signed to minimize the effects of short wordlength and truncation inherent in the computer. Several alternate sets of equations developed during the Cytac study were discarded because of the difficulty of programming them for the computer. The set of equations used gave satisfactory control of the aircraft and indicated satisfactory bomb release during several test runs made with this computer in a B-29 aircraft.

The computer program was also tested, prior to this time and apart from the actual system, on the Florida Automatic Computer (FLAC) at the Patrick Air Force Base. Furthermore, complete simulation trials were made at a Reac installation at the Sperry Gyroscope Company laboratories using the Cytac-digital computer and the radio time-measuring equipment which had already been thoroughly debugged and flight tested apart from the computer.

The final program used about 1000 orders, 150 constants, and 50 temporary storage addresses. Five channels of 320 words were allocated for test-program storage. The actual length of the computation cycle was set for about one second whereas the time required was about 0.8 second. The one-second period was chosen since it was consistent with airframe-stability requirements and the smoothing factors desired.

This project demonstrated that a digital computer could be utilized as a very flexible part of a control system with reliability and size to make it a practical component of an airborne system.

A typical analog computer arrangement which might have fulfilled all the functions provided by the digital computer would have required more than 25 servoamplifiers, 21 assorted synchros, 45 potentiometers (many of which would require special or high-precision windings), 20 servomotors, 8 tachometers, 20 differentials and assorted gear trains, supporting hardware and electronics, and power supplies. Using present-day techniques, this equipment could also be expected to weigh at least 150 pounds and fill more than three cubic feet, with the question of ultimate accuracy left unanswered. On the other hand, a digital computer designed for the same problem with present-day techniques would require no more space or weight and would definitely be capable of meeting the accuracy requirements. Servicing of either type of computer would not be a pleasure, and reliability and serviceability of each would be on the same order of magnitude.

CONCLUSION

At the time that the Cytac program began, neither the equations to be solved nor all the functions to be performed had yet been stipulated. Faced by a short development time, an existing general-purpose computer for the job seemed most advisable since it provided ease of making changes in programming and addition of control functions with no extra equipment development. Optimum programming permitted the achievement of computation time commensurate with airframe-stability requirements with a magnetic drum-memory computer.

On the other hand, where there is sufficient time to develop a computer best suited for the job, a special-purpose machine may turn out to be fastest, lightest, and smallest, with a resulting loss of flexibility in making program changes with the ease provided by a general-purpose machine.

Some Experimentation on the Tie-In of the Human Operator to the Control Loop of an Airborne Navigational Digital Computer System

CORWIN A. BENNETT[†]

INTRODUCTION

ONE of the human operator's most important tasks in contemporary bombing and navigational systems is crosshair error correction or "tracking." Due to navigational or intelligence errors, the system's crosshairs may not fall on the target or other reference point. When the operator recognizes this error he sends correcting signals, by means of a hand control, to the computer which then corrects the display.

Typically, bombing and navigational systems have used analog computers to process the operator's control signals. However, when a digital computer is utilized, the operator is faced with the new problem of seeing the results of his corrections periodically on the display at the solution rate of the digital computer.

With this "sampled-data" tracking, when the operator

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moves the target across the display it seems to "jump" from point to point. The apparent discreteness is an inverse function of the inertia in the system. Since the operator's control signals are accepted by the computer only at sample times, part of them are ignored. This becomes particularly noticeable at low solution rates. Since the complexity of the digital computer is determined in part by its solution rate, it is necessary to minimize this rate. On the other hand, if the sampling of the operator's control produces poorer tracking performance with lower solution rates it should be maximized. The problem faced by the engineering psychologist is to determine a computer solution rate at which neither of these two goals—equipment simplicity and tracking performance—is unduly sacrificed.

DESCRIPTIVE EXPERIMENTATION

A series of experiments was carried out over a period of three years to provide systems engineers with design requirements for digital tracking. While initially the question of required solution rate was the sole object of investigation, later study was devoted to related sampled-tracking problems and to possible ways of circumventing stringent equipment requirements.

Fig. 1 shows the digital control loop studied in most of these experiments. The operator's near-continuous control signals are sampled by analog-to-digital converters. These numbers are processed by the digital computer which, among other things, integrates the signals. This integration means that a rate of crosshair movement is proportional to a displacement of the control which is known as a rate or velocity-tracking control. The computer's outputs are converted back to analog form and displayed as periodic display changes. Feedback is then provided through the operator.

