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SERVO CONTROL USING SWITCHES FOR DISCRETE POSITIONAL FEEDBACK

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13. ABSTRACT *(Maximum 200 words)*

This report describes an approach for providing and/or assisting in the positional control of a one degree-of-freedom servomechanism *using switches*. The switches, positioned along the path of a moving mechanism, can also be simulated using continuous feedback sensors for certain applications. Real time feedback of the discrete time at which each switch is tripped during motion is provided to the controller. Based on this time-position information, *constant motor forces to be applied between switches* are determined to sustain and complete the required repositioning task. A definitive control procedure is not presented here, but rather a promising one that may have important applications as we have found in our work. Also, the method is not intended to compete with more sophisticated and complicated approaches using higher component quality and quantity and computer power. On the contrary, one of the intended goals is to go somewhat the other way to make use of existing or even less expensive components. The main contribution that we make to this overall control technique is to introduce and use *probability and statistical concepts in determining the switch locations and the required real time motor forces*. A probabilistic approach is needed because of the uncertainty in the actual position and velocities of the mechanism as it travels between switches. These uncertainties in turn are derived from uncertainties in the disturbing forces that are encountered during any given motion cycle. In this report, we develop the theory for a statistically-based approach for control using switches. We then verify the results using simulation and experimentation. In our experimental work, we applied our techniques to the ramming mechanism of a large caliber tank autoloader with excellent results. From our experimental work, we also developed some modifications to the theoretically-derived control procedure to improve the overall response.

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NOTATION

$\bar{v}$	a bar over a variable implies average value of a random variable
$\tilde{v}$	a tilde (~) over a variable implies a sample outcome or a statistical estimation of a random variable
E[-]	expected value or average of a random variable
$\sigma(-)$	standard deviation of a random variable
i	section number; all positions between two consecutive switches *(i-1)* and *i*
m	mass
x, v	position and velocity of mass m
t	time
$\Delta \tilde{t}_i$	random time increment for section *i* that is measured in real time
u	servo motor force
u_d	disturbing force
$\tilde{u}_{di}$	random constant disturbing force for section *i*
$\tilde{u}_i$	random constant servo motor force for section *i*
u_m	maximum allowable average motor force
u_t	total force acting on mass *m*
$\tilde{v}_i$	random velocity at the end of section *i* that can be estimated in real time
v_{igoal}	a fixed target velocity at the end of section *i*
v_m	maximum allowable average velocity of mass *m*
v_{nmax}	maximum target velocity at the last switch
x_i	location of the *i*th switch
Δx_i	known width between two switches *(i-1)* and *i*

x_n	location of the last switch
x_r	desired or command position of mass m
z	the z-statistic for the normal distribution

SUMMARY AND BACKGROUND

There are a number of potential advantages to be gained in control using switches to either *replace* or *support* some other continuous state feedback method such as proportional-integral-derivative (PID) control. These are summarized and then discussed as follows:

- minimizes noise effects and feedback controller instabilities
- has potential to minimize resonance effects from reduction of noise
- simplifies servo system to increase reliability and decrease cost
- provides a degraded mode of operation in the event of continuous feedback malfunction
- automatically seeks optimum time control

Noise and instabilities are minimized because the controller using switches essentially operates in an open loop mode between switches. The motor force is fixed at a constant value until the next switch is detected. At that time a new motor force is calculated based on the history of the current motion cycle. Common feedback and noise problems are minimized or eliminated in open loop control.

Resonance effects might also be minimized because of the elimination of noise and instability problems. One potential problem in the area of resonance, however, might arise from the switching from one motor force level to another. This effect can be diminished by frequency shaping the actual switching since the switching itself is open loop and totally controllable. The main effect of switch shaping is to introduce a net artificial disturbing force to the method. This disturbing force will be automatically handled by the control scheme as a measurable disturbing force, which in turn will be reflected in the required constant motor forces used between switches. Our most significant resonance problems in application to the tank autoloader arose from torque noise derived from feedback noise and sampling rate effects. This torque noise was completely eliminated using the proposed techniques.

Reliability can be increased in two ways. First, higher reliability switches can be used in comparison to lower reliability continuous feedback sensors such as positional transducers, encoders, and tachometers. Secondly, control using switches can be used in conjunction with continuous feedback control and used as a backup degraded mode in the event of continuous feedback malfunction. A backup mode provides functional redundancy that directly increases mission reliability. Also, switches and associated monitoring hardware and software are cheaper than transducers and encoders resulting in a lower cost servo system.

Finally, using the developed procedures presented in this report, we continuously monitor disturbing forces for the most recent repositioning cycles. Consequently, we can recalculate optimum switch locations to minimize cycle times. The computer controller can notify the operator of suggested new switch locations to decrease cycle times based on the recent operating data.

The following is a list of the specific contributions and conclusions made based on our work on control using switches:

1. Disturbing force statistics are required to adequately devise an adaptive semi-open loop control procedure using switches.
2. Statistical results are theoretically derived for the velocity at the final switch position for a given set of assumptions. In effect, our goal is to control the *statistical mean and variance of the velocity at the final switch position.*
3. An important theoretical result of our work is that the *distribution of velocity at the final switch position depends only on the statistical distribution of the disturbing force in the final section*, under certain assumptions. A section here is defined as all positions between two consecutive switches. The final velocity distribution is independent of the disturbing force statistics in all sections prior to the last section.
4. The control procedure can be time-optimized for given maximum allowable average motor force and maximum allowable average velocity.

