C. A. Bennett

Experiments on The Relation of the Operator to the Control Loop Of an Airborne Digital Computer

Abstract: Some laboratory experiments were performed over a period of three years to provide design information for digital computer systems for error correction in aircraft navigation. In a simulated digital control loop, the operator observed crosshair error and fed control signals to the computer. The studies showed relationships between recovery time and solution rate, transmission delays, hand-control sensitivity, sampling rate, and scanning rate.

Introduction

One of the human operator's most important tasks in contemporary bombing and navigational systems is crosshair-error correction or *tracking*. Because of 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 crosshair position and the display.*

In a bombing and navigational system using an analog computer to process the operator's control signals, the operator sees the results of his corrections as a steady movement of the display, known as *analog tracking*. However, when a digital computer is used, the operator is confronted with a periodical shifting of the display at the solution rate of the computer, thus making tracking more difficult. This is termed *sampled-data* or *digital tracking*.

With such sampled-data tracking, the target seems to "jump" from point to point when the operator moves it across the display. The degree of discreteness that is apparent is an inverse function of the inertia in the system. Thus, if no inertia is present, the controlled element appears only at those specific points on the display which the computer has calculated at the previous sampling time. With inertia, however, a finite time is required to get the blip to the calculated point, and the blip "moves" rather than "jumps." If the time constant of the inertia is sufficiently great, this movement is completely smooth. These effects are shown in the oscilloscope traces of Fig. 1.

*Such corrections must obviously also apply to the aircraft's position, either directly or indirectly. Just how this is accomplished is of no immediate importance to the operator's control behavior.

Since the operator's control signals are accepted by the computer only at sample times, part of them are ignored by the computer, an occurrence that becomes particularly noticeable at low solution rates. Therefore, the solution rate should be maximized because the sampling

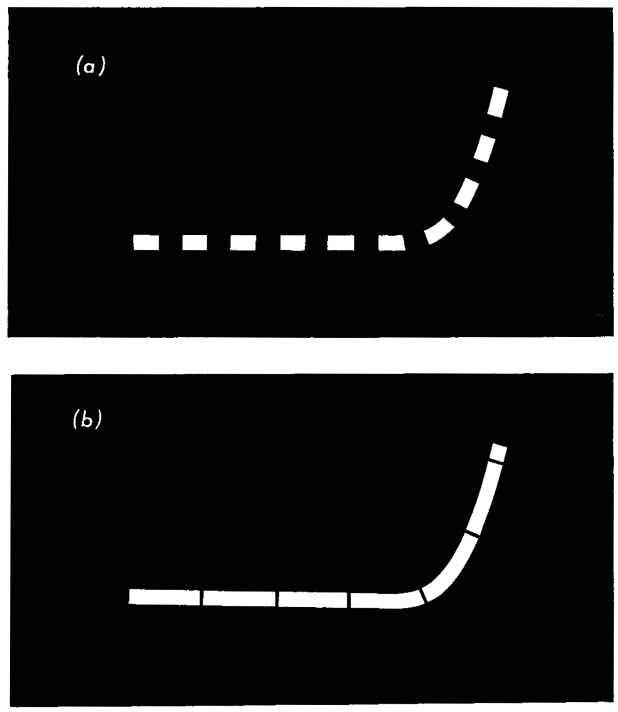


Figure 1 **Form of oscilloscope traces contrasting (a) low and (b) high inertia.**

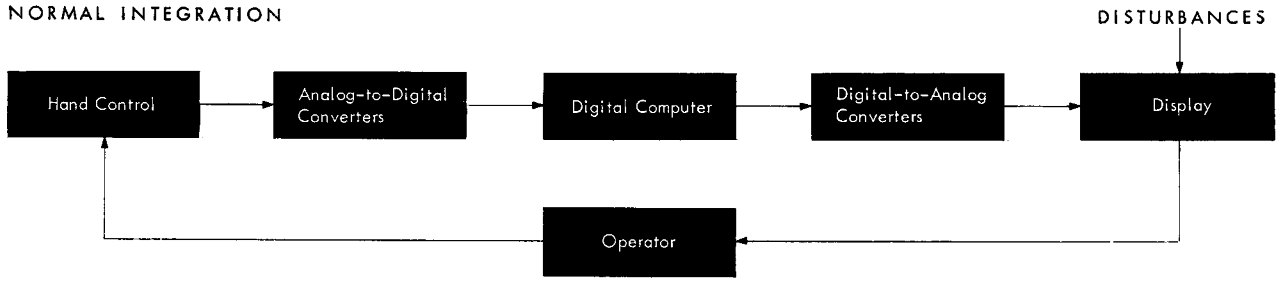


Figure 2 **Digital rate-control loop.**

of the operator's control at lower solution rates produces poorer tracking performance. However, because the complexity of the digital computer increases with increased solution rates, the sampling rate must be minimized. Consequently, the engineering psychologist is faced with the problem of determining an optimum computer-solution rate at which neither of these two goals—equipment simplicity nor good tracking performance—is unduly sacrificed.

