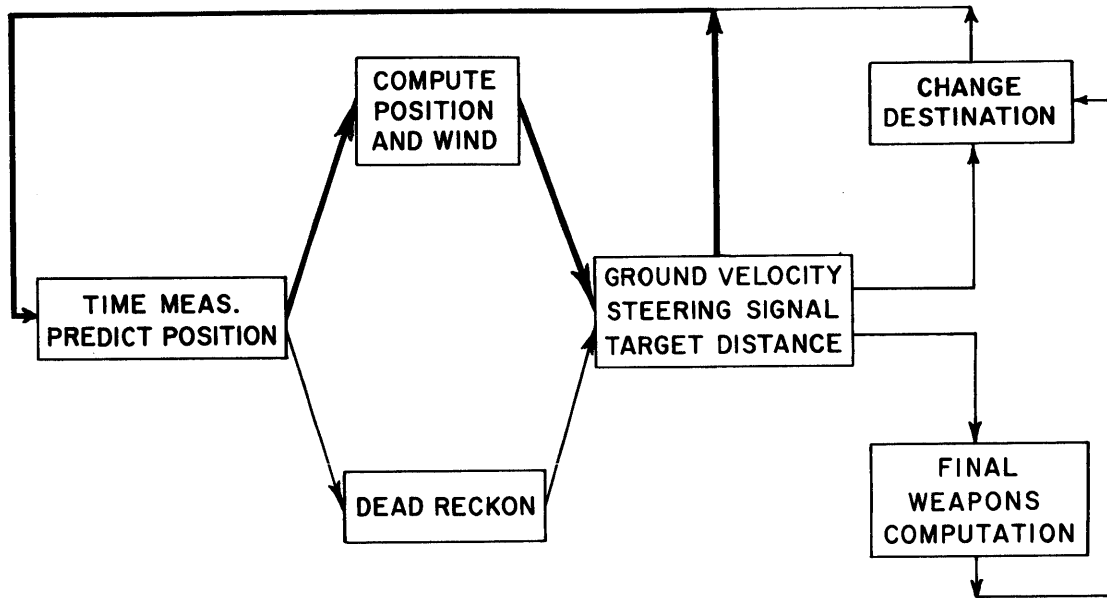
Figure 4

Navigation Problem

in X-Y-Z coordinates, with the X and Y axes corresponding to N-S and
E-W directions. A fast-converging iterative method involving predicted
position was used for transforming hyperbolic to rectangular coordinate
position. The wind is determined from the computed ground velocity
and the measured true air speed. A steering signal is then computed
which provides a heading correction for the aircraft to direct it to a
selected destination. In the absence of time measurement signals, dead
reckoning was carried out using a ground velocity computed from the
previously computed wind and the measured air speed. In the final
stages of the flight test program the computer determined smoothed
position, smoothed wind, ground velocity and steering signal. The
program, consisting of approximately 350 steps, required about 0.5 of
a second. The computation time for the dead reckoning mode of opera-
tion was 0.3 of a second, and since the iteration time was held fixed at
0.5 of a second, there remained 0.2 of a second dead time. By peri-
odically forcing the computer into the dead reckoning branch of the
program, computations for the weapons control part of the system were
solved during this additional 0.2 of a second. Thus, many auxiliary
computations can be carried out without increasing the length of
computation time or decreasing accuracy of control.

Figure 5 shows the manner of connecting the coupler to the auto-
pilot system. The upper loop shown in this figure without the differential
is the normal loop for autopilot control, while the lower loop modifies
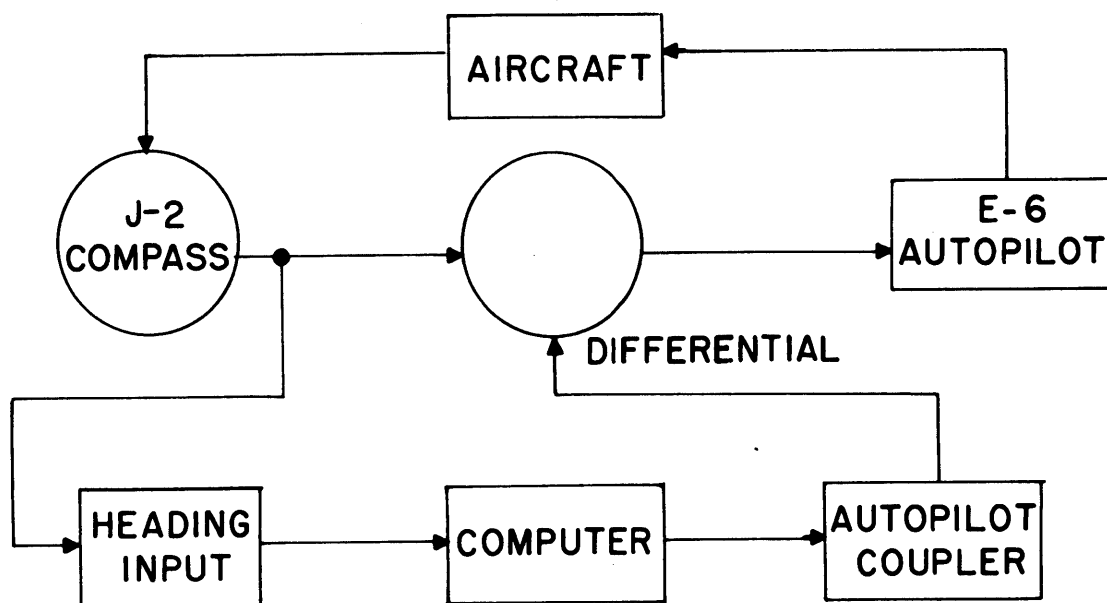
8

Figure 5

Autopilot Control

the autopilot heading through a differential for automatic digital computer control. This approach provides control without interfering with the normal operation of the autopilot loop. Details of the autopilot coupler used in the system are being reported in another paper at this convention.[6]

For checking out the program in the laboratory before flight testing, an automatic plotting board was connected with the computer, making it possible to "fly" in the laboratory. This was done by entering a position, wind, air speed, and heading into the computer together with the coordinates of a sequence of way points, and the dead-reckoned course of the computer through these way points was plotted on the board. The output steering signal was used to modify the heading input through the autopilot coupler as if the aircraft had zero response time. This technique was valuable in determining errors in the program and also provided an excellent laboratory demonstration.

After laboratory checkout had been completed the third objective of navigating the aircraft through a series of four way points was carried out. Four accurately known locations in the West Los Angeles area are shown in Figure 6 together with the baselines. The point nearest the baseline is a roofhouse at Hughes Aircraft Company. The other points are the Santa Monica water tower, a street corner in the San Fernando
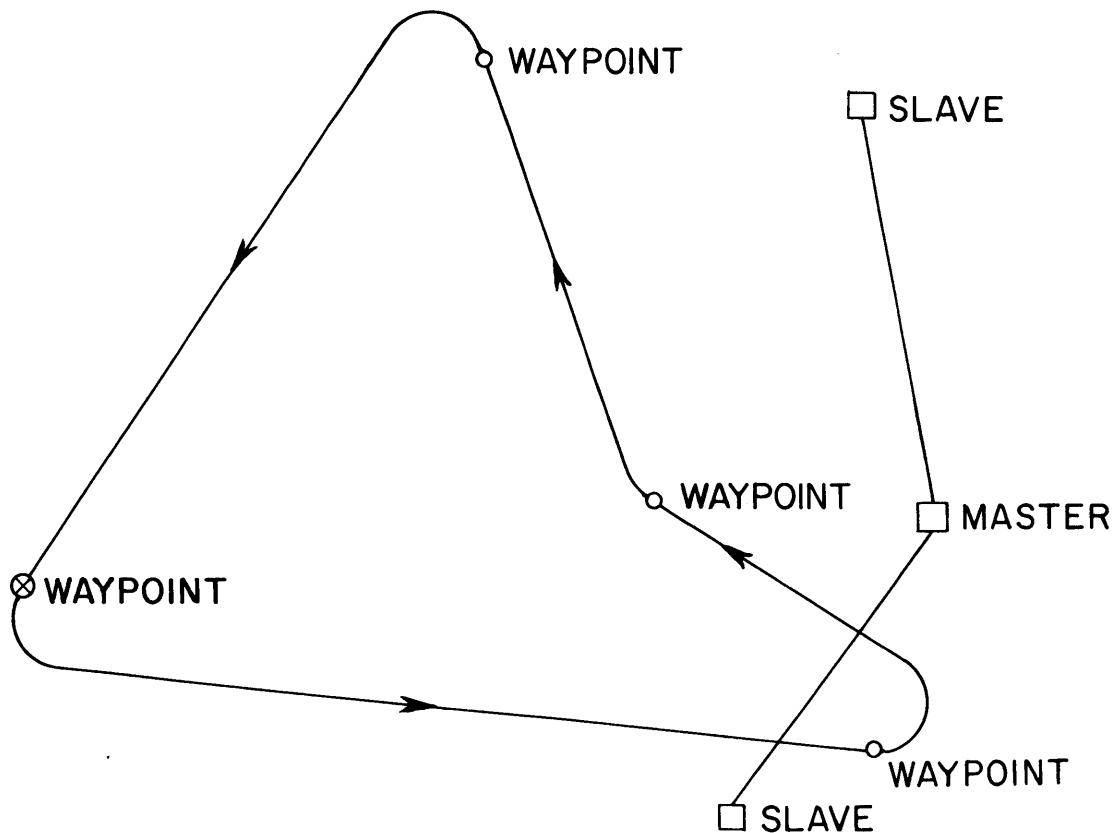
Figure 6