INTRODUCTION

Our goal is to design a servo system that does not rely solely on continuous closed loop feedback (refs 1-3), if at all. We intend to accomplish this by using strategically located switches tripped by a moving single degree-of-freedom mechanism. The time at which these switches are tripped during a motion cycle is monitored by a computer controller. The controller in turn determines the constant motor forces to be applied between switches based on the discrete time-position information obtained at previously tripped switches.

The minimum number of switches we considered is three corresponding to the three basic motion phases of acceleration, constant velocity, and deceleration. These three switches do not include an endpoint switch that might be required to signal the end of a motion cycle. Also, we did not consider fewer switches, although it is conceivable to run with no switches. Without switches, for example, the motor force can be pulsed to limit maximum velocity of the system. The system could be run for a sufficient time predetermined to ensure completing a motion cycle. One or two switches might also be possible if only acceleration and deceleration were adequate assuming that there was no restraint on the maximum system velocity.

More than three switches might be required if greater positional accuracy is needed, particularly during the deceleration phase. We developed the theory for an arbitrary number of switches and applied it to the three and four switches cases.

Figure 1 schematically depicts a velocity versus distance plot for a typical one degree-of-freedom system using four switches and one endpoint switch. The switch locations x_i depend on a number of factors including control design parameters as well as anticipated or measured disturbing forces. The disturbing forces can include such effects as friction, gravity, and/or coupling terms. In our experimental work, friction was the predominant disturbing force. Control design parameters include maximum average motor force, maximum average mechanism velocity, and the moving mass of the system. These are usually specified by the control or design engineer.

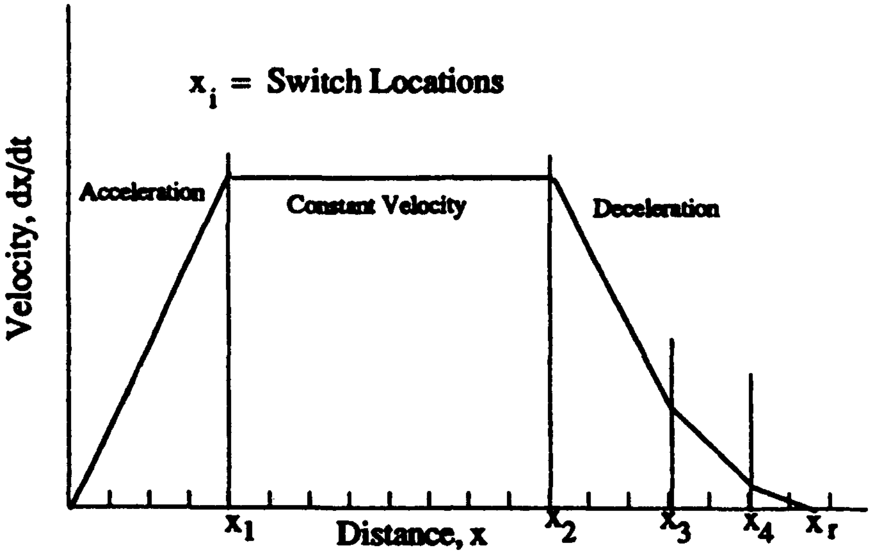

Figure 1. Schematic of velocity versus distance for control using switches.

We can determine initial switch locations from preliminary estimates and/or measurements of the disturbing forces. As the system operates, disturbing forces are continuously measured along with their statistics. These updated estimates can then be used to redefine optimum switch locations. This procedure can be repeated indefinitely if required.

To facilitate the design of the controller using switches, we need to make a number of simplifying assumptions. The most important of these are listed below where the term 'section' used here is defined as all of the points between two consecutive switch locations.

<u>**List of Assumptions**</u>

1. Disturbing forces vary randomly from cycle to cycle.
2. Disturbing forces in the different sections are statistically independent of each other and each follow a normal distribution with given mean and variance (refs 4,5).
3. During any single motion cycle, the disturbing force is constant within a section but may be different in the different sections.

4. The motor force applied is constant within a given section, the value of which is determined adaptively during each new motion cycle.

5. The statistics of disturbing forces can change gradually as a function of the number of cycles or time. These are long term changes and trends, for example, as the system wears.

6. The maximum allowable average motor force and maximum allowable average velocity are specified by the control or system designer.

Most of the listed assumptions seem reasonable. However, one possible exception is the assumption that the random disturbing forces are statistically independent in the different control sections. This assumption is essentially a "conservative" one, since it leads to an overestimation of the standard deviation of velocity at the last switch. If there actually is correlation of disturbing forces, this additional information can be used to better predict the final velocity variability. Therefore, assuming statistical independence leads to an upper bound on the controller design.

Based on the above listed assumptions, we derived a *control procedure that allows the specification of the statistics of the velocity distribution at the last switch.* That is, we can specify as a design goal the *mean and standard deviation of the velocity at the last switch.*

If high positional accuracy is required toward the end of a cycle, then an arbitrarily large number of switches would be required with distances between switches being arbitrarily small. However, if accuracy is needed in a particular application, then consideration might be given to a transition to a continuous feedback mode near the end rather than using many switches. In this case, control using switches could be used for most of the cycle to minimize the cycle time and to eliminate feedback noise and controller instabilities before switching to PID or some other continuous state feedback control (refs 1-3).

If some velocity and/or soft stop collision or docking can be allowed, then control using switches might be ideal. In this case, the maximum endpoint velocity can be specified which can be designed for using the procedures described in this report.

We verified our results using both computer simulation and experimentation. The simulation results verify the theoretical approach and conclusions. We also used simulation for initial studies of robustness. In these studies we assume some deviations from our assumptions and then check the consequences of using the theoretical approach. Most of the results thus far are encouraging, but there may be limitations depending on the actual application involved. We also successfully applied the developed control using switches techniques to the loading cycle of a large caliber tank ammunition autoloader as discussed later in the report.

