A Nonlinear Photoformer
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A Nonlinear Photoformer

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Digital Waveform Processing

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Nature of the Problem

It was desired to construct a function generator capable of producing any of a wide class of signals $v = f(t)$, where the particular function needed for any specific application was to be specified by an ordinary graph of that function. A known device which meets these needs is the photoformer function generator in which *some* form of the graph of $f(t)$ is mounted on an oscilloscope screen and a photomultiplier tube associated with a control system of *some* kind is used to keep the beam following that graph.[1,2,3,4] It will be seen from the foregoing description that an infinity of different photoformers are possible; ordinarily, however, the photoformer will suffer from certain characteristic difficulties which have been removed in the present design. In particular, the ordinary photoformer suffers from drift and requires that the graph $f(t)$ be presented in some way that distinguishes the region $v > f(t)$ from $v < f(t)$. The present device, by contrast, has been designed to follow a simple clear line in an otherwise opaque negative, and it is inherently drift-free. These two features are related, because the nonlinear system that is necessary for following the line also eliminates the problem of drift.

Design

We require a control system capable of keeping an oscilloscope beam following a clear line in an otherwise opaque negative. Suppose that the line has the form $f(t)$ and that the output of the system at some instant is $v_o(t)$. It would be natural to apply $v_o(t)$ to the scope and attempt to measure the error, but it will be seen at once that this is impossible, since $v_o(t) \neq f(t)$ implies that the beam is hidden and the system has no information as to its whereabouts. (The situation is not improved by using a black line on a clear negative; in that case the beam is not hidden, but the total light intensity still gives no information as to where it is). Instead, therefore, we apply to the scope not $v_o(t)$ alone, but $v_o(t) + v_p(t)$ where $v_p(t)$ is a high-frequency (15 kHz) triangular wave. Now consider an interval of time sufficiently long to include several cycles of $v_p(t)$ but sufficiently short to prevent substantial variation of $v_o(t)$. The function $v_o(t)$ is slowly varying compared with $v_p(t)$, so that such an interval always exists. Now during such an interval we may have, for example, $v_o(t) > f(t)$, but because we have applied to the scope $v_o(t) + v_p(t)$ we will find that the beam oscillates at 15 kHz, crossing the function $f(t)$ twice per cycle. The oscillation is centered on $v_o(t)$, however, and hence the time spent above $f(t)$ is not equal to the time spent below it, the difference being a measure of the error. Now suppose we could generate a square wave that was ON whenever $v_o(t) + v_p(t)$ (which determines the instantaneous position of the beam) above $f(t)$ and OFF whenever the beam was below. Such a square wave would be a pulse-width modulated error signal. The required transition times for the square wave would be precisely those times at which the beam crosses the clear line $f(t)$. These are precisely the times at which light appears at the photomultiplier. Thus the desired square wave can, in fact, be generated by having the photomultiplier output toggle a flip-flop. Care must be taken that a pulse which occurred from a transition of the beam crossing the clear line on its way up can only set the flip-flop ON and vice-versa. This is accomplished by the circuit of Figure 1.

The pulse-width modulated error signal is detected (after amplification) in a drift-free manner by the circuit of Figure 2. In Figure 2 the symmetric clamp centers the pulse-width-modulated signal so that the ON and OFF states have equal absolute values with opposite sign. The filter output may be thought of as a time-average of the centered pulse-width modulated signal; the average being taken over times long compared with the oscillations of the beam but short compared with signal frequencies. The Bode and Nyquist plots (experimental) are shown in Figure 3, along with a Bode plot of the closed-loop error transfer function that would be achieved by putting the filter in a loop with gain 100. From the figure it is seen that stability may be expected for gains up to 100, and that with such gain there is a bandwidth of about 1 kHz with 1% accuracy at the lower frequencies. The circuit of the closed loop system is shown in Figure 4.

Conclusions

In performance tests the accuracy and bandwidth are about as predicted. Drift (which could be introduced by the input preamplifier to the scope though not elsewhere) was in fact not observed at all. The main sources of noise were the residual high frequency components of the square wave which survived transmission through the filter; these could be removed by further filtering the output (outside of the loop, so as not to introduce destabilizing phase shifts).

No effort was made in this project to push the bandwidth as high as possible. Clearly the way to do this is to increase the frequency of the triangular wave $v_p(t)$, so that $f(t)$ is, in effect, sampled more often. The limit on how far one can go with this process will be set by the photomultiplier response time, but it is one of the virtues of this design that we require only that some kind of poor excuse for a pulse be emitted by the photomultiplier. The exact size and shape of the pulse is unimportant since it can be amplified and shaped at will.

Also, no effort was made to have the system improve its performance on successive sweeps by taking advantage of information gained on the previous sweep. This was shown to be possible, but the theoretical scheme that was devised has not yet been implemented.