Initial experimentation

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

Figure 2 shows the digital control loop studied in most of these experiments. The operator's control signals are sampled by analog-to-digital converters. These numbers are processed by the digital computer, which integrates the signals, among other things. The integration means that a rate of crosshair movement is proportional to a displacement of the control. This is known as a rate- or velocity-tracking control. The outputs of the computer are converted back to analog form and displayed as periodic display changes. Feedback is then provided through the operator.

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. These characteristics are shown in Fig. 3. At the top of the Figure, a hypothetical analog-control signal is shown as a function of time. In the central Figure, this signal has been sampled in time; that is, every T seconds (the solution time) the signal is sampled and held. The inverse of T is the sampling rate, S, in cycles/sec.* The lower Figure shows the same signal quantified as well as sampled, that is, it is allowed to take on only integer values. Physically, this corresponds to the numbers which are sent from the analog-to-digital converters to the computer, and which are then used in whatever computations the computer may perform. We might speak of the difference between any two adjacent values as the resolution of the converters—an important matter in position control.

In each of the experiments surveyed here, an incidental sample of seven laboratory technicians and engineers were used as subjects, although not the same individuals in all experiments. In the typical experimental design, each subject served under each experimental condition several times with the order of conditions randomized.

In all but one of the experiments the target was displaced instantaneously in random direction and magnitude (one inch or less) from the fixed crosshairs. The subject's task was to return the target by means of his hand control as quickly as possible to within a one-eighth-inch tolerance circle. In the remaining experiment, the disturbance function was a 0.1-inch/sec rate rather than a position change.

Time records of error similar to the functions of Fig. 3 were made. The usual performance measure was "recovery time"—the time it took the operator to place the target under the crosshair to tolerance. A logarithmic transformation of these time scores was applied to promote homogeneity of variance. Analyses of variance were performed to enable testing the statistical significance of the various effects. Regression analyses were performed for curve fitting.

Figure 4 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, recovery time asymptotically approaching that obtained under analog-tracking conditions. Statistical tests were applied to determine a specific solution rate which could be considered to yield performance equivalent to analog conditions. The results of most of these tests showed the solution rate to be on the order of 10 cps—an engineering design value which would insure no loss of tracking performance with the digital system.

The one exception was the experiment in which rate disturbances were used. The *continuous-equivalent sam-*

*The abrupt change at each sample time is the jump. With inertia the value would rise exponentially to the asymptote rather than jump.