THEORETICAL DERIVATIONS

In this section, we derive some of the theoretical expressions required for control using switches. These derivations are based in part on the simplifying assumptions presented earlier.

Assume that we have n total switches yielding n sections between switches. Figure 2 shows some of the variables involved for a typical section i.

In Figure 2, x_r is the final position desired that may or may not coincide with the last switch position x_n. There may also be an endpoint switch to indicate completion of a motion cycle. The starting point x_0 is not assumed to be a switch, but it could be. In Figure 2, the symbol ~ (tilde) over a variable indicates a sample outcome of a random variable that can be estimated from data.

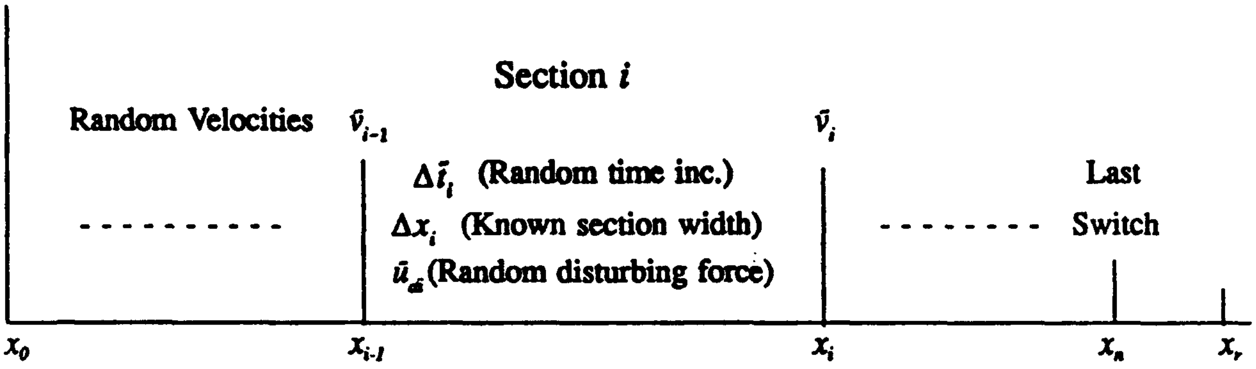

Figure 2. Schematic of variables for control using switches.

For each section, the equation of motion for a one degree-of-freedom system is given by

$$\tilde{u}_{ti} = \tilde{u}_i + \tilde{u}_{di} = m\ddot{x} \tag{1}$$

where $\tilde{u}_i$ = constant motor force in section i, which is itself a random variable to be determined from other random quantities. Although random from cycle to cycle, the motor force is fixed at the onset of a given section during a given cycle. The value that it is fixed at is discussed shortly.

The solution of Eq. (1) assuming constant sample outcomes of the disturbing and motor forces is trivial. Some of the useful expressions derived in solving Eq. (1) assuming only positive (or negative) velocities and positive (or negative Δx_i) are summarized as follows:

$$\tilde{u}_{ti} = \frac{m(\tilde{v}_i^2 - \tilde{v}_{i-1}^2)}{2\Delta x_i} \tag{2}$$

$$\tilde{v}_i = \frac{2\Delta x_i}{\Delta\tilde{t}_i} - \tilde{v}_{i-1} \tag{3}$$

$$\tilde{u}_{di} = \frac{2m}{\Delta\tilde{t}_i}\left[\frac{\Delta x_i}{\Delta\tilde{t}_i} - \tilde{v}_{i-1}\right] - \tilde{u}_i \tag{4}$$

The main problem here is that the disturbing force $\tilde{u}_{di}$ is a random variable. Also, the only information that we measure directly is the random time increment $\Delta\tilde{t}_i$ required to traverse from one switch to the next. We also fix the motor force for section *i* and is therefore known. We have no positional information except at the exact time when a switch is crossed and no velocity feedback information. We can, however, estimate the velocity at the switch locations using Eq. (3) above. At the beginning of a motion cycle, the velocity is assumed to be zero, and hence the velocity at the subsequent switches can be estimated from previous velocity information. Equation (3) holds as long as the motor and disturbing forces are effectively constant within each section. Once we cross a switch, we can also estimate the disturbing force in the previous section just traversed using Eq. (4) and the known motor force $\tilde{u}_i$. We can use this estimate to update the mean and variance of disturbing forces which in turn can be used to update the controller design.

The main question now is how to determine the required motor force $\tilde{u}_i$ for the next section at the moment a given switch is crossed. We propose the following expression which leads to a useful control approach:

$$\tilde{u}_i = \frac{m\,(v_{igoal}^2 - \tilde{v}_{i-1}^2)}{2\Delta x_i} - \bar{u}_{di} \tag{5}$$

in which $\bar{u}_{di}$ = Mean value of the disturbing force for section *i* that has been measured, estimated, or calculated from previous motion cycles using Eq. (4).

v_{igoal} = A target velocity that is the goal desired at the end of the current section *i*. This is to be specified in the overall design of the controller.

$\tilde{v}_{i-1}$ = Estimate of the velocity at the end of the previously traversed section using Eq. (3) by setting *i* to *i-1* and *i-1* to *i-2*.

Equation (5) is a key equation for control using switches. The motor force $\tilde{u}_i$ is a random variable because $\tilde{v}_{i-1}$ is a random variable to be estimated in real time after the (*i-1*) switch is tripped.