Typical Programed Course

Valley, and a radio tower in the Santa Monica mountains. This group
of points includes the geometrical cases of high, medium, and low
divergence of hyperbolic coordinates and one point behind the baseline.

Initial flights through this series of way points were made by having
the pilot control the aircraft from output signals displayed on a Pilot
Director Indicator. These flights with manual control were highly success-
ful and many improvements in programing were made on the basis of the
operational results. They also served to provide a basis for comparison
with completely automatic control. The steering signal from the computer
is such as to guide the aircraft in a straight-line path to a selected
destination from any point in the service area. In this manner the aircraft
is guided to the first point of the sequence from any starting point. On

reaching a preselected range from this point the computer selects the next point in the sequence, etc. On reaching the fourth point the aircraft is then again directed to the first point.

This ability to program a computer through a sequence of way points is an extremely important characteristic which should prove very valuable in operational automatic flights. It is estimated that 20 to 30 way points could easily be programed in the computer memory in this fashion.

One of the big steps in the flight test program was the first completely automatic flight around this same array of way points. The autopilot coupler was installed and the flight through the first way point was made under pilot's control. The system was then switched to automatic control and it successfully guided the aircraft through the sequence of way points. In comparison with manual control the automatic control was smoother and more accurate. The computer iteration time of 0.5 second did not lead to any difficulties in stability; in fact, stable control was obtained in later flights with longer iteration times.

For the final objective of determining the accuracy of automatic navigation and dead reckoning, the digital data recorder described earlier in this paper was used extensively. For automatic navigation, data were recorded at 0.5-second intervals and the control accuracy was determined by comparing computed position with position derived from raw time measurement data for points along the flight course. Vertical photographs also were taken in some tests. Dead reckoning accuracy also was very easily checked by forcing the computer into this mode of operation and simultaneously recording dead reckoned position and raw time measurement data for comparison. As indicated previously, quantitative results of these accuracy tests are classified.

It should be noted that one of the way points in Figure 6 lies behind the baseline in a region where some position ambiguity might be encountered; however, the computation technique, using predicted position, permitted accurate flight through this area. The point in the Santa Monica mountains lies in a region of the hyperbolic field where the coordinate divergence is high; however, the programing for the problem also gave smooth control in this area.

Many changes were made in the programing of the computer during the course of the flight test program in order to improve the system operation. Constants in the program, as well as program steps, may be readily changed. For example, various constants were tried in

flight to determine optimum velocity smoothing, and the final choice was to smooth by taking one-half the position computed from time measurements and one-half the predicted position. Dead-reckoned position was computed from the smoothed wind and air speed vectors, and during dead reckoning no changes were made in the wind. In smoothing the wind, 1/32 of the computed wind was combined with 31/32 of the previous smoothed wind to obtain a new value. This provided a heavy damping on the wind computation and 20 to 30 seconds are required to accumulate a stable wind. It is not required that the aircraft fly a straight, level course during this settling time, but only that coordinate information be received during this period. The constants chosen for smoothing the aircraft position and wind are for this particular aircraft-autopilot combination and, in general, will be different for other systems.

All of these programing changes indicate clearly the value of being able to make quick changes in the problem without changes in equipment. This is especially valuable in flight tests for system evaluation in which delays may ground an aircraft with a field test crew standing by.

Conclusion

These flight tests have shown that the use of a digital computer in an airborne control system is practical and that it adds tremendous versatility and flexibility to an automatic control system that would be difficult to obtain by other techniques. The unique advantages of a digital computer for flight control as demonstrated by these tests are as follows:

(1) High computational accuracy is easy to obtain with a digital computer. This is especially important since there is a tendency toward higher accuracy in new systems.

(2) The problem formulation can be readily changed without changes in the computer equipment. This also means that one airborne digital computer may be used in a variety of different airborne control systems.

(3) A programed flight through a selected series of way points is possible. Up to 20 or 30 way points may be used and a selector switch may be provided to select any destination or sequencing may be followed automatically.

(4) The equipment is easy to mass-produce, since essentially no precision parts are required. The use of plug-in sub-assemblies not only makes for ease of fabrication but also simplifies maintenance, repair, and spare parts problems.

In looking to the future we may predict that the day is not too far off when one standard airborne digital computer will be used in a variety of different military and commercial systems for automatic navigation and control. Such a digital computer in an aircraft can not only handle the control functions of the system but also may act as the central computing point for a variety of auxiliary computations, such as cruise control, air data reduction, predicted time of arrival, and other problems.

In concluding, it should be stated that these flight tests have been a milestone in the history of airborne digital computers. The computer equipment used in these tests reflects the state of the design art three to four years ago and is now obsolete. However, the big step has been taken to demonstrate that airborne digital computers are practical and that they have such a versatility and flexibility that future use of air-borne digital computers will be widespread.

The program described in this paper was made possible through the cooperative efforts of a small group of engineers at Hughes Aircraft Company and the sponsoring agency, the Armament Laboratory, Wright Air Development Center.

List of References

[1] E. C. Nelson, "A Digital Computer for Airborne Control Systems," 1952 IRE Western Electronic Show and Convention, Long Beach, California.

[2] E. E. Bolles, "The Digitac Airborne Digital Computer."

[3] D. W. Burbeck, E. E. Bolles, W. E. Frady and E. M. Grabbe, "The Digitac Airborne Control System," Western Computer Conference, Los Angeles, California, February 1954.

[4] D. W. Burbeck and W. E. Frady, "Precision Automatic Time Measurement Equipment," 1952 IRE National Convention, New York, N.Y.

[5] A. D. Scarbrough, "An Analogue to Digital Converter," 1953 Western Electronic Show and Conference, San Francisco, California.

[6] W. L. Exner and A. D. Scarbrough, "A Digital Autopilot Coupler."

THE DIGITAC AIRBORNE DIGITAL COMPUTER

by

E. E. Bolles

Introduction

Digitac is a completely automatic navigation and weapons control system incorporating the first airborne digital computer. The development of the digital computer for this system was undertaken in 1949, a time when the computer field was almost totally concerned with the design and construction of large-scale scientific computers. It was felt that a general purpose digital computer that would be compact enough to be airborne, and thus make the accuracy and versatility of digital computation available to an aircraft control system, could be developed. Such an airborne digital computer has been developed and flight tested. Because this computer was a general purpose machine, it was capable not only of accurately solving the required navigation and weapons control problems, but also demonstrated the advantages of a control element whose method of operation could be rapidly and easily changed. The ability of a digital computer to select alternate modes of operation, based on numerical data, was utilized repeatedly.