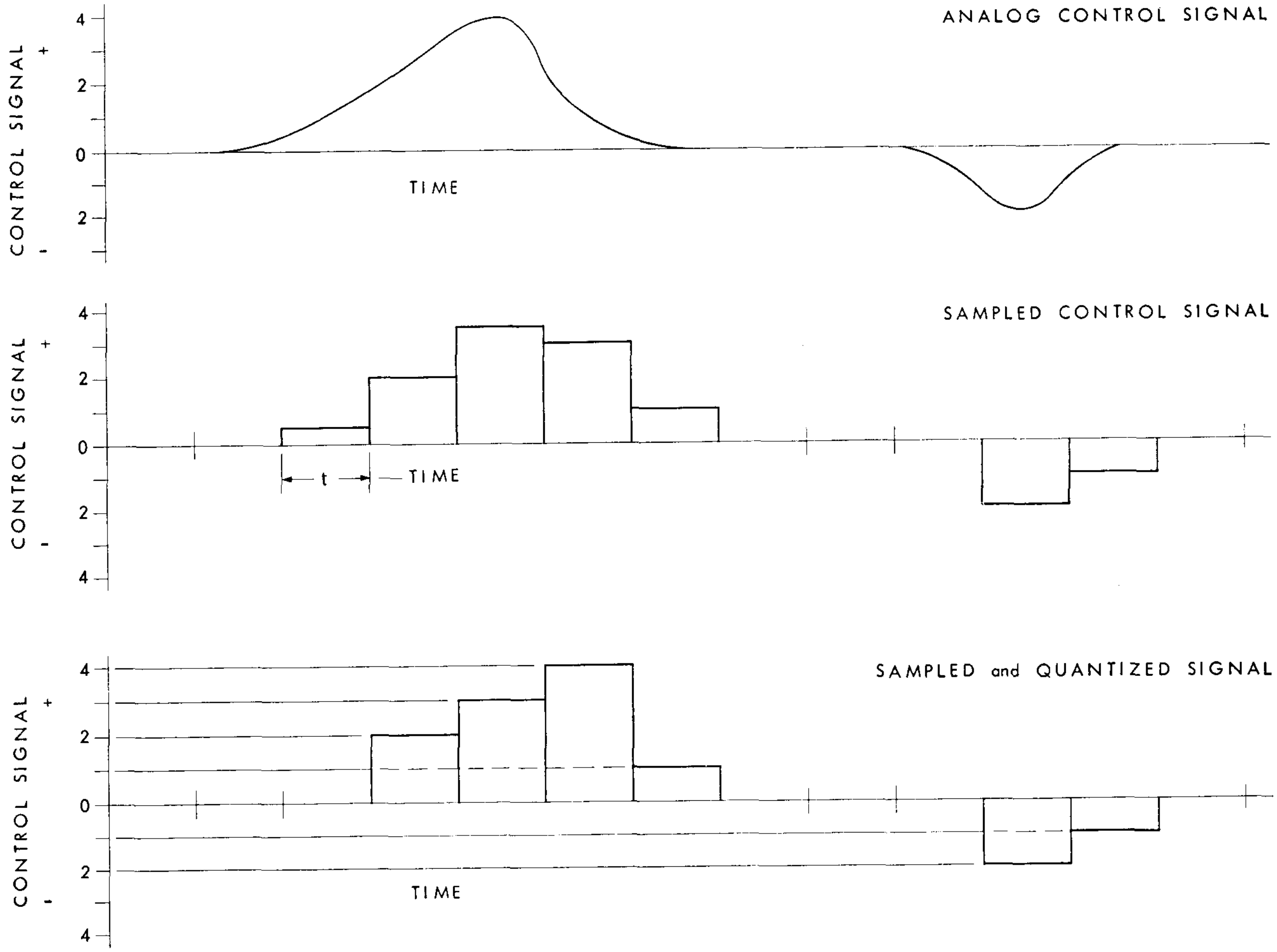
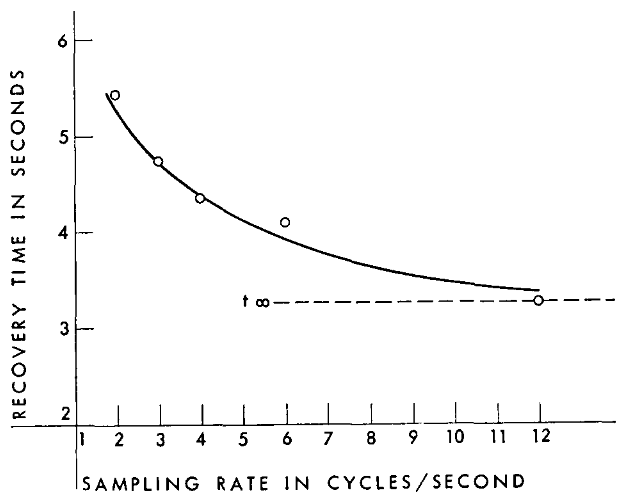


Figure 3 **Sampling and quantization.**

pling rate was 5 cps in this experiment. Because no further study was made along these lines, no explanation for this result is available.