From Eq. (2), we can calculate the velocity at the last switch position $i = n$:

$$\tilde{v}_n^2 = \frac{2\Delta x_n}{m}\tilde{u}_{tn} + \tilde{v}_{n-1}^2 \qquad (6)$$

where

$$\tilde{u}_{tn} = \tilde{u}_n + \tilde{u}_{dn} \qquad (7)$$

Substituting $\tilde{u}_n$ from Eq. (5) into Eq. (7) gives

$$\tilde{u}_{tn} = \frac{m}{2\Delta x_n}(v_{ngoal}^2 - \tilde{v}_{n-1}^2) + (\tilde{u}_{dn} - \bar{u}_{dn}) \qquad (8)$$

Substituting Eq. (8) into Eq. (6) finally gives for the velocity at the last switch

$$\tilde{v}_n^2 = v_{ngoal}^2 + \frac{2\Delta x_n}{m}(\tilde{u}_{dn} - \bar{u}_{dn}) \qquad (9)$$

This also is a key equation in addition to Eq. (5). For the assumptions made, Eq. (9) shows that the statistics of $\tilde{v}_n^2$ depend only on the statistics of $\tilde{u}_{dn}$ in the last section with no dependence on previous sections (refs 4,5). The main reason for this is that the effect of random disturbing forces in previous sections is eliminated in the calculation of motor force for subsequent sections. From Eq. (9)

$$E[\tilde{v}_n^2] = \textit{mean of } \tilde{v}_n^2 = v_{ngoal}^2 \qquad (10)$$

and

$$\textit{variance of } \tilde{v}_n^2 = \sigma^2(\tilde{v}_n^2) = \left(\frac{2\Delta x_n}{m}\right)^2 \sigma^2(\tilde{u}_{dn}) \qquad (11)$$

$$\textit{Standard Deviation of } \tilde{v}_n^2 = \sigma(\tilde{v}_n^2) = \frac{2\Delta x_n}{m}\sigma(\tilde{u}_{dn}) \qquad (12)$$

For Eq. (12), we assumed only positive Δx_n, which implies only positive velocities. We consider the possibility of velocity going negative near the last switch later in the report.

DESIGN PROCEDURE FOR CONTROL USING SWITCHES

In this section we define a systematic procedure for designing a controller using switches. Specifically, we consider how to position the switches based on design criteria and goals for the servo system. We limit servo control here to the repositioning of a mass m from some given rest state to some final position. The basic trajectory to be used for this repositioning was shown earlier as Figure 1. This trajectory involves the three phases of acceleration, constant velocity, and deceleration. The following information is assumed given or specified by the designer:

u_m = maximum allowable average motor force (absolute value)

v_m = maximum allowable average system velocity (absolute value)

v_{nmax} = maximum allowable velocity at the last switch n

Because we are dealing with random outcomes of disturbing forces, we can only specify average values of motor forces and velocities as design goals. The actual values of these quantities will vary randomly from cycle to cycle. The goal is to have the sample outcomes stay near the average specified values. The only requirements for u_m and v_m are that they satisfy design needs for limiting the maximum average motor force and velocity primarily for structural integrity purposes or because of motor limitations.

The location of the first switch will be near the end of the acceleration phase assuming that we initially apply the full motor force u_m. From Eq. (5),

$$\Delta x_1 = \frac{m v_m^2}{2(u_m + \bar{u}_{d1})} \tag{13}$$

from which we calculate the location of the first switch. Note that this equation requires the value of $\bar{u}_{d1}$, the average disturbing force in section 1. In an actual application, this is initially estimated or measured. After a few motion cycles, the value of $\bar{u}_{d1}$ can be recalculated from the data and used to reposition switch #1.

The velocity goal at the end of section 1 is v_m. Section 2 of the motion cycle will be the constant velocity section. In locating switch #2 at the end of the constant velocity section, first we need to consider the deceleration phase switch locations to make sure that enough deceleration distance is provided to slow down from the average maximum velocity v_m. In order to do this, we need to fix the last switch and work backwards toward the constant velocity section.

The quantity v_{nmax}, the maximum allowable velocity at the last switch n, requires special consideration. Again we cannot specify an exact last switch velocity goal because of the random disturbing forces and lack of total state feedback information. However, we can estimate the standard deviation of the velocity squared term at the last switch using Eq. (12). This requires an estimate of the standard deviation of the disturbing force in the last section. Again, we initially estimate this but eventually calculate it from cycling data. We can fix the velocity goal,

v_{ngoal}, at the last switch from the specified maximum value v_{nmax} using the following relation:

$$v_{ngoal}^2 = v_{nmax}^2 - z\sigma(\bar{v}_n^2) \tag{14}$$

The intent here is for v_{nmax}^2 to be the $z\sigma(\bar{v}_n^2)$ point of the distribution of $\bar{v}_n^2$. The z factor is to be chosen to yield high probability that the actual $\bar{v}_n^2$ term will not exceed v_{nmax}^2 for any given cycle. For the normal distribution assumption, for example, a value of $z = 3.0$ to 5.0 is adequate (ref 4). This would yield a probability as high as 0.9999 of not exceeding v_{nmax}^2. Also, the minimum value of $\bar{v}_n^2$ should be at least zero for the same z factor. Hence, we get the following relation:

$$v_{ngoal}^2 = \frac{1}{2} v_{nmax}^2 \tag{15}$$

We can now calculate the maximum distance between the last two switches Δx_n using Eqs. (12), (14), and (15).

$$\Delta x_n = \frac{m v_{nmax}^2}{4 z \sigma(\bar{u}_{dn})} \tag{16}$$

Δx_n is a maximum value because larger values would require larger values of v_{nmax}. However, smaller values of Δx_n would only increase the probability of not exceeding v_{nmax}.