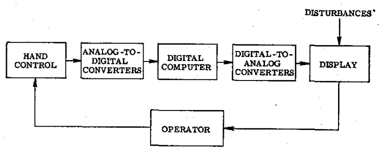
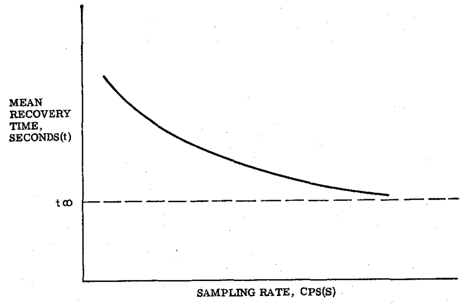


Fig. 1—Digital rate-control loop.

In the experimentation such a loop was simulated by means of an analog computer and relays, a spring-loaded joystick, and a laboratory oscilloscope. The simulation was such that sampling in time (at the "solution rate") was carried out, but sampling in amplitude (at the "quantization level") was not. While quantization could be critical for tracking, the systems converter resolution was such that with a rate control no great problem existed.

Laboratory technicians and engineers served as subjects in each of the experiments. The actual running of a given experiment would last just a few days, although weeks of preparation and equipment "debugging" were generally required. Time records of error were made to obtain performance measures. The usual performance measure was "recovery time"—the time it took the operator to place the target under the crosshair to a given tolerance for a specified initial error. Conventional statistical analyses and significance test were performed on the data.

Fig. 2 shows a typical curve for the relationship between recovery time and solution rate. As the solution rate is decreased, recovery time increases; as the solution rate increases, performance improves, and recovery time approaches that obtained under analog-tracking conditions asymptotically. Statistical tests were applied to determine a specific solution rate which could be considered as yielding performance that was equivalent to analog conditions. In most cases this rate turned out to be on the order of 10 cps—a number to which engineers could design in order to insure no loss of tracking performance with the digital system.



$$t = \frac{K_1}{K_2\sqrt{S}} + t_\infty$$

Fig. 2—Recovery time as function of sampling rate.

One parameter which was discovered to be highly critical in this initial experiment was the display-control ratio, or gain or sensitivity of the hand control. This may be defined as the displacement of the display (or one of its derivatives) for a given control-displacement. Numerous investigators have shown the control sensitivity to be a significant determinant of tracking performance. For example, our results showed a U-shaped relationship between recovery time and sensitivity; that is, as the sensitivity is raised or lowered from optimum sensitivity, performance deteriorates. Furthermore, we demonstrated that, as the sampling rate is decreased, the optimum sensitivity is decreased. This required us to predetermine optimum sensitivities for all experimental conditions prior to testing. For the systems engineer, whether dealing with a digital system or not, the practical implication is apparent. Since, within limits, sensitivity or scale factor is one of the easiest equipment changes to make, an optimum value should be selected for any given situation.

One way of reducing the complexity of the digital computers (other than by reducing the solution rate) is to allow more solution periods for processing each set of inputs. Computer delays or "transmission-type delays" were therefore studied in one experiment.

Fig. 3 shows the results of one solution-period delays, as compared to no delay on tracking performance—re-

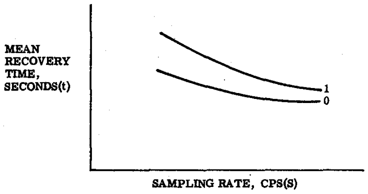


Fig. 3—Effects of transmission delays on recovery time.