One parameter which was discovered to be highly critical 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 investigations have shown the control sensitivity to be a significant determinant of tracking performance. (Our results in Fig. 5 showed, for example, 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 that we predetermine optimum sensitivities for all experimental conditions prior to testing. For the systems engineer, whether he is 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

Figure 4 **Recovery time as function of sampling rate.**



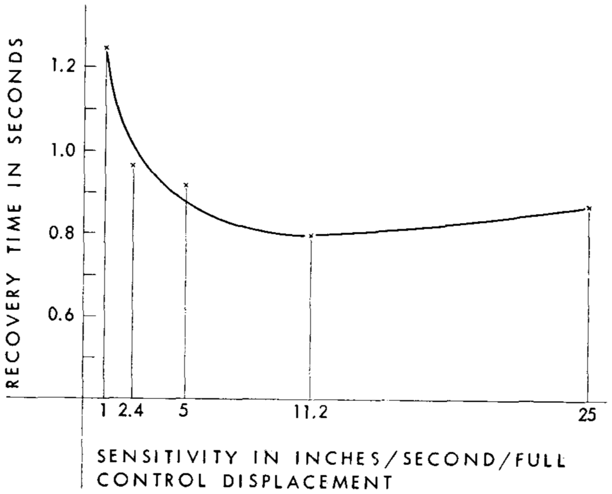


Figure 5 **Sensitivity effects.**

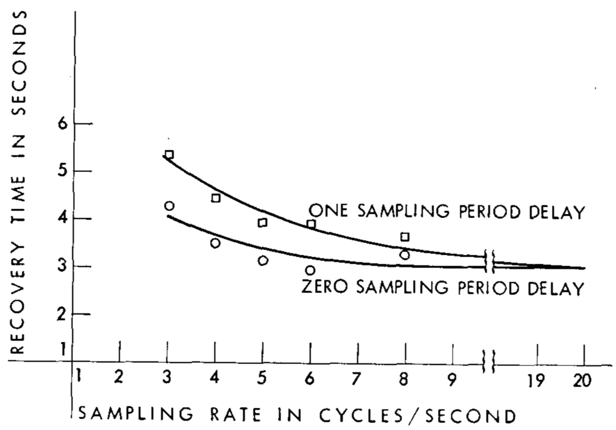


Figure 6 **Effects of transmission delays on recovery time.**

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 to process each set of inputs. By doing this it is possible to process more information in series and less in parallel. Thus, some of the parallel computing units may be eliminated. Such additional computational periods result in *transmission-type delays,*[1] that is, a fixed length of time before the operator sees the results of his control actions. One experiment conducted compared a one-solution period delay with a no-delay condition; that is, for a two cps sampling rate, a delay of one-half second as compared with no delay.

Figure 6 shows the results of this study: recovery time increases with the addition of delays. Similar results have been found for other types of delays such as the *exponential delays* associated with equipment inertia.[2] Extrapolation from the present results suggests that the performance differences between zero and one-period delays would disappear at about 20 cps.

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. Whereas sampling means that control signals are utilized only periodically, scanning means that the display is "painted" periodically. 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.

Figure 7 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 to be true. The addition of an 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, since a solution period of 100 sec would require greater time-judging capabilities than the human being possesses in order that the operator might make his correction at sample time.

Improvement phases of investigation

In summary, 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 otherwise be necessary. Obviously, it would be desirable to try to find some way to improve the performance without increasing the sampling rate.