We now know the location of the last two switches. The average velocity at the next-to-last switch, the *(n-1)* switch, can be estimated by assuming a maximum deceleration motor force of $-u_m$ and by using Eq. (5):

$$\bar{v}_{n-1}^2 = v_{ngoal}^2 + \frac{2\Delta x_n}{m}(u_m - \bar{u}_{dn}) \tag{17}$$

Note that if $\bar{v}_{n-1} < v_m$, the maximum allowable average velocity, then we will need at least one more switch in the deceleration phase to bring the pre-deceleration velocity up to v_m.

By applying the above procedure, we can fix the location of a minimum number of switches required to satisfy the design criteria which includes u_m, v_m and v_{nmax}. We could also add more switches to improve the statistical estimations required, especially if the assumption of constant forces is not robust enough.

CONTROL ALGORITHM

So far, we have presented a procedure for locating the switches required in designing a controller. In this section we briefly summarize the algorithm required for actually performing the controller functions. A suggested procedure is outlined as follows:

1. Begin a motion cycle using a fixed motor force:

$$\tilde{u}_1 = \frac{m v_m^2}{2\Delta x_1} - \bar{u}_{d1}.$$

2. Monitor switch #1 until it is tripped. This gives $\Delta\tilde{t}_1$. Estimate velocity at the end of section 1:

$$\tilde{v}_1 = \frac{2\Delta x_1}{\Delta\tilde{t}_1}.$$

3. Estimate the disturbing force in section 1 and store for later updates of the statistical mean and variance:

$$\tilde{u}_{d1} = \frac{2m\Delta x_1}{(\Delta t_1)^2} - \tilde{u}_1.$$

4. Repeat steps (1) through (3) for each subsequent section using Eqs. (5), (3), and (4) to calculate motor force, velocity, and disturbing force, respectively.

A special finishing procedure may be required for the last section *n*. A number of alternatives are possible depending on the needs of an actual application. Recall that we have fixed the maximum velocity at the last switch *n*, v_{nmax}. We can also estimate the actual velocity at the last switch once this switch is tripped

$$\tilde{v}_n = \frac{2\Delta x_n}{\Delta\tilde{t}_n} - \tilde{v}_{n-1} \qquad (18)$$

If some final velocity and/or docking force is allowed or required, the cycle then is essentially finished once the last switch is tripped. We either set the motor force to zero or to some predefined docking force as a final step. However, a potential problem in this case is that the last switch is never reached and the system reverses velocity. This results from the negative motor force being applied for deceleration with a possible high frictional or other negative disturbing force sample outcome. To handle this situation, we can estimate a maximum time for the last section just as we enter it using Eq. (18) by setting $\tilde{v}_n = 0.0$. We do this as soon as switch *(n-1)* is tripped.

$$\Delta \tilde{t}_{nmax} = \frac{2\Delta x_n}{\tilde{v}_{n-1}} \tag{19}$$

During an actual run, if the time spent in section n exceeds $\Delta \tilde{t}_{nmax}$, we then assume that the velocity is close to zero and that a reversal in direction might or has occurred. Therefore, we immediately set the motor force to zero or some positive docking force to complete the motion cycle. This procedure has worked well in all of our applications to the autoloader.

If high endpoint accuracy is required, we either need to use more switches in the final section or transition from control using switches to full state feedback control using, for example, an encoder and PID control. In this situation, the goal is to run most of the motion cycle using switches with transition to full closed loop control only in the last section or near the endpoint. We can use the encoder itself in this case to simulate the switch locations. This makes it easy to change to new "switch locations" to time-optimize a motion cycle. Recall that the motivation for control using switches for a system that already has full state feedback would be to minimize cycle time and to minimize detrimental effects of feedback noise, resonances, and/or closed loop instabilities. Increased reliability and/or decreased cost are not the goals in this particular instance. Finally, control using actual switches can be used as a backup degraded mode in the event of state feedback control failure.

SIMULATION

The procedure for control using switches was tested using a limited number of Monte Carlo computer simulations. In the Monte Carlo trials, the control parameters were fixed as were the means and variances of the disturbing forces. Control using switches was then simulated by generating random sample outcomes of the disturbing forces for each control section using a random number generator. The resulting velocity at the last switch was then calculated using both the exact Eq. (1) and Eqs. (3), (4), (5), and (19) for simulation of control using only the switches. This was repeated many times, and the statistics of the final switch velocity were determined. *Using constant motor and disturbing forces within each section, the simulation results verified Eqs. (10) and (12) for control using switches* as expected. We used the Simnon non-linear simulation software for these studies (ref 6).

The biggest foreseeable problem in actual applications might occur whenever the assumptions are not satisfied, but we assume that they are anyway in deriving the control procedure. We conducted limited studies for two cases of this situation: (1) when the actual disturbing force varies randomly about some random mean within any given section rather than remain constant for a given cycle, and (2) when the actual disturbing force increases linearly within any given section.

Randomly Varying Section Disturbing Forces

For this case, we assumed that the disturbing force varied randomly within a section rather than remain constant. The average value within a section, however, is itself a random variable that varies from motion cycle to motion cycle. Figure 3 shows this situation schematically.

