Simulation of a Laser Beam Automatic Depth Control

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PRESENT grading methods using sight-bars, stretched wires, etc., are slow, costly, and unsatisfactory for high speed drainage equipment. A laser beam automatic depth control system was developed specifically to meet the requirements of this equipment. It was successfully tested on a plow-type machine, called a "draintube plow", for installing corrugated plastic drainage tubing (Fouss, 1968 and Fouss and Reeve, 1968). Laser control systems are now commercially available and are being used on tile trenching machines (Studebaker, 1971). Through proper design and adaptation, laser control systems can be used for both elevation and guidance control on several types of machines such as those used in earth moving, land leveling, ditching and road grading, not only for agricultural purposes, but for civil and military projects as well.

The purpose of this paper is to report on a design procedure which utilizes analog computer simulation to adapt a laser control system to various kinds of machines. As an example, the design, adaptation, and adjustment of the laser control system for the draintube plow machine will be discussed.

DESCRIPTION OF CONTROL SYSTEM

The automatic grade control system uses a laser beam projected from a portable, tripod-mounted source as an elevation reference and a machine-mounted receiver (Fig. 1). The laser beam is projected above and parallel to the proposed drain line toward the drainage machine and the receiver output is sensitive to deviations from the beam. An on-board controller unit detects changes in the receiver output and energizes the solenoid of a hydraulic valve. The valve activates a hydraulic cylinder to correct the hitch point elevation, thereby controlling the plow depth automatically.

The laser is basically a light amplifier emitting a well-collimated light beam that can serve as an elevation reference line from which the operating depth of the drainage machine is controlled (Fouss and Reeve, 1968). Since the effective range of this reference line exceeds 1,000 ft under most conditions, its use eliminates the need for setting a multitude of sight-bars, or stretching a guide wire supported at 50 to 100 ft intervals.

The laser unit used in the research was a compact, lightweight, helium-neon gas type with a light beam output of 0.3 milliwatt at 6328 A deg wave length. The laser beam was "chopped" mechanically by a motor-driven, slotted disc at a frequency of 150 Hz so that the receiver can distinguish it from extraneous light. The beam was also projected through a 10-power telescope to increase its diameter and to reduce its divergence. The light intensity was distributed across the diameter of the laser beam in a Guassian wave-front.

Consideration was given to the use of a laserplane type reference created by either optically spreading the beam of light (a pie-shaped plane) or by rotating the laser source (much like a light house beacon), but this was determined not necessary for early experimental work.* A laserplane system is now available commercially, however, and is in use on several kinds of drainage and earth moving machines (Studebaker, 1971).

Receiver

The receiver consisted of two horizontal rows of phototubes closely spaced one above the other in a multibaffled shadow box to reduce the effect of sunlight, and two follower amplifiers (Fig. 2). Each row had 7 phototubes connected in series with a 90-volt battery and a 1 M ohm resistor. The voltage drop across the resistor was amplified by a follower amplifier and used to drive the controller. The receiver could be positioned on the plow frame anywhere between the hitch point and the plow blade. Assuming that the plow would operate very close to the design depth, the change in receiver elevation would be a fraction

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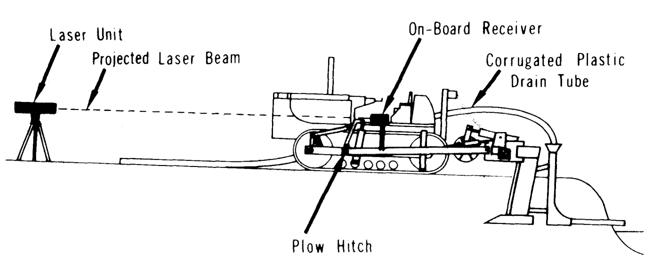

FIG. 1 Schematic of the laser beam automatic depth and grade control system for a draintube plow.