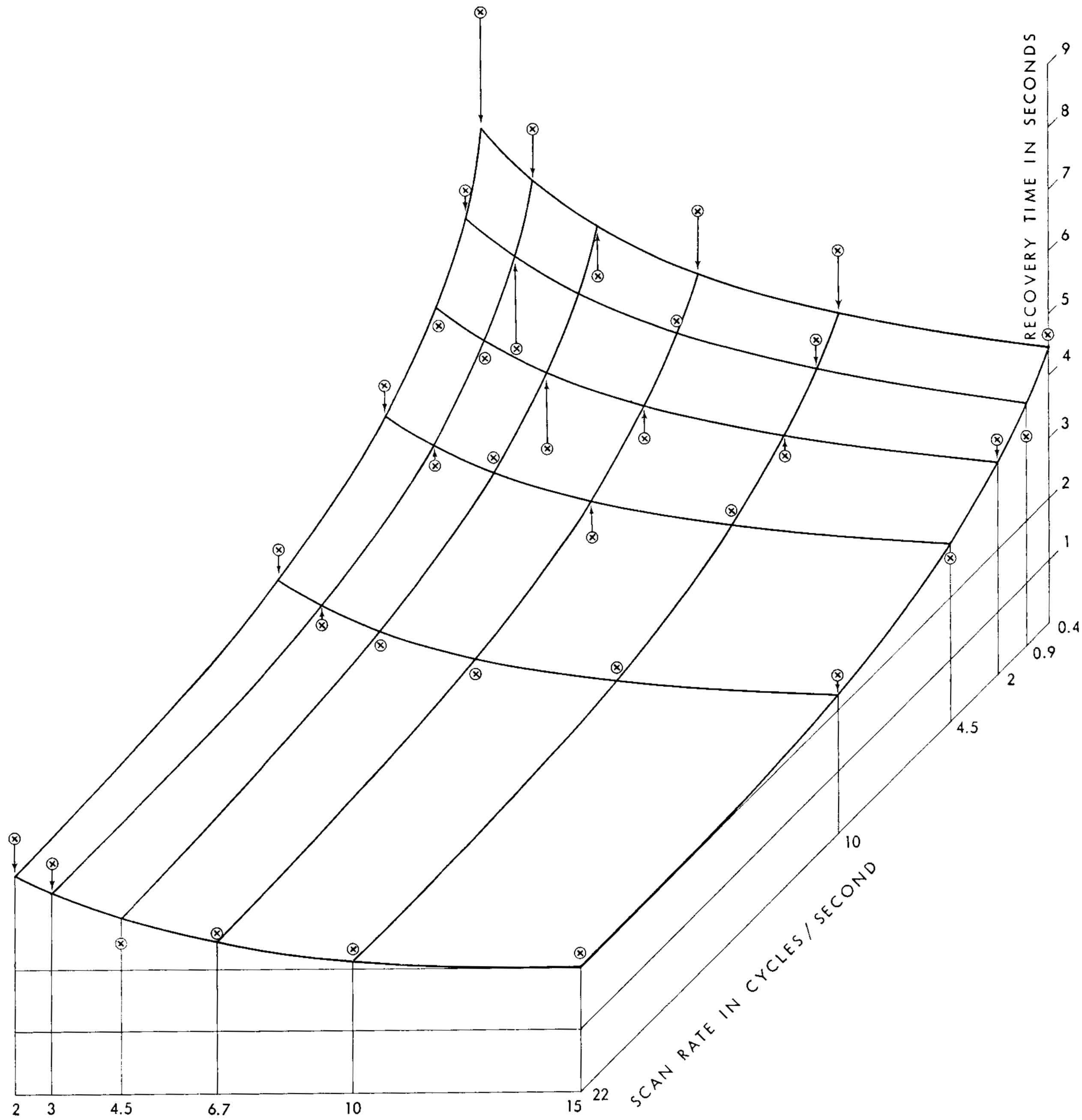
There are several possible reasons why time-sampling degrades tracking with a rate control. First, at low rates a noticeable number of the signals the operator imparts to his control are not seen by the computer at all, since they do not occur at sample time. If, however, the hand-control signals were to be integrated (analog) 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

*A multiple correlation of 0.95 showing the goodness of fit of the linear regression surface (for log recovery time), indicates little interaction between scanning and sampling, as did the analysis of variance.

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. 8, the essential differences from *normal* or *digital* integration being the locus of the integration in the control loop. Figure 9 shows qualitatively the effects of prior and subsequent integration. Thus, it may be noted that the "spike" from the hand control between sample times 8 and 9 results in an input to the display only for the prior integration case. Also, the smoothness of the input to the display of subsequent integration should be compared to the other cases.

Comparisons were made between the performance yielded for the three locus-of-integration conditions. The two analog integration conditions proved to be inferior to the digital integration loop. Just why this happened

Figure 7 **Recovery time as a function of both sampling and scanning rate.**



is not clear, but in any case they offered no solution to the practical problem of building a low-solution-rate computer.