The problem of controlling an aircraft smoothly with the quantized steering information supplied by the computer is discussed in another paper being presented at this convention. [1] The results of the flight tests of this system are also being presented at this convention. [2] It suffices to say here that the flight tests were successful in proving not only that airborne digital computers can accurately solve the complex problems of aircraft control, but also that they can provide numerous advantages never before realized.

Design Features

The aircraft's position in the Digitac system is determined by measuring the difference in time of arrival of pulses transmitted by two pairs of ground stations. These pulse pairs define two hyperbolas, the intersection of which is the aircraft's position. The required navigation accuracy of this system indicated the need of developing a new method of measuring automatically these time differences. The measuring system is basically a counting technique combined with a vernier interpolation scheme. The equipment based on this principle is capable of measuring time differences to an accuracy of 0.02 microsecond, or about one part in 30,000. To take full advantage of this accurate digital input data it was decided that digital computation was necessary. Further investigation indicated that though the accuracy consideration is important, actually the versatility of digital computers is their predominent advantage.

Since this computer was to be a part of an airborne system and thus be subjected to the rigors of an aircraft environment, many of the basic computer design considerations were predetermined. The requirement of minimum size and weight indicated that the computer be a straight binary machine with operations performed in a serial manner. An early analysis of the system accuracy led to the use of numbers consisting of 16 binary digits plus sign. The choice of a general purpose design, with the problem instructions stored in the computer memory, was made to facilitate the many changes it was felt would arise during the flight test program. This internal program storage also allows the computer to be readily adapted to handle other system problems and new field situations.

The memory of the computer is a rotating magnetic drum, chosen principally because it is a nonvolatile storage system. Power and equipment failures, therefore, cannot destroy the memory contents. The magnetic drum memory conforms to the need for minimum size since the information stored per unit volume is very high. This type of memory is also well suited to use in a serial computer.

The memory has storage space for 768 two-address orders and 192 constants. Ninety-six storage locations and a six-word, fast access circulating register are available for the storage of the results of computation.

The arithmetic element of this computer is similar in logic to most present serial machines. It is composed of three static registers, an adder, and a sign control unit. Numbers are stored in the memory as absolute value plus sign. Subtraction is accomplished by adding complements; therefore, the sign of each number transferred to or from the memory is sensed and if necessary the number is complemented during the transfer operation.

The order code of the machine consists of 37 operations; 24 of these direct the sampling of inputs and ordering of outputs for navigation and weapons control. The remaining operations are the normal arithmetic operations of addition, subtraction, multiplication, division, and the associated transfer operations. To achieve minimum solution time, the arithmetic element is mechanized so that the result of any operation may be used as the first operand of another operation without the necessity of storing this result in the memory. To accomplish these series or cumulative operations, special addition, subtraction, multiplication, and division orders are provided.

One decision operation, which is used to select one of two alternate successive orders dependent upon the sign of the number in the arithmetic element, is provided. The use of this type of order, which is quite common in digital computers, provided a system capable of selecting alternate modes of operation based on prevailing conditions, rather than predicted conditions.

To achieve minimum problem solution time it was felt desirable to have a two-address, rather than single-address, code for the control element. In order to save memory space it was necessary to compress the information consisting of an operation, an operand address, and the next order address into a single word of 17 digits. Figure 7 shows the digit designation for an order word. Four digits
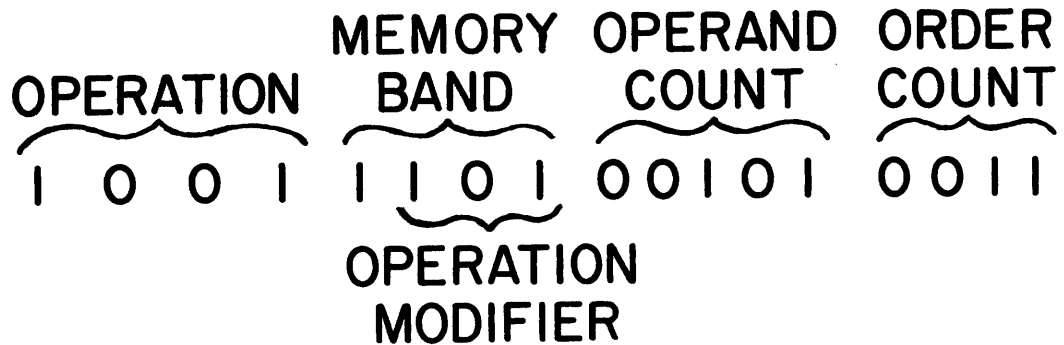
```
          MEMORY  OPERAND  ORDER
OPERATION  BAND    COUNT   COUNT
⏞          ⏞       ⏞       ⏞
1  0  0  1  1 1 0 1  0 0 1 0 1  0 0 1 1
              ⏝
           OPERATION
           MODIFIER
```

Figure 7

Order-Word Structure

18

of the word are used to designate the memory band (head) of the operand. This same band information also designates the band from which the next order will be obtained. Order and number bands are physically separate heads so the same band number can designate both a number and an order head. Four binary digits are used to designate the operation to be performed. Of the 37 operations performed by the machine, only 13 are arithmetic operations requiring reference to the memory. Since the four binary digits can designate a maximum of 16 operations, only three operations remain for input and output control. These operations, however, do not require memory reference so the information normally designating the band of the operand is not required. These three basic operations are each modified by three of the band digits giving a total of 24 input-output operations.

The last nine digits of the order word are used to complete the designation of the location of the operand and the next successive order. As previously mentioned, the band of the operand and the next order are specified so it is only necessary to indicate the desired sector. In most magnetic drum machines a sector is specified by a number given with reference to an origin or zero location on the magnetic drum. In the Digitac computer the address reference is not fixed, but rather the address is referenced to the completion of the last order operation. The ninth through thirteenth digits of the order word are the number of sectors between the location of the present order and that of the operand. After the order is read it is only necessary to count the indicated number of sectors and then perform the operation. The last four order digits are the number of sectors to count after completing the operation until reading the next order word.

This floating reference addressing system not only allows a compact order word, but also is a great aid in minimum time programing since the coder is aware of the access and operation time for every order in the program sequence.

Since each step of the order sequence is dependent upon the previous step, random errors may cause one of two types of sequence failures. An order may be selected from a blank address in the memory; in this case the sequence will immediately return to the beginning of the routine. If the selected address does contain an order, then the sequence will continue from that point. Both of these failures may cause discontinuities in the output; however, the filtering action on the outputs will minimize these discontinuities and the outputs will be normal during the next iteration.