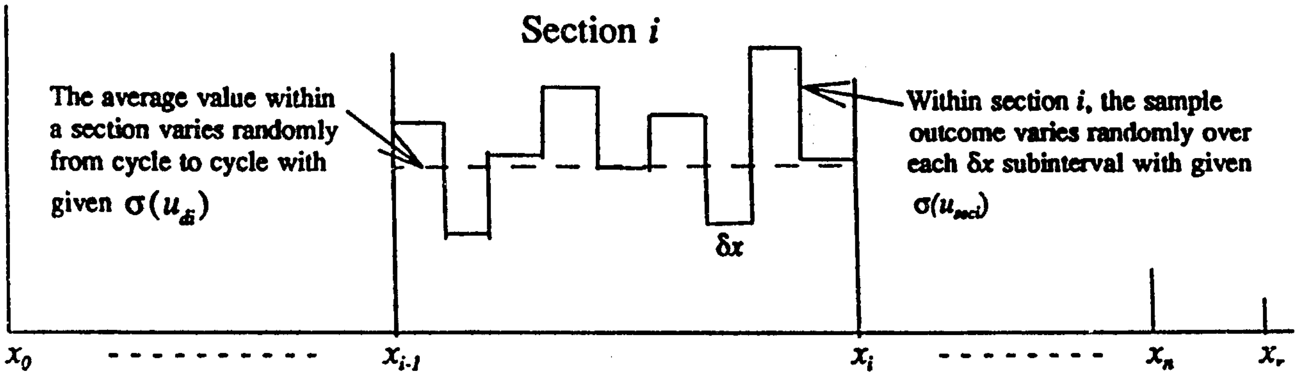

Figure 3. Schematic showing random variation of disturbing force within each section *i*.

Simulations consisted of 100 trials each assuming the following control parameters:

Three sections: $x_1 = 33.15$; $x_2 = 80.0$; $x_3 = 105.0$

Weight = 80 lbs $u_m = 75$ lbs

$v_m = 120.0$ in./sec $v_{3goal} = 40.0$ in./sec

We ran three sets of trials using the following statistical parameters for disturbing forces:

Run #	$\bar{u}_{d1}$	$\sigma(u_{d1})$	$\bar{u}_{d2}$	$\sigma(u_{d2})$	$\bar{u}_{d3}$	$\sigma(u_{d3})$	δx for Secs. 1,3	δx for Sec. 2	$\sigma(u_{seci})$
1	-30.0	5.0	-20.0	5.0	-30.0	2.0	5.0	10.0	2.0
2	-30.0	5.0	-20.0	5.0	-30.0	2.0	5.0	10.0	1.0
3	-30.0	2.0	-20.0	2.0	-30.0	1.0	5.0	10.0	1.0

Table 1 summarizes the results of the simulations.

Table 1. Simulation Results Assuming Random Variation of Disturbing Force Within Each Section

Run #	Theoretical Values		Simulation Results for Section 3		
	v_{3goal}	$\sigma(v_3^2)$; Eq. (12)	$\bar{v}_3$	$\sigma(v_3^2)$	$\sigma(u_{d3})$
1	40.0	749.0	40.1	645.0	3.11
2	40.0	550.0	40.4	514.0	2.28
3	40.0	368.0	40.2	316.0	1.53

The results indicate that control using switches assuming constant disturbing forces within a given section yields somewhat lower standard deviations of final section velocities than theoretical values for this case. This would lead to conservative estimates of maximum final velocities. That is, the actual maximum final velocity would be less than predicted using Eqs. (12) and (15).

Linearly Increasing Disturbing Force Within a Section

We also looked at a somewhat extreme case to determine its effect on final velocity statistics. For this case, we assumed that the actual disturbing force increased linearly within a section rather than remain constant. The average section value, however, varies randomly from cycle to cycle. Figure 4 shows this schematically.

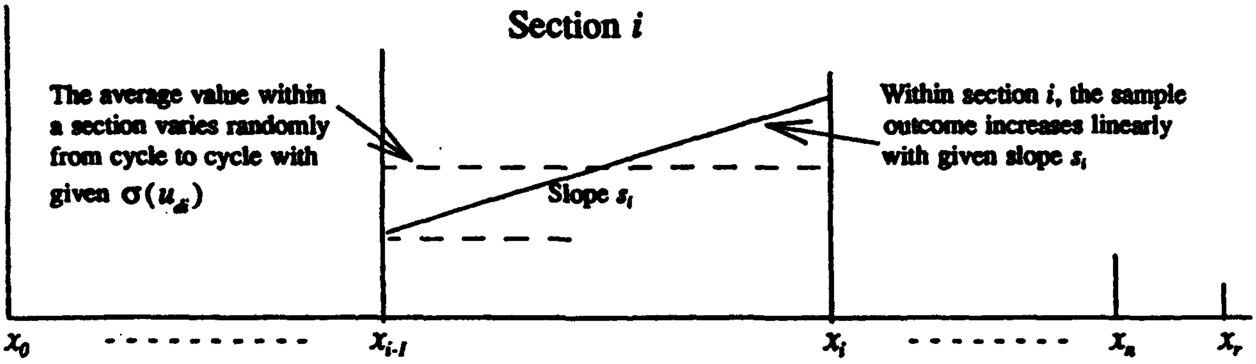

Figure 4. Schematic showing linearly increasing disturbing force within each section *i*.

The control parameters used here are the same as in the previous case. The sectional statistical parameters used, however, are defined as follows:

$\bar{u}_{d1}$	$\sigma(u_{d1})$	Slope s_1	$\bar{u}_{d2}$	$\sigma(u_{d2})$	Slope s_2	$\bar{u}_{d3}$	$\sigma(u_{d3})$	Slope s_3
30.0	5.0	20.0	20.0	5.0	10.0	30.0	2.0	5.0

The results for 100 Monte Carlo trials are summarized as follows:

Table 2. Linearly Increasing Disturbing Force Using Prior Statistical Data for the Simulation

Theoretical Values		Simulation Results	
v_{3goal}	$\sigma(v_3^2)$	$\bar{v}_3$	$\sigma(v_3^2)$
40.0	581.0	41.1	596.0

More research studies of the above nature are required to determine robustness for other situations or in general. In any case, control using switches assuming constant disturbing forces seems to provide a good start. Modifications may be required for particular applications depending on the adequacy of results based on experience.