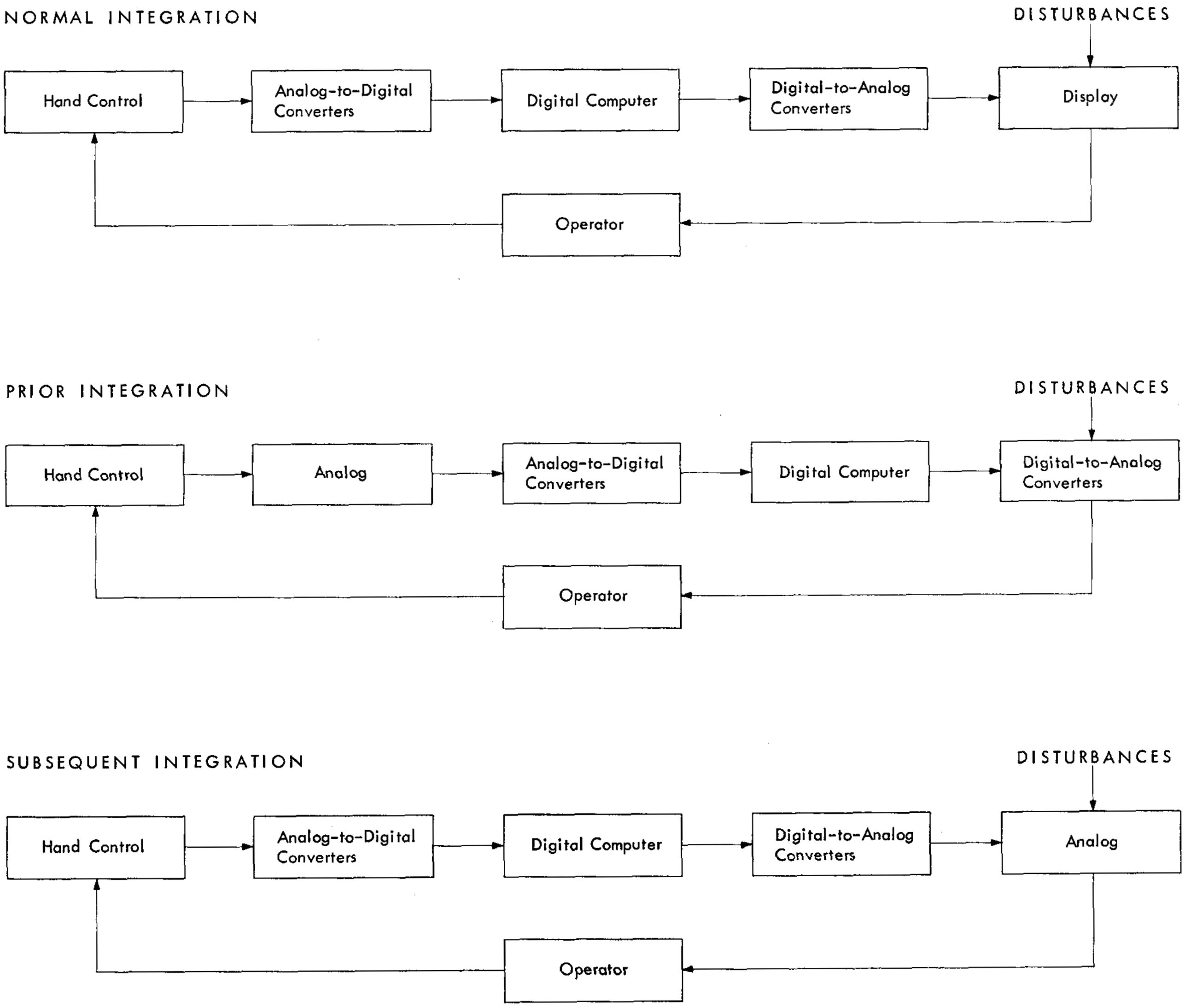
Another line of attack to the problem of excessively high solution rates is to change from a rate control to a position control, that is, to drop the integration completely. Data exist for analog tracking to show position control superior to rate control.[3,4,5,6] Furthermore, since a position control is not time-dependent, it should prove less sensitive to the solution rate. Observations indicate that a digital position control is less sensitive to solution rate, but is poorer over-all in the practical tracking range. The most undesirable characteristic of digital position control is quantization or equipment resolution, whereas with a rate control, amplitude sampling is not particularly critical. With a position control, the analog-to-digital converters must have at least half as much resolution as the final precision required in tracking.

An alternative solution to the problem of excessively high computer rates—and one which we hope is a final solution—is one that occurred to us quite early in our program of investigations and again at the end of it.

As shown in Fig. 10, an analog control loop within the over-all digital system loop is being instrumented by feeding information simultaneously to the display and sampling it for the digital computer. For the operator's purposes the system will be analog, and for other computational purposes it is digital. With such a "mixed" loop we hope that the sampled-data tracking problem will be solved by giving the operator an analog loop, although this instrumentation will probably create problems of its own.