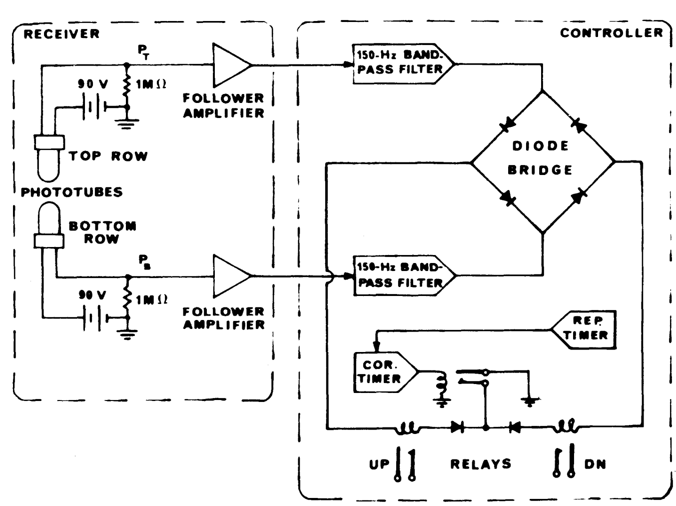

FIG. 2 Receiver and controller circuit diagrams.

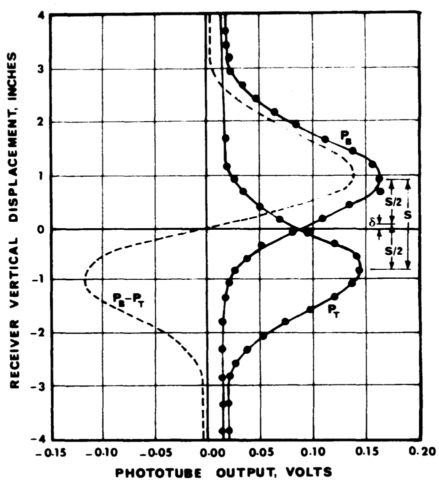

FIG. 3 Variation of phototube outputs with vertical displacement.

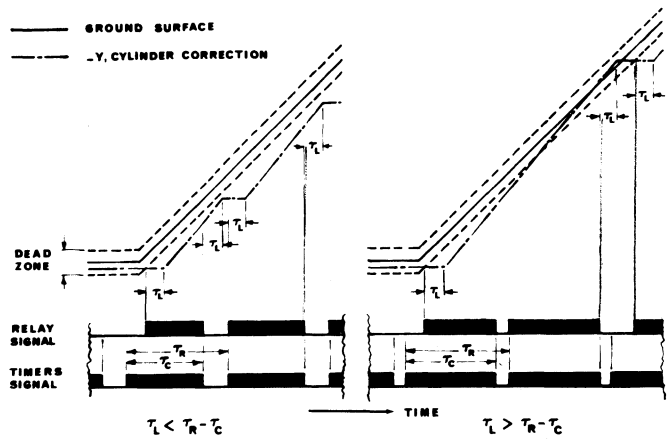

FIG. 4 The effect of the controller setting on the cylinder correction.

L_R of the change in hitch elevation, where L_R is the distance of the receiver from the blade relative to the frame length. A more detailed description of the receiver and specifications for the phototubes are given by Fouss and Reeve (1968).

The receiver elevation was adjusted relative to the beam until the outputs of both rows of phototubes were equal. The output of the top row, P_T, and bottom row, P_B, were then measured through a vertical displacement of ± 4 in. (Fig. 3). The two outputs are not identical and the receiver geometrical center (half the distance S between peaks) deviates a distance δ from its null point (where the two outputs are equal). The difference between the two outputs, P_B - P_T, which the diode bridge of the controller detected, is essentially linear and very sensitive to the receiver motion relative to the beam over a fairly wide range around the null. The hydraulic system would bring the receiver null point to coincide with the beam center-line, that is, bring it to zero elevation.

Controller

The controller unit consisted of electronic filters, a diode bridge, timers and relays (Fig. 2). A band-pass filter was used for each receiver row to filter out all signals except those with a frequency in a narrow band around 150 Hz, thereby causing the system to ignore light sources other than the 150 Hz chopped laser beam. The polarity of the voltage difference, which indicates the direction in which the receiver was off-center, was discriminated by the diode bridge circuit. Subsequently, the bridge would activate the proper up or down relay to energize the solenoid of the hydraulic valve. The dead-zone of the diode circuit was adjustable by changing the gains of the follower amplifiers. The receiver was adjusted to a ± 1/4 to ± 3/8 in. deadzone.