EXPERIMENTAL RESULTS

We applied the procedures for control using switches experimentally to a large caliber autoloader ramming mechanism (ref 7). This autoloader uses an absolute encoder to measure real time distance and velocity. We simulated different switch locations using the encoder by measuring the time when particular fixed positions on the encoder were encountered during motion.

A schematic of the XM91 140-mm tank autoloader is shown in Figure 5. The autoloader shown here is comprised of a 17-cell carousel ammunition storage and repositioning system (only 2 cells are shown in the figure) and a loading mechanism. The loading mechanism is comprised of two servo systems: a telescoping cell and rammer. The telescoping cell is used to bridge the gap between the ammunition storage area in the bustle of the tank turret and the breech end of the gun tube. The ramming mechanism pushes the round of ammunition from the storage position through the telescoping cell into the gun tube.

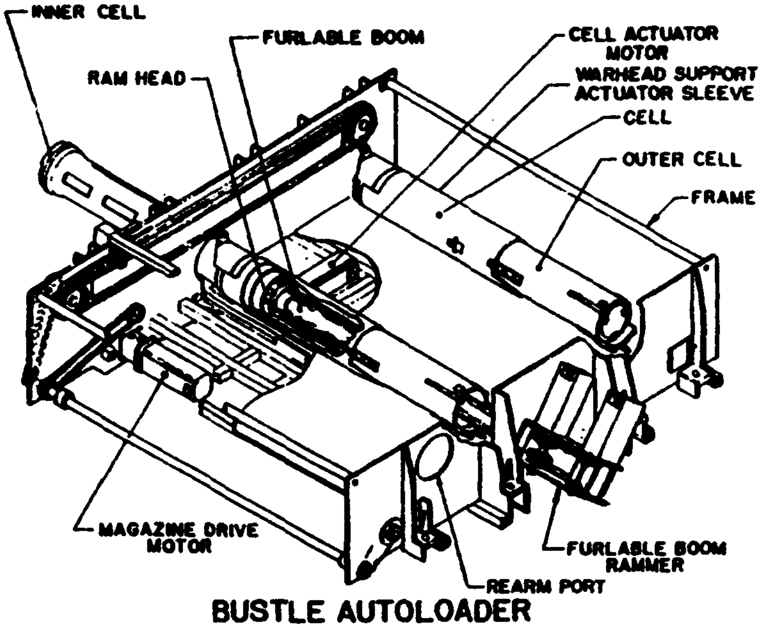

Figure 5. Schematic of XM91 140-mm tank autoloader.

Both the telescoping cell and ramming mechanism require some endpoint velocity to complete cell docking and seating of the round of ammunition into the gun tube. Control using three and four switches was successfully applied to the ammunition ramming cycle. The switches in these trials were simulated using a positional encoder that is part of the actual autoloader. In the course of conducting the experiments, we developed some modifications of the theory required to get better estimates of velocity and disturbing forces for the last sections of the motion cycle.

Before applying any control procedures, we made estimates of disturbing forces, which for our case were predominantly high friction forces. These also varied considerably as a function of ramming distance, rammer velocity, direction of force application, and number of cycles on the ramming boom. Friction values of from 20 to 50 lbs were measured. Measurements were performed by applying a known constant motor force and observing the resultant nearly constant acceleration or deceleration.

We experienced mixed success in our initial runs. These initial switch control runs yielded somewhat inaccurate estimates of velocity and particularly disturbing forces in the last switch section. We traced the major portion of the error to the somewhat inaccurate estimates of $\tilde{v}_1$ and $\tilde{v}_2$, the velocities at the ends of the acceleration and constant velocity sections. These velocities were determined using Eq. (3). In particular, inaccurate values of $\tilde{v}_2$ contributed to most of the error in estimating the final section velocity and disturbing forces. *A solution to this problem was to estimate the section 2 velocity as an average value rather than using Eq. (3) directly.* That is,

$$\tilde{v}_{2avg} = \frac{\Delta x_2}{d\tilde{t}_2} \tag{20}$$

instead of

$$\tilde{v}_2 = \frac{2\Delta x_2}{d\tilde{t}_2} - \tilde{v}_1.$$

This minimized any propagating effects of inaccuracies in $\tilde{v}_1$ and yielded a satisfactory estimate of the final section 2 velocity. Since section 2 is a constant velocity section, Eq. (20) provides an estimate of the velocity at all points in section 2 including the endpoint.

Control Using Three Switches

Ten trials were conducted for the case of three switches. The following parameter values were used for the controller:

u_m = 65.0 lbs; v_m = 65 in./sec; Weight = 55 lbs; v_{3goal} = 20.0 in./sec

$x_0 \approx$ 4.4 in.; x_1 = 16.5 in.; x_2 = 35.5 in.; x_3 = 39.5 in.;

$\bar{u}_{di}$ = (-35.0; -32.0; -25.0);

$\sigma(u_{di})$ = (1.0; 1.0; 2.0).

Figure 6 shows the encoder velocity, position, and motor forces for a typical run using three switches. A summary of results obtained for ten trials is given in Table 3.