Thus we have investigated various digital instrumentations of the hand-control loop, and have determined the computer solution rate required for satisfactory tracking performance. But we have been unable to determine

Figure 8 **Normal, prior, and *subsequent* integration loops.**



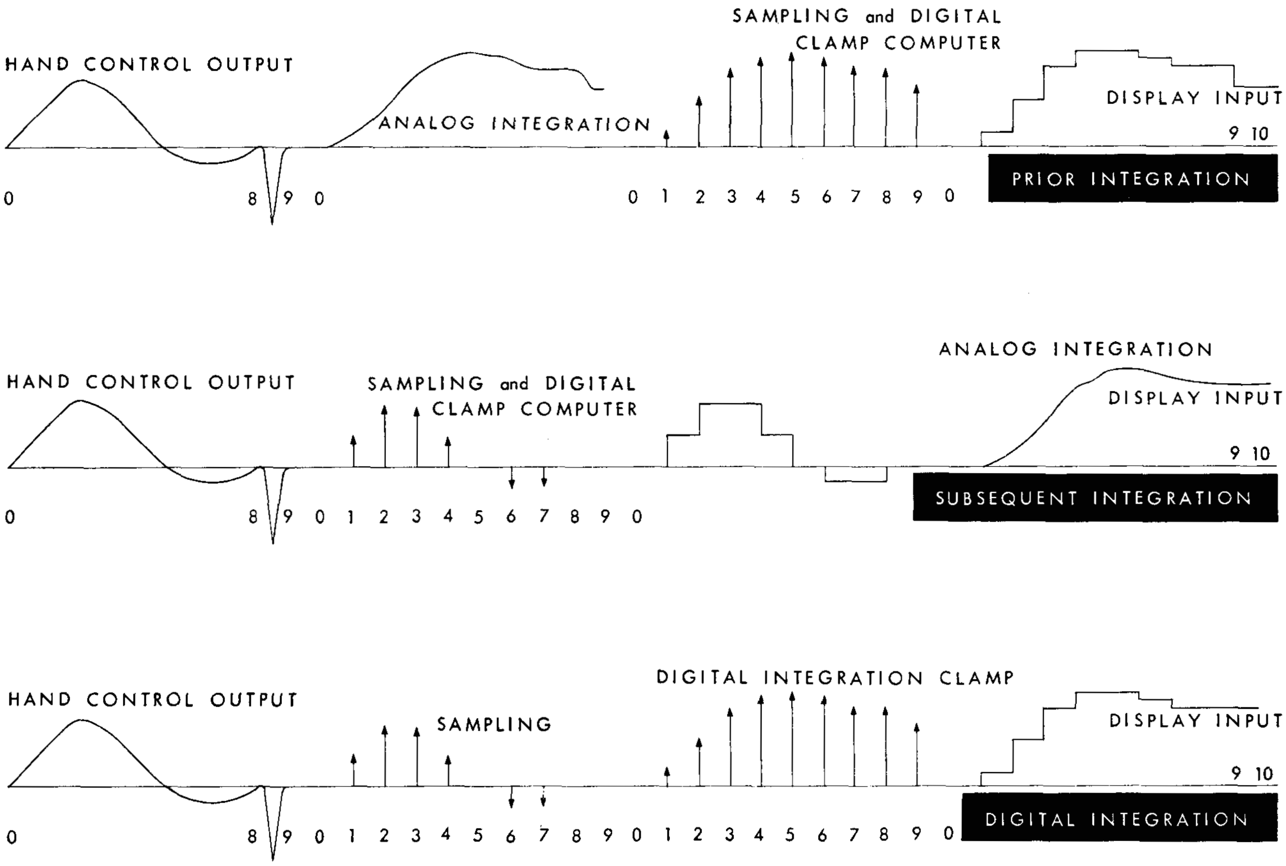


Figure 9 **Effects of locus of integration on a common signal.**

any digital instrumentation which would permit the use of lower solution rates. We hope that by substituting an analog tracking loop within the over-all digital loop we will meet our original objectives.

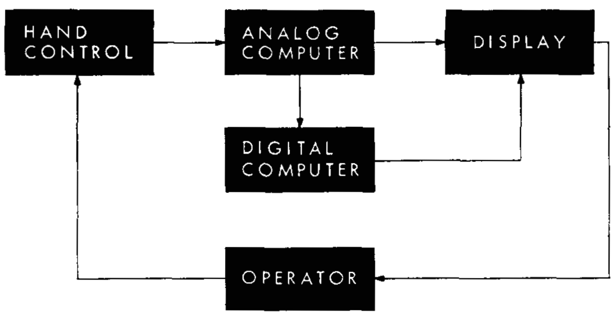


Figure 10 **Analog tracking with a digital computer.**

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