The controller had replication and correction timers which acted as a synchronizing clock to control its mode of operation. The replication timer determined the period τ_R of a replicated cycle at the start of which the controller would be set and able to energize the hydraulic valve solenoid. The correction timer determined the portion τ_C of the replication period during which the controller could energize the solenoid, and beyond which it would be disabled until the start of the following replication cycle. The controller circuity was designed such that once a relay was closed, it remained closed until the end of τ_C and then would open for the remainder of τ_R regardless of the receiver elevation after closure. The replication period τ_R could be adjusted to any length greater than 0.002 sec, and the correction period τ_C could be adjusted to any portion of τ_R. The controller operation will be illustrated after the hydraulic components are discussed.

Hydraulic Components

The hydraulic system consisted of a solenoid valve and a double acting cylinder to control the hitch elevation. An adjustable flow-divider valve was used on the high pressure pipeline feeding the cylinder side containing the piston rod. It was adjusted to reduce the oil flow into that side to make the piston velocity equal in both directions. The piston velocity was essentially a step function with a time lag $\tau_L \approx 0.15$ sec behind the controller signal; the durations of its acceleration and deceleration were extremely short.

The operation of the controller logic and the hydraulic system is illustrated in Fig. 4 for two cases: τ_L less than and greater than τ_R - τ_C. The first case shows the disruption in the cylinder motion when the controller was disabled even though the error persisted. The second case shows that the hydraulic valve was not allowed sufficient time to close and when the error persisted, the piston motion was not disrupted while the controller was disabled. Both cases could be called "sampled-digital" control modes, indicating that the error signal is "sampled" by the controller before energizing the valve solenoid. As τ_C approaches τ_R, a pure "on-off" control mode is approximated and eventually approached if τ_R becomes infinitesimal.

COMPUTER SIMULATION

An attempt was made to simulate the entire control system (receiver, controller, hydraulic valve, and cylinder) on a fully expanded EAI TR-48 analog computer (Electronic Associates, Inc.)† The computer, however, did not have enough logic capacity to simulate the controller. There was also some concern that the nonlinear characteristics of the available logic (dead-zone, hysteresis, etc.) may not match those of the controller.

The approach was modified to incorporate the controller itself into the circuit to provide the needed logic. This necessitated the addition of the follower amplifiers to drive the controller since the computer did not generate enough current to drive it. The use of the controller and follower amplifiers as

†Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product listed by USDA.

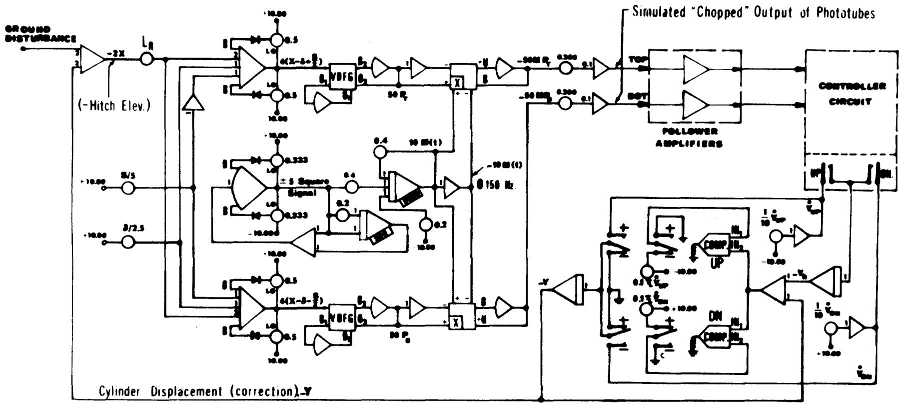

FIG. 5 Analog computer circuit and hybrid components.

"hybrid" components of the analog circuit also meant using their actual characteristics in the program which would have been very difficult to simulate. The computer circuit (Fig. 5) had to be programmed for real time operation because of the presence of the hybrid components. The analog sections which simulated the phototubes and the valve and cylinder will be discussed in some detail.

Phototube Simulation

The output of each row of phototubes (Fig. 3) was generated by a 19-segment VDFG (variable diode function generator) as a function of the row elevation measured at the point producing the peak output. Defining the receiver null point elevation x, the elevation of the top and bottom rows would be $(x - \delta + \frac{S}{2})$ and $(x - \delta - \frac{S}{2})$, respectively. Each row elevation was computed by a separate amplifier and used to drive the corresponding VDFG. The δ and S signals were generated by one potentiometer each for both amplifiers for convenience.