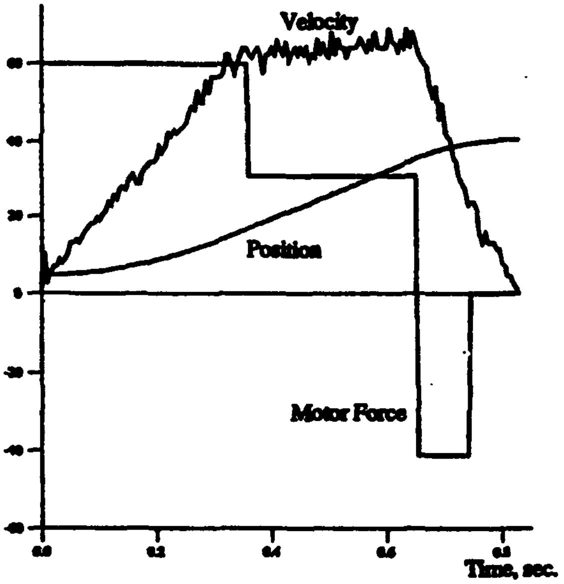

Figure 6. Encoder velocity, position, and motor force for control using three switches.

Table 3. Results of Ten Trials for Control Using Three Switches

Run #	Velocity (encoder), in./sec			Velocity (Switches), in./sec			Disturbing Forces, lbs			Total Time, sec	Final Pos., in.
	v_1	v_2	v_3	$\tilde{v}_1$	$\tilde{v}_{2avg}$	$\tilde{v}_3$	$\tilde{u}_{d1}$	$\tilde{u}_{d2}$	$\tilde{u}_{d3}$		
3-0	64.0	65.7	22.7	67.7	64.2	23.7	-32.9	-34.0	-22.1	0.745	40.40
3-1	59.8	68.2	21.1	66.4	64.0	20.2	-33.9	-33.6	-24.8	0.757	40.25
3-2	62.3	68.2	19.4	66.9	63.8	18.7	-33.5	-34.1	-25.9	0.757	40.14
3-3	65.7	70.8	16.8	67.7	66.2	15.4	-32.9	-32.2	-27.9	0.740	39.93
3-4	62.3	64.0	21.9	66.4	63.3	20.9	-33.9	-34.2	-24.4	0.760	40.27
3-5	62.3	70.8	26.1	66.9	66.2	24.7	-33.5	-31.7	-21.3	0.735	40.39
3-6	63.2	65.7	18.5	66.7	64.0	18.5	-33.7	-33.8	-26.0	0.757	40.17
3-7	64.0	65.7	20.2	66.5	63.5	20.7	-33.8	-34.1	-24.5	0.758	40.25
3-8	62.3	65.7	18.5	66.1	64.2	18.3	-34.1	-33.3	-26.2	0.759	40.07
3-9	65.7	69.1	25.3	64.9	64.2	23.7	-35.1	-32.7	-22.1	0.760	40.46
						Averages:	-33.7	-33.4	-24.5	0.753	40.23
						Standard Deviations:	0.63	0.88	2.12	0.009	0.16

Using the data for $\tilde{v}_3$ in Table 3, we can calculate the standard deviation of $\tilde{v}_3^2$ and compare to the theoretical result, Eq. (12):

$$\sigma(\tilde{v}_3^2) = 119.2, \text{ from data;}$$
$$= 112.3, \text{ from Eq. (12).}$$

As can be seen from these results, control using switches performed very well in this particular instance.

Control Using Four Switches

In an attempt to increase endpoint accuracy, we conducted a series of trials using four switches where the final velocity goal was 10 in./sec instead of the 20 in./sec used for the three switches case. The following parameter values were derived for this controller:

u_m = 65 lbs; v_m = 65 in./sec; weight = 55 lbs;

v_{3goal} = 30 in./sec; v_{4goal} = 10 in./sec; x_0 = 4.4 in.;

x_1 = 16.5 in.; x_2 = 35.5 in. x_3 = 38.5 in.; x_4 = 39.5 in.;

$\bar{u}_{di} = (-35;\ -30;\ -20;\ -50);$

$\sigma(u_{di}) = (1;\ 1;\ 4;\ 4).$

The values used for $\bar{u}_{di}$ and $\sigma(u_{di})$ were determined from preliminary trials. Also from preliminary trials, we occasionally observed that the fourth switch failed to be reached, and a reversal of velocity direction occurred. This is a statistical outcome. For this situation, we used Eq. (19) to stop motion after a maximum time elapsed in the last section to prevent reversal of direction. This worked satisfactorily.

Figure 7 shows the encoder velocity, position, and motor force for a typical run using four switches. Even though we measured velocity with the encoder, this information was not used when running the control using switches trials. A summary of individual results obtained for 15 trials is given in Table 4.

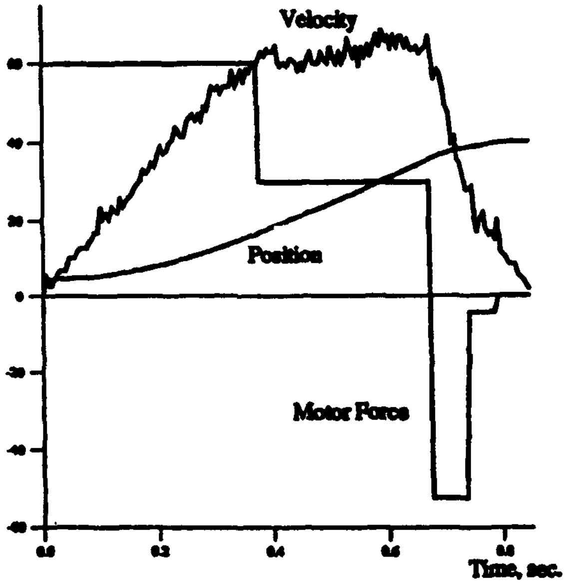

Figure 7. Encoder velocity, position, and motor force for control using four switches.

Table 4. Results of Fifteen Trials for Control