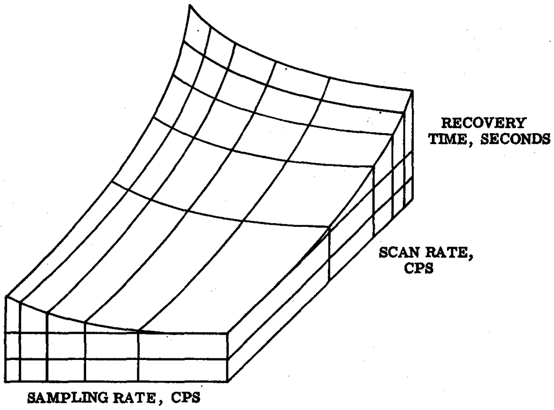


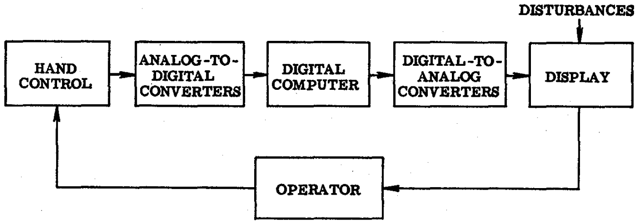
Fig. 4—Recovery time as function of both sampling and scanning rate.

covery time increases with the addition of delays. Similar results have also been found for other types of delays such as the "exponential delays" associated with equipment inertia. Analysis of the two-delay conditions, studied here, indicated that the performance differences would disappear at about 20-cps solution rate.

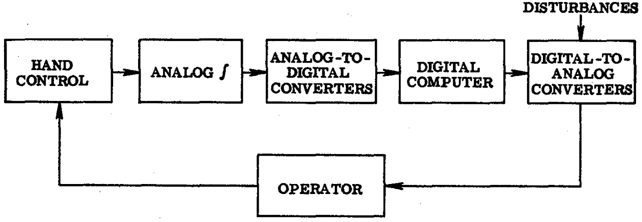
One further parameter studied was that of scan rate. In the navigation system using a radar display for tracking as well as digital computation, a second kind of time sampling, that of scanning, takes place. Two alternative hypotheses for the possible combined effects of scanning and sampling were suggested. First, the effects of sampling and scanning on tracking might be completely independent. Second, it might be that if the scan rate of the display were very low it would be unnecessary to have high solution rates to optimize performance, that is, there would be an interaction between sampling and scanning effects.

Fig. 4 shows the results of this study. In brief the effects of sampling are of the same nature regardless of scan rate. Both scanning and sampling degrade tracking and they do so independently. Thus, within equipment limitations, both rates should be maximized.

In this study the two rates were unsynchronized. We thought that if we synchronized the scanning and sampling, or set up some phase relation between them, that the scanning could prove a useful signal of sampling time. Thus, at low rates, the operator might benefit from knowing when sample time was going to occur. This did not prove true. The addition of any auditory signal preceding sample time did not prove useful either in the range of practical rates. It is obvious, however, that at very low rates, say 0.01 cps, such a signal would be essential.



PRIOR INTEGRATION



SUBSEQUENT INTEGRATION

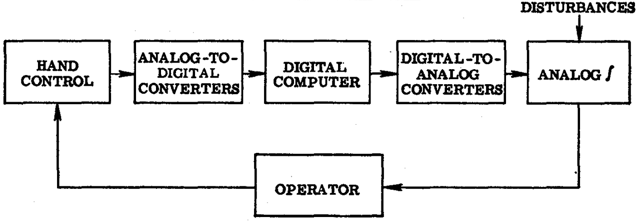


Fig. 5—"Normal," "prior," and "subsequent" intergration loops.

IMPROVEMENTS PHASES OF INVESTIGATION

Summarizing the results described, sampling of the operator's control loop reduces the tracking performance, and the lower the solution rate the poorer the performance. The engineer is thus faced with the problem of building a digital computer to operate at higher rates than would be otherwise necessary.

In considering why time sampling degrades tracking with a rate control, some possible solutions suggest themselves. First, at low rates, a noticeable number of the signals the operator imparts to his control are not seen by the computer at all, since they do not occur at sample time. If, however, the hand-control signals were to be integrated analogwise before sampling, all signals would have an eventual effect on the display. This is labeled "prior integration." Second, the discontinuities in events on the display may be causing the trouble. If the integration were performed after the reconversion to analog form, there would be no discontinuity in the positional information on the display. This has been called "subsequent integration." These loops are shown in Fig. 5, with the essential differences from normal" or "digital" integration being the locus of the integration in the control loop. Comparisons were made between the performance yielded for the three loci of integration conditions. In sum, not only did the two analog-integration conditions not prove superior to the digital-integration loop, they proved to be inferior. Just why this happened is not clear, but in any case they offered no solution to the practical problem of building a low solution-rate computer.

Another line of attack to the problem of too high solu-