Equipment

Figure 8 shows the Digitac computer. This computer is in a frame approximately 20 inches high, 26 inches wide, and 19 inches deep, a volume of about 5-1/2 cubic feet. All units of the computer are constructed on plug-in chassis, each chassis having a maximum of twelve tubes. The left half of the lower section contains the ten chassis of the arithmetic element and the control unit is in the remainder of the lower section. The wide chassis in the center of the rack contains the magnetic drum memory. The remaining chassis in the middle section are the memory read-write circuits and a group of timing pulse generators. The top portion of the rack contains the power wiring, heater transformers, and cooling system.
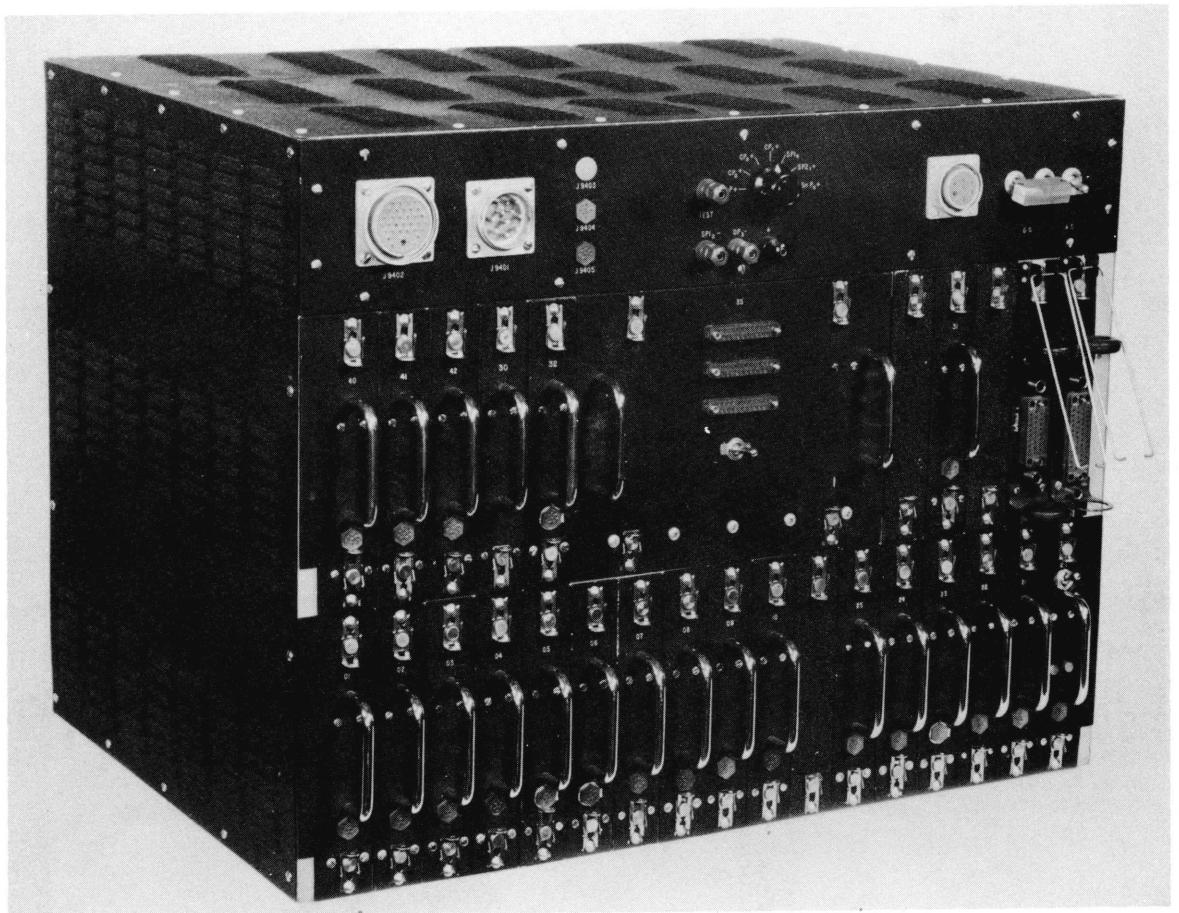

Figure 8
Digitac Computer

The entire computer contains 260 tubes and about 1300 diodes. The total power consumption is 1300 watts, including the cooling system.

Figure 9 shows the memory chassis when withdrawn from the rack. The drum is four inches in diameter, eight inches long, and rotates at about 7,000 rpm. It is a hollow aluminum cylinder with an oxide coating. There are 16 order heads, six number heads, two timing heads, and a pair of heads for a six-word circulating register. The pulse rate of the machine is 100 kc, which results in a recording density of about 75 cells to the inch. The non-return-to-zero form of recording is used. The read-back signal from these heads is a little over a volt peak-to-peak allowing the use of diode gating directly at the heads, rather than requiring individual preamplifiers before gating. Only one amplifier is used for each group of eight heads; the amplifiers are on the chassis to the left of the drum.
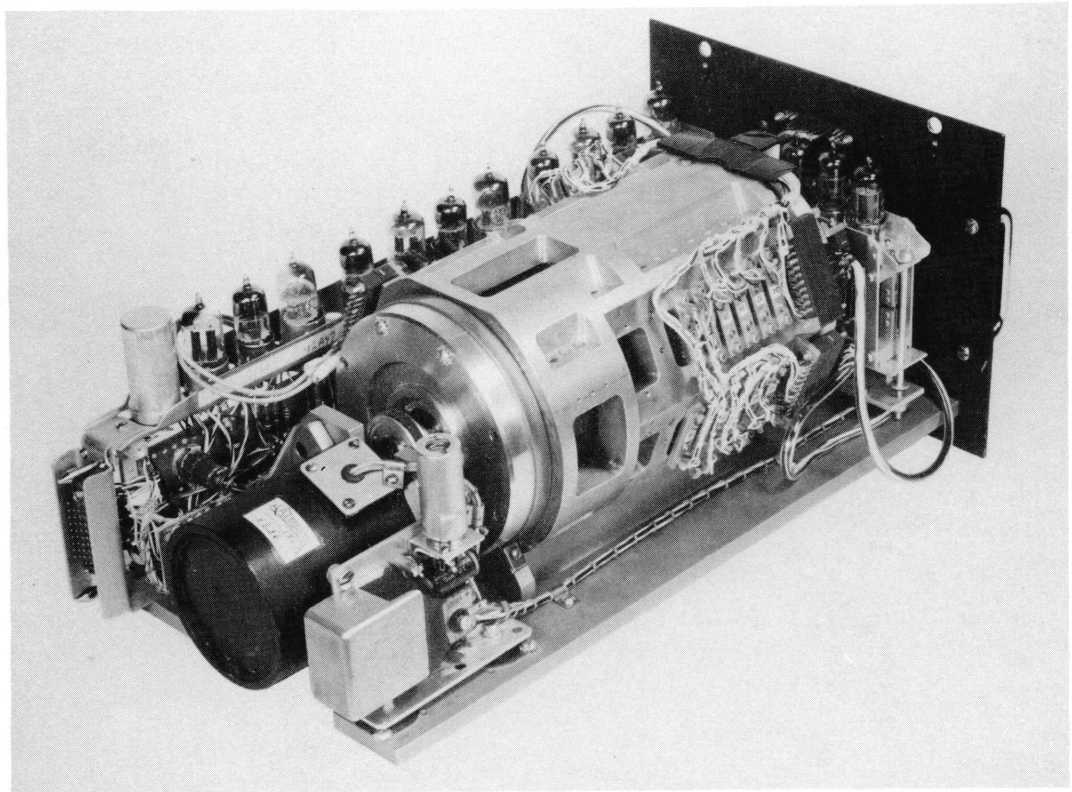

Figure 9

Magnetic Drum Memory

Computer Programing

The navigation problem the computer was required to solve in the air was essentially that of determining present position, selecting desired destination, and computing the control necessary to reach this destination. This over-all problem was, of course, actually composed of many smaller problems relating to either position determination, smoothing, or prediction dependent upon the particular situation.

As previously mentioned, the basic position information is in the form of two time difference measurements. These measurements define two hyperboloids of rotation whose intersection is a curve. Knowing the aircraft's altitude it is possible to define a point on this curve of intersection, thus establishing the aircraft's position in three dimensional space. Figure 10 shows the general form of the position equations of the system; x, y, and z are present position and r is the slant range to the origin. At the time of turn-on of the

$$X = f_1 (T_1, T_2, Z, R)$$

$$Y = f_2 (T_1, T_2, Z, R)$$

$$Z = f_3 (L, X, Y)$$

$$R = \sqrt{X^2 + Y^2 + Z^2}$$

Figure 10

Position Equations

computer, x, y, and r are assumed to be zero. Under these conditions, z is computed, and then x, y, and r are computed in turn. Since each computation is based upon the other computed quantities, the first few computed quantities will not be accurate; however, it has been shown that this form of iterative solution will converge anywhere in the service area within six iterations. During normal computation the value of r is predicted from past values. This prediction allows the computation of accurate values of x, y, and z, even though only one iteration is performed each program cycle.