The row elevation amplifiers had a gain of two to magnify the input to the VDFG's around the peak elevation and were soft-limited at about ± 10 v to prevent overloading. The VDFG's were set to take advantage of these variable gains. The break points were taken on each side of the peak elevation at ¼-in. intervals, which gave excellent accuracy in a ± 2½-in. range around it. The soft limits extended the usefulness of the VDFG's to at least ± 5 in. around the peak elevation with reasonable accuracy (the row outputs changed very little beyond ± 2½ in.), thereby covering the full range shown in Fig. 3.

The outputs of both rows were modulated by the "chopped" laser beam at a 150 Hz frequency. The outputs at a fixed receiver elevation were observed on a scope to study the chopping effect. The modulating function M(t) was found to resemble a square on-off periodic function with first order transitions caused by the gradual covering/uncovering of the beam source. A 150-Hz, ± 5-v square wave generator was, therefore, included in the computer program and its output was passed through a first order filter. The generator used an integrator with a gain of 600 which later had to be reduced slightly to correct for the wave imperfections due to the hard limiting diodes. The filter used an integrator which was biased to produce a signal between 0 and 10 v (instead of ± 5 v) and its gain was adjusted until its output matched those of the receiver rows (at a gain of 2,000).

The VDFG's outputs were modulated by multiplying them by the filter output. The miltipliers' outputs were properly scaled down to drive the follower amplifiers. The controller was tested and found to respond to the simulated phototube outputs.

Valve and Cylinder Simulation

The up and down switches in the controller were used in the computer circuit to obtain the up and down piston velocity signals, respectively. It is not necessary for the up and down piston velocities to be the same in order to accomplish the simulation. Their combined output was integrated to provide the hypothetical piston displacement y_h which would have been obtained if the hydraulic system had no time lag τ_L. The difference between y_h and the actual piston displacement y was used to operate the up and down double-pole, double-throw, relay comparators (shown in their "open" position in Fig. 5). Each comparator was biased through one of its switches such that, assuming that the piston was not moving (y = constant), the up or down comparator would "close" at τ_L behind the controller up or down relay, respectively. Once it was closed, the bias was removed and it could not open until $y = y_h$ which occurred only at τ_L after y_h had stopped changing, that is, at τ_L after the controller relay had opened.

The comparators operated identically to, and with a time lag τ_L behind, the controller switches, and, therefore, were synchronized with the piston motion. Their second switches were used to conduct the appropriate up or down piston velocity into an integrator to compute the piston displacement y and provide the correction in the hitch elevation. The hitch elevation is simply the tractor deviation from the ground datum less the piston displacement. The tractor deviations were assumed to follow the ground surface irregularities.

COMPUTER ANALYSIS

The computer simulation was based on "standardized" ground surface profiles consisting of step, ramp, saw-tooth, and sinusoidal functions and their combinations. It was felt that if the control system displayed good performance and stability with these inputs, its performance should be acceptable for the irregular and random inputs typical for the actual ground surface profile.

The computer analysis was checked against the observed response of the actual control system to step and ramp inputs and by its hunting characteristics at zero input while the tractor was not moving. A step input was obtained in the field by deactivating the control system, displacing the receiver vertically by the desired step, and then reactivating the control system. The ramp input was obtained by steadily moving the receiver vertically at a prescribed rate using a hand crank and screw mechanism. The observed response agreed very closely with that determined by computer simulation. In addition, the observed and simulated hunting cycle at zero input had both the same amplitude and frequency.

Since the controller timers were independent of, and not synchronized with, the computer circuit, simulation runs could not be repeated. Therefore, all computed information needed to evaluate the system performance had to be recorded simultaneously for each run. A Honeywell, 7-channel, FM magnetic tape recorder (Model 8107) was used to record this information and to play it back later, one channel at-a-time, for observation and plotting.

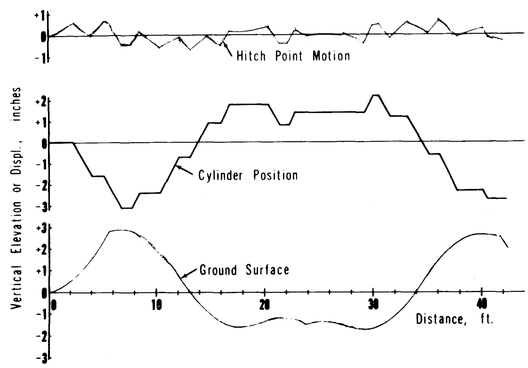

FIG. 6 Sample of computed results for 2½ ips cylinder velocity.