The chief application of any photoformer would be in analog computation where it might be desired to test a simulation scheme by applying some test input $f(t)$. It should be noted also that that one need not use time as the independent variable, since the horizontal input to the scope could as well be controlled by some variable $x(t)$. The output would then be $f(x)$. Because of its low-drift properties, the nonlinear photoformer is especially suited to this application.

The design of the present system is effective because it combines the techniques of analog and digital circuitry in ways that use the best features of each. The active circuits are logic circuits, or could easily be replaced by logic circuits since the design is nowhere dependent on their linearity. Where linearity is called for, only passive circuits are used. Pulse width modulation forms the natural link between the two systems since a pulse-width-modulated wave can be formed by a nonlinear device (flip-flop) and detected by a linear one (filter).

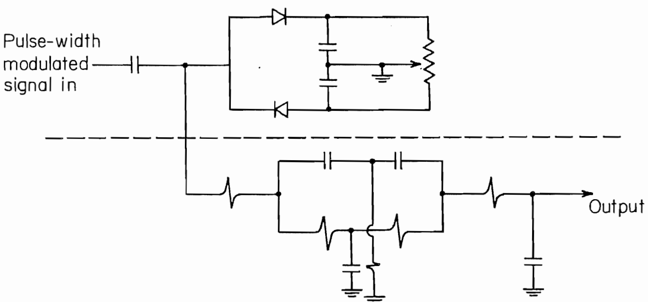

FIGURE 2—**Symmetric clamp and demodulating filter for drift-free detection of pulse-width modulated error signal.**

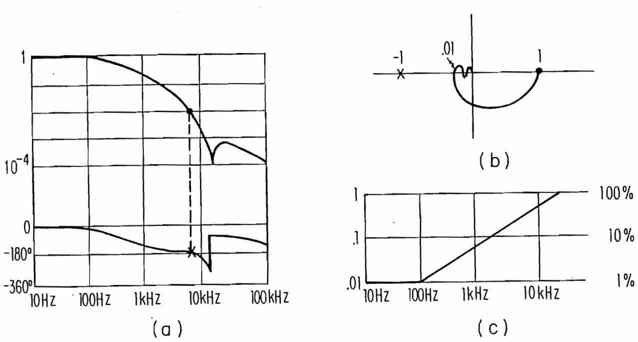

FIGURE 3—**Filter characteristics (experimental, approximate)**
(a) Bode Plot
(b) Nyquist Plot
(c) Expected system error with d.c. gain 100.

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The Nonlinear Photoformer was developed first during an electronics course taught by Dr. A. A. Pandiscio at Harvard and later as a special project under his direction; he deserves a large share of the credit. Thanks are also due to Frank DeCosta, who was extremely helpful with the actual construction of the device.

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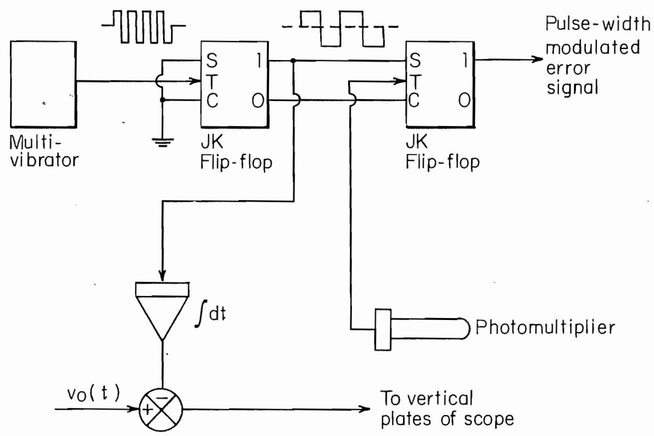

FIGURE 1—**Formation of pulse-width modulated error signal.**

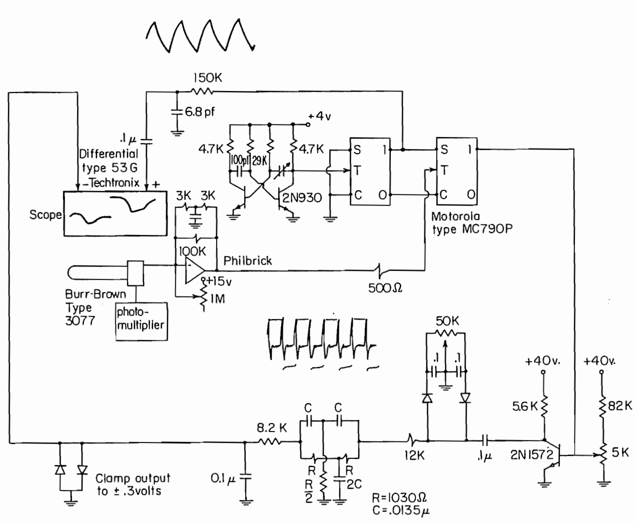

FIGURE 4—**The Nonlinear Photoformer.**