Figure 11 is a flow diagram of the navigation problem. In the initial portion of the routine a measurement of the two time differences
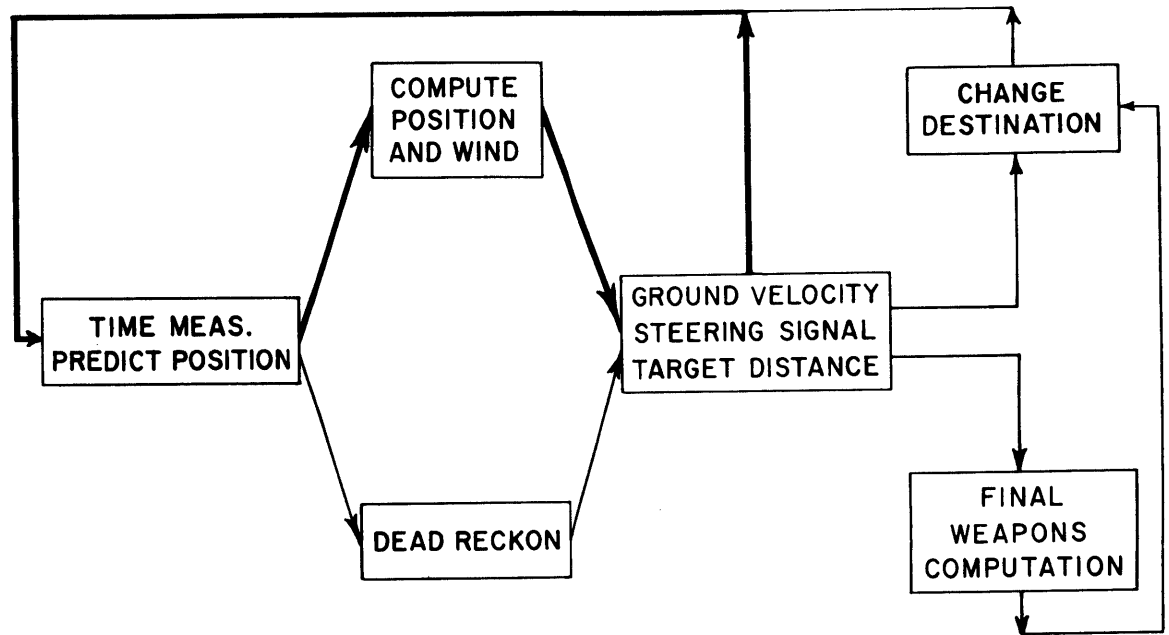

Figure 11
Navigation Problem

is ordered. These measurements are then examined to determine if they fall within a reasonable range. If these measurements are unreasonable, either due to interference or loss of signals, then the information is discarded and the lower branch of the routine is utilized. This dead-reckoning branch utilizes the past computed positions, accumulated wind values, and aircraft instrument data to predict present position. If the measured time differences are

usable, then the previously mentioned position solution is employed. In this branch of the routine the predicted or dead-reckoned position is combined with the computed position to achieve a smoother position.

The final block of the normal routine is a computation of ground velocity, wind components, and a steering signal. At this time the remaining distance to the destination is checked also. Assuming the destination has not been reached, then a return is made to the beginning of the routine. If the desired destination has been reached, either a change of destination is made or the final weapons' computation is made.

It is of interest to note that the weapons' computation does not normally require additional computing time. The dead-reckoning branch of the routine requires considerably less time than the upper branch, and this time is utilized for the weapons' computation. To insure that these computations are carried out periodically, the computer is forced into this routine every 32 cycles.

Figure 12 shows the method of position and velocity smoothing used. This smoothing is necessary, since the computed positions will jitter due to noise on the received signals, the quantized nature of the time measurements, and the divergence of the hyperbolic lines. A predicted position is obtained from the past position and the distance travelled in one iteration time. The present position is obtained by combining the computed and the predicted positions. In the flight tests it was determined that the combination of these quantities should be equally weighted. Each cycle, a rough ground velocity is computed by the differences of position since the past iteration. The time base used in these velocity computations is not fixed, but rather is a function of the routine length and the magnetic drum speed. To simplify the magnetic drum system, this speed is allowed to vary, and a portion of the time measurement equipment is used to measure the drum speed each iteration. The rough ground velocity is used in the cycle only to allow the computation of a rough wind. The smooth wind is accumulated by combining a very small portion of this rough wind with a major portion of the past wind value. A very heavy smoothing factor is used, about 31 to 1, assuming that the average wind value will not change rapidly. This heavy damping factor does not affect the prediction of position even during maneuvers, since the ground velocity used for prediction is formed by combining the smooth wind value and the airspeed as presently measured from the aircraft instruments. All the computations mentioned are actually performed in rectangular coordinates requiring that the airspeed be broken into its components based on the measured heading.

$$\widetilde{P} = \text{COMPUTED POSITION (rough)}$$

$$\overline{P} = P_{n-1} + (V_a + W_n)\, \Delta t \quad \text{(predicted)}$$

$$P_n = c\overline{P} + (1-c)\, \widetilde{P} \quad \text{(smoothed)}$$

$$\widetilde{V}_g = \frac{P_n - P_{n-1}}{\Delta t} \quad \text{(rough)}$$

$$\widetilde{W} = \widetilde{V}_g - V_a \quad \text{(rough)}$$

$$W_n = d W_{n-1} + (1-d)\, \widetilde{W} \quad \text{(smooth)}$$

Figure 12

Smoothing Equations

The aircraft instrument inputs to the computer are altitude, heading, and true airspeed. The analog-to-digital converters for these quantities are continuous reading devices that are sampled by direct order of the computer. Each instrument input quantity is checked by the computer to determine if it is reasonable prior to its use. If any quantity is not reasonable, the previous value is utilized.

The normal routine requires about half a second, during which time 360 operations are carried out. A total of 700 orders are required to include all the possible alternate routines and the weapon computations. Approximately 90 of the operations are multiplications or divisions.

In programing a problem of this type for a machine with a magnetic drum memory, it is important to minimize the average memory access time. The access time is the time wasted waiting to obtain numbers or orders from the memory. In the normal cycle of this problem there are 660 references to the memory with an average access time of only one and one-half word times.

It is of interest to note that the program for this system uses the decision or alternate routine orders more than 50 times. The extensive use of this type of order is one feature that makes airborne digital computation so attractive. By properly programing these decisions the computer is used to check all input data and select the proper method of computation to best utilize this information. Each input quantity, such as altitude, is first checked to determine if it is within a maximum and minimum bound and then is checked by comparison with the past value. If the quantity either exceeds the bounds or the change from the past value is too great, then this quantity is discarded and the previous value is used. This checking technique greatly reduces the effects of any noise present in the input data.

Conclusions

The Digitac system has shown very successfully that digital computers can be extremely powerful tools when applied to airborne control problems. The accuracy potential of digital computation is quite well known; it is not as well known that the versatility of digital computers can be their greatest asset. One computer such as the Digitac computer can be used as the computation element of many different systems without the need for any equipment changes. New situations in field operations can be handled by easily-made program changes. Digital computers are definitely the airborne control elements of the future.

List of References

[1]W. L. Exner and A. D. Scarbrough, "A Digital Autopilot Coupler."

[2]E. M. Grabbe, D. W. Burbeck, and S. B. Neister, "Flight Testing of an Airborne Digital Computer."

A DIGITAL AUTOPILOT COUPLER

W. L. Exner and A. D. Scarbrough

Hughes Research and Development Laboratories
Culver City, California

Introduction

The autopilot coupler which will be discussed in this paper was developed as a part of an automatic, precision, aerial navigation and weapon control system. This system, which was developed and successfully flight tested under a U.S.A.F. contract, is known as Digitac. One of the noteworthy features of this system is that it marks the first successful use of an airborne digital computer to control an aircraft.

This paper will deal with some of the problems associated with the use of a digital computer in such a control system and describe the autopilot coupler which was developed for this application. Two other papers, describing the Digitac computer and the flight testing of the complete Digitac system, are being presented at this convention.[1, 2]

Problems of Digital Control

In contemplating the use of a digital computer in any automatic control system, careful consideration must be given to two characteristics of digital computation.

The computer requires a finite time to complete a problem solution. This inevitably results in some delay in the computation of the control function, and since the inclusion of delay in a closed-control loop tends to cause instability, this delay cannot be ignored. The magnitude of the computation delay depends upon the speed of the computer, the complexity of the problem, and the skill with which the problem has been coded. The Digitac computer, for example, is a fairly high speed machine, which can add 2640 sixteen-digit binary numbers per second and perform other arithmetic operations with corresponding rapidity. However, the problem to be solved is so complex that each complete solution requires approximately one-half second.

The second characteristic of digital computation which can cause trouble is the fact that it is possible for the computer output to fluctuate violently, either as a result of rough input data, or because of malfunctioning of the computer. The effect of input data noise may be satisfactorily minimized by proper programing of the problem, but spurious transients resulting from computer malfunction can best be rejected by analog filtering of the computer output. It is obvious that, in a practical system, computer errors must be infrequent and of short duration. However, in a system such as Digitac, where the

computer controls an aircraft, it is imperative to include enough analog filtering to protect the aircraft in the event of occasional computer error. Unfortunately, such filtering results in increased delay.

Problems of Aircraft Control

The basic aircraft-autopilot control loop is shown in Figure 13. Here the heading of the aircraft is measured by the compass, which
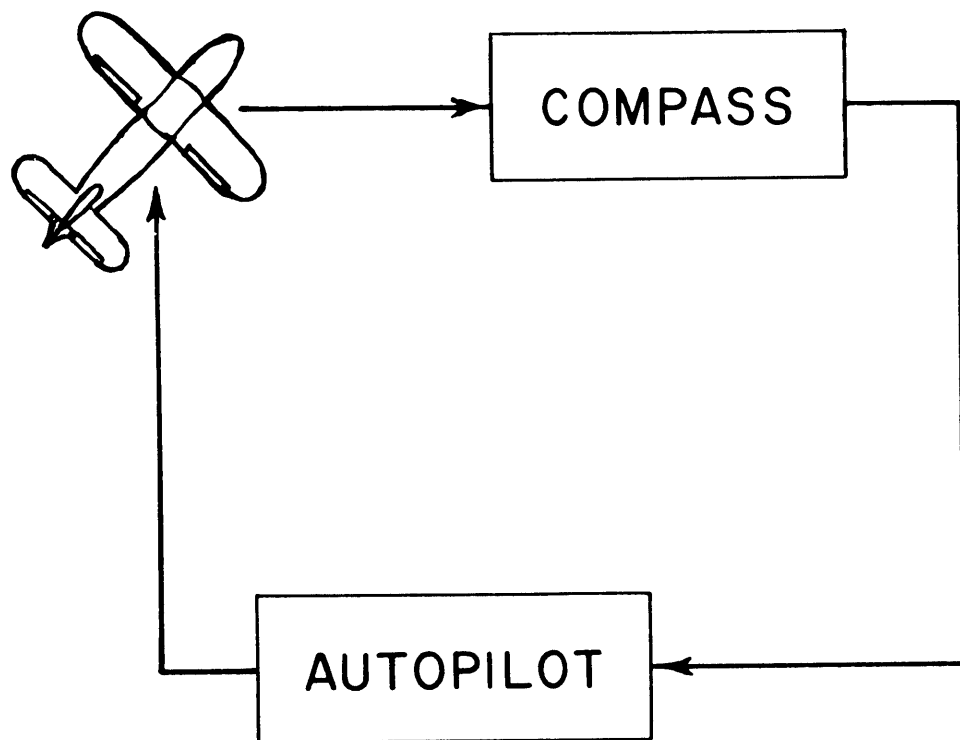

Figure 13

Basic Heading Control Loop

supplies the proper control signal to the autopilot to enable it to hold the heading constant. If a change in heading is required, it must be made manually through the autopilot turn control, after which the system will hold the aircraft on the new heading.

Perhaps the most obvious way to incorporate a navigation computer into such a system is shown in Figure 14. Here the computer
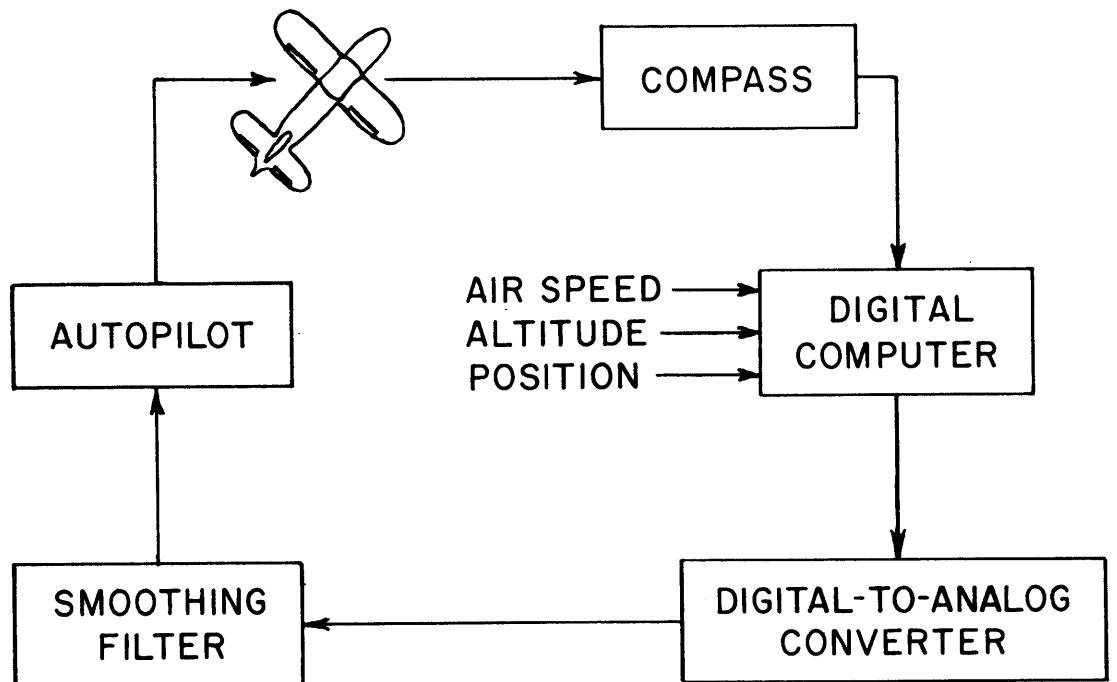

Figure 14

Control Loop, Including Navigation Computer

receives input data consisting of heading, airspeed, altitude, and ground position, from which it computes the required heading and, through a digital-to-analog converter and filter, supplies the autopilot with a steering signal to achieve this heading.

The basic function of the computer is to compute a desired heading which, since it depends on the aircraft position relative to its destination, and the drift due to wind, is a slowly varying function of time. Since in the system shown in Figure 14 the computer and filter are included in the aircraft-autopilot stability loop, the computer is required to pass all frequencies handled by this loop, some of which are many times higher than those associated with changes in the desired heading. This system therefore puts much more stringent requirements on the digital computer than its basic function demands.

In the Digitac system, the stability problem has been approached from a different point of view, as shown in Figure 15. Here the burden of providing aircraft stability is carried by the unbroken
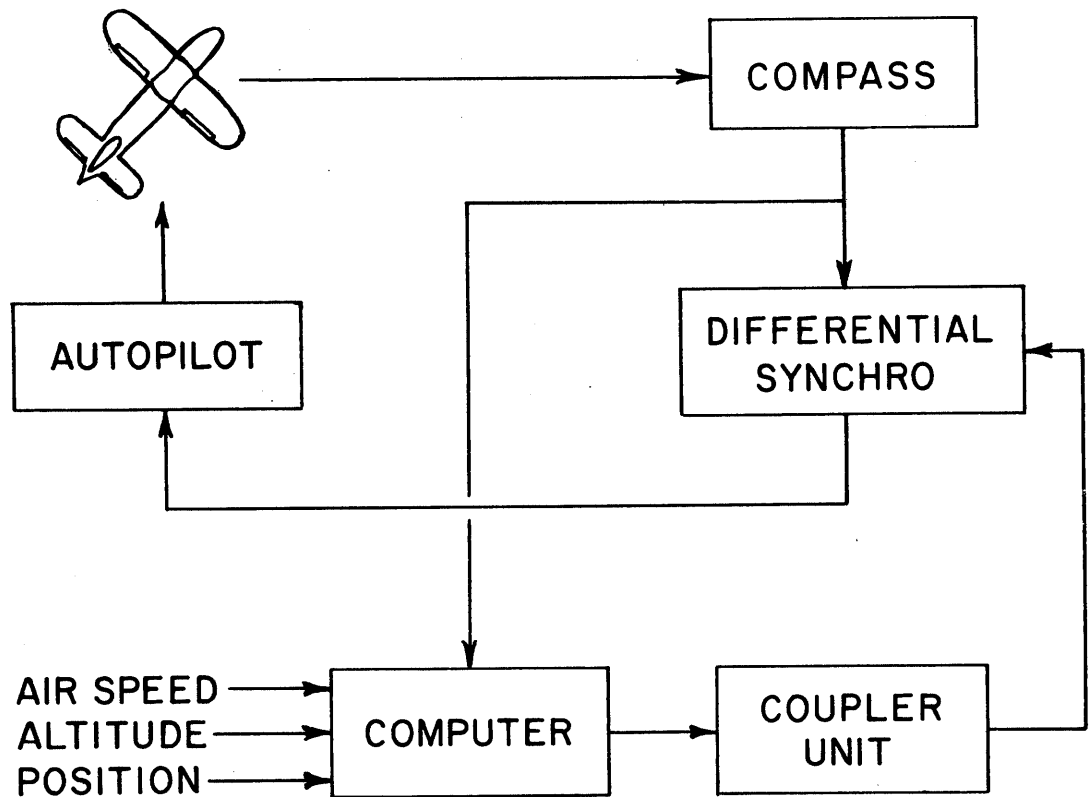

Figure 15

Digitac Heading Control

analog control loop consisting of aircraft, compass, and auto-pilot; and the computed heading error is added as a relatively slowly varying quantity. Although the computer output is heavily filtered to minimize the effect of spurious transients, this filtering, which is outside the control loop, has no effect on the aircraft-autopilot stability. It is apparent that the use of this method tends to simplify both computer and filter design, since it now becomes advantageous to filter out high frequency components of the computed steering signal which might be generated in turbulent air. Further-more, digital prediction and smoothing techniques can be employed with greater success when applied within this limited bandwidth.

It is fundamental to the operation of this system that the rate at which variations in steering signals are transmitted through the autopilot coupler be slow enough to provide adequate filtering, but fast enough to follow normal course changes. When radical course changes are required, the coupler saturates and holds the aircraft at a fixed bank angle until its heading approaches the heading required. This will be discussed further, after a description of the coupler equipment.

The Digitac Coupler

The E-6 autopilot, to which the Digitac coupler was tailored, is a precision autopilot designed primarily for the control of bombardment aircraft. It is a stable and precise autopilot and has excellent dynamic characteristics. All heading control is achieved through coordinated turns, the bank angle being a direct function of the heading error, up to a predetermined maximum bank, which for the Digitac tests was set at 20 degrees.

The heading reference for the autopilot was supplied by a J-2 Gyrosyn compass, the transmission between the compass and autopilot being by means of a pair of synchros. In order to modify this heading reference in response to the steering signal, it was only necessary to interpose a differential synchro between the compass and the autopilot and arrange for the shaft position of this differential to be positioned in accordance with the steering signal. The heading reference, as seen by the autopilot, is thus the compass heading plus-or-minus an angle which is a quasi-integral of the computed steering signal.

In addition to the differential synchro, the Digitac autopilot coupler consists of equipment and circuitry which smooths the digital steering signal supplied by the computer and positions the shaft of the differential synchro in response to the resultant function.

A block diagram of the complete coupler is shown in Figure 16. The mechanical drive for the differential synchro is provided by a bidirectional notching motor, whose shaft revolves 1/50 of a revolution for each applied voltage pulse and is locked in position
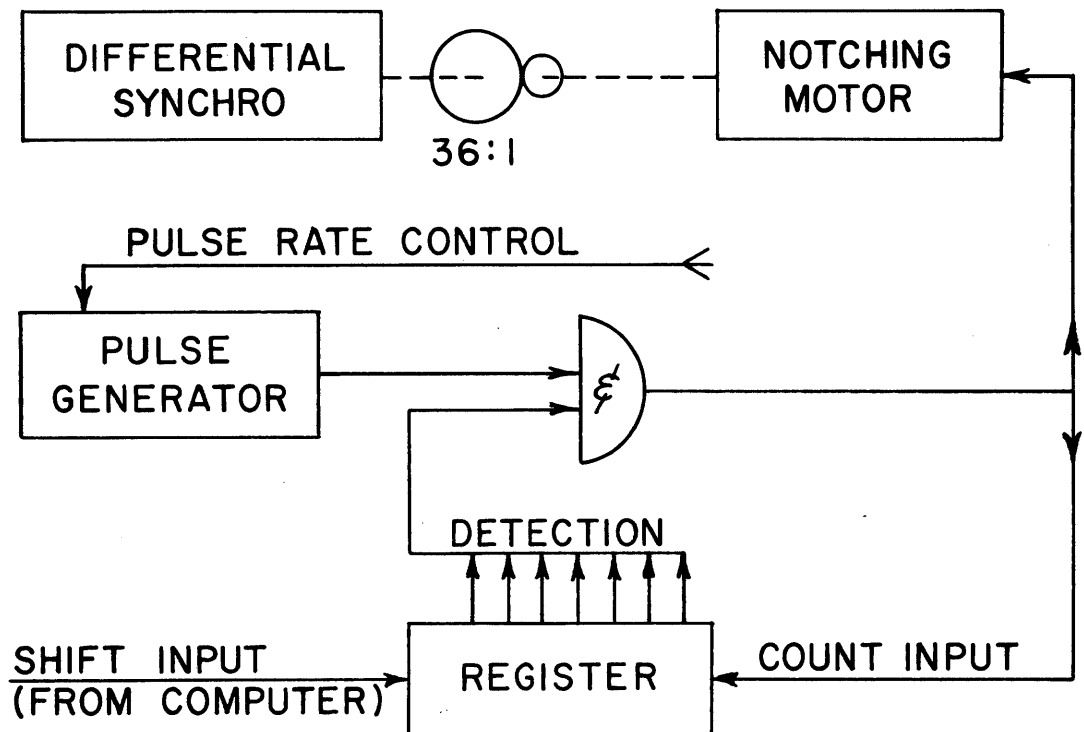

Figure 16

Digitac Coupler Block Diagram

at all other times. Direction of rotation is determined by a reversing relay, which is controlled by the sign of the computed steering signal. Since the notching motor is coupled to the differential synchro through a 36:1 gear train, each pulse applied to the motor corresponds to a heading increment of 1/5 of a degree.

Application of pulses to the notching motor is controlled by a seven-digit-plus-sign shifting-counting register, as shown in

34

Figure 16. The gate circuit allows pulses from the pulse generator to be applied simultaneously to the "count" input of the register and to the notching motor, except when the contents of the register are zero. Since the register is designed to count down, a number shifted into it (representing the steering signal) is then counted down to zero, whereupon the pulses are stopped. During this counting operation the notching motor and the differential synchro will have been rotated through an angle proportional to the magnitude of the steering signal. It should be noted, however, that, except for very small steering signals, there is never time for a complete count-down to occur. A new steering signal, representing the latest computed information, is shifted into the register each half-second, regardless of whether the previous count-down was completed or not. Thus, spurious steering signals of high amplitude but short duration have little effect on the autopilot.

In order to achieve the rapid correction of heading errors up to the full capacity of the register, without danger of over-control when the steering signal approaches zero, it has been found desirable to make the pulse rate proportional, within limits, to the steering signal. Since a voltage proportional to the steering signal is developed elsewhere in the system for operation of the PDI (Pilot Director Indicator), this voltage is used to control the repetition rate of the pulse generator shown in Figure 16, over a range of approximately four to 15 cycles per second.

Figure 17 is a photograph of the two chassis which include most of the circuitry of the research model of the autopilot coupler. These chassis are plug-in units which fit into a rack along with the rest of the input and output equipment of the Digitac system. The upper chassis holds the shifting-counting register, and the lower chassis includes synchronizing and control circuitry. Figure 18 is a photograph of the differential synchro and notching motor assembly, together with the circuitry required for the operation of the notching motor.

The coupler, operating as described above, has been demonstrated to be highly satisfactory for controlling the aircraft when the required heading changes are within the ±12.6 degree capacity of the shifting-counting register. However, the Digitac system must be able to control the aircraft over a preprogramed course, involving heading changes of up to 180 degrees, and for such heading changes a different mode of operation is required.

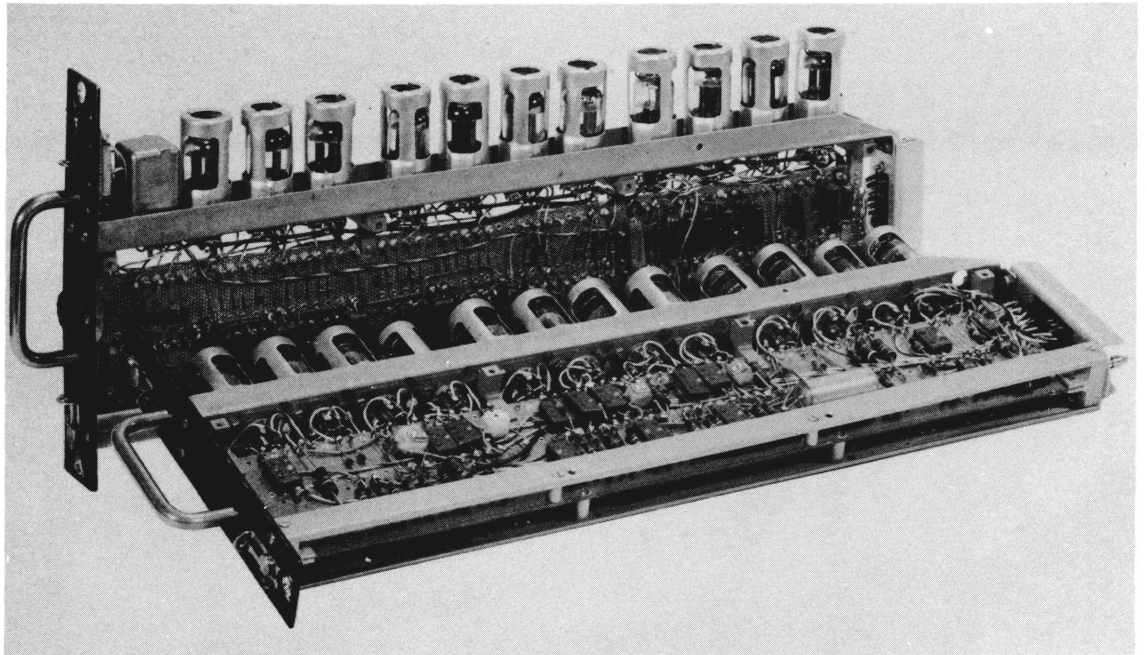In order to explain how this is accomplished, it will be
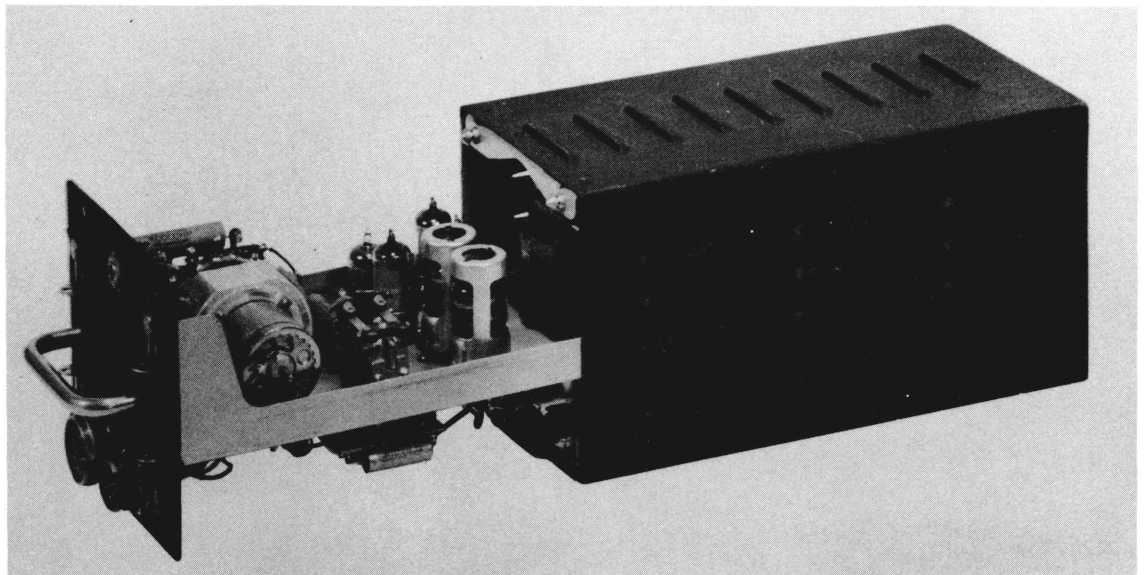
Figure 17

Register and Control Chassis

Figure 18

Differential Synchro Drive Assembly

necessary to describe the shifting-counting register in somewhat greater detail. Although the register consists of seven stages, only six of these are required to accommodate its full capacity of ±12.6 degrees, each bit being equal to 1/5 of a degree. The seventh, or most significant stage, contains a "one" whenever the computed steering signal indicates a heading error greater than this saturation value. Since there is no count propagation into the overload stage, whether it contains a "one" or a "zero" is determined solely by whether the last computed steering signal is greater or less than saturation. Whenever such saturation does occur, the pulse gate is held open, and simultaneously the repetition rate of the pulse generator is increased to approximately 30 per second. This causes the differential synchro to be rotated faster than the maximum rate of turn allowed by the autopilot, with the result that the aircraft is held in a fixed 20 degree bank.

During the turn a new steering signal is shifted into the register every half-second. As the turn progresses, the magnitude of these numbers progressively decreases, until eventually one appears which is within the normal capacity of the register. This indicates that the aircraft is within approximately 12 degrees of the required heading. As soon as this occurs the pulse gate is closed for five seconds, stopping the notching motor and allowing the aircraft to roll out of its bank. In accomplishing this roll-out, the aircraft turns through an additional 12 degrees which brings it to approximately the required heading; therefore, when the coupler returns to its normal mode of operation at the end of the five second delay, only very small heading corrections remain to be made.

Conclusions

When digital computers are applied to automatic aircraft guidance systems, their limited bandwidth may be insufficient to achieve stable operation if the computer is required to handle the entire control problem. The most promising approach to the stability problem appears to be to recognize that it consists of two nearly independent parts; namely, the aircraft stability problem, and the guidance stability problem.

The aircraft stability problem involves a wide band of frequencies, but the computations are simple and of a type which can readily be solved by analog techniques, as exemplified in conventional autopilots. The guidance stability problem is much more complex and, since several modes of operation may be required, the flexibility of digital computation is desirable. Fortunately,

37

the required bandwidth is well within the capabilities of moderate speed digital computers.

The method proposed in this paper for combining the two types of computation has been proven by extensive flight tests to provide smooth and accurate control, even during periods of operation when, for one reason or another, the steering signal was so erratic as to make it almost impossible for the pilot to hold the aircraft on course by following the PDI. Once the optimum range of pulse rates had been determined, there was no tendency for the system to overcontrol, yet required heading corrections were accomplished by the coupler at least as efficiently as by the human pilot.

The design of an autopilot coupler for use with any particular system must inevitably depend to a considerable degree on the peculiarities of the computer and the autopilot with which it will be used. However, it is believed that the basic principles of the Digitac coupler will prove widely applicable, not only to other airborne digital control systems, but also to many other automatic control systems where it is desired to take advantage of the accuracy and flexibility of digital computation.

List of References

[1] E. E. Bolles, "The Digitac Airborne Digital Computer."

[2] E. M. Grabbe, D. W. Burbeck, and S. B. Neister, "Flight Testing of an Airborne Digital Computer."