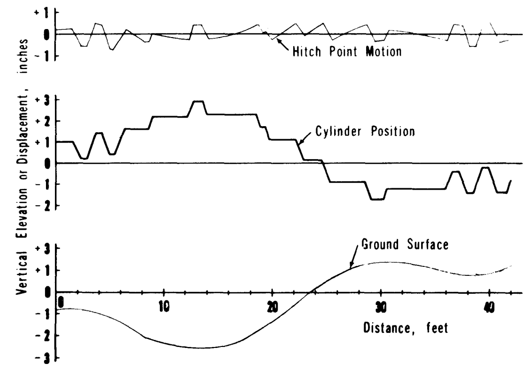

FIG. 7 Sample of computed results for 3 ips cylinder velocity.

No attempt will be made here to present the results for all combinations of variables and parameters covered in this study. Only sample results will be presented to illustrate the value of computer simulation in analyzing and adjusting a control system. The results of two simulation runs using hydraulic piston speeds of 2½ and 3 in. per sec are shown in Figs. 6 and 7, respectively. The values of other pertinent parameters used in both runs are given in Table 1. All parameters were set by potentiometers in the computer circuit except the dead-zone (set by the gains of the follower amplifiers) and the replication and correction periods (set by potentiometers in the controller timers circuit).

Comparison of the simulation results of Figs. 6 and 7 reveals that the higher piston speed improves the control system accuracy in maintaining the hitch point position near zero elevation. This was found true for several types of ground surface inputs. The hitch motion did not "overshoot" the zero elevation with each corrective motion and was above or below it for prolonged periods. The double-step correction occurred in both Figs. 6 and 7 and the hitch point was maintained to within about ± 3/4 in. of the zero elevation. This agreed well with field observations where the auto-control maintained the hitch within ± 1.0 in. of the zero elevation for several ground surface conditions.

DISCUSSION

The computer simulation of the automatic depth control system offers an excellent method to analyze and adjust the system for optimum performance. To accomplish this using field tests alone would be difficult, expensive, and time consuming because of the random variation in field conditions and the numerous combinations of system parameters. The computer simulation does not eliminate the need for field evaluation, but can significantly reduce the number of parameter combinations that need to be tested under natural field conditions.

The simulation results revealed that the "sampled digital" control mode with $\tau_L > (\tau_R - \tau_C)$ tended to improve the system performance over that obtained with a pure on-off control mode when the receiver dead-zone was $\geqq \pm 1/4$ in. and the piston speed was $\geqq \pm 3.0$ in. per sec. For many inputs, particularly those changing slowly or gradually, the pure on-off control mode may not provide sufficient "overshoot" and the hitch elevation would be above or below the zero elevation for prolonged travel distances. The pure on-off mode gave a performance comparable to the sampled-digital mode only when the hydraulic gain was increased considerably, which often resulted in high amplitude hitch point "hunting". On the other hand, the simulation showed that for a receiver with a narrow dead-zone (e.g., $\leqq \pm 1/16$ in.), the pure on-off control mode was satisfactory and the hydraulic gain could be adjusted to give acceptable hunting characteristics. The use of a proportional control mode would be hard to accomplish with the fixed discharge oil pump and may not improve performance; in fact, for some inputs it may result in a larger displacement of the hitch point from the zero elevation.

TABLE 1. PERTINENT PARAMETER VALUES

Parameter	Value
L_R	1.00
S	1.50 inch
δ	0.00 inch
τ_L	0.15 sec
τ_C	0.60 sec (approx)
τ_R	0.70 sec (approx)
Dead-Zone	± 0.25 inch (approx)

In general, for the on-off type control mode, optimum performance occurred when the control system caused the laser receiver to "hunt" about the beam center-line for a zero input. For the draintube plow, a "hunting" cycle with a frequency of about 1 Hz and an amplitude of 1 in. (measured at the hitch point) provided a good compromise of sensitivity and stability over several types of ground surfaces.

In the study reported here, the system performance was evaluated on the basis of the accuracy of maintaining the plow hitch near the zero elevation. The plowing depth was assumed to follow the hitch elevation with a time lag behind it. In later studies (not reported here) by Fouss, et al. (1971), the dynamics of the plow were modeled and included in the simulation, thus providing a means to optimize the position for mounting the laser receiver on the frame of the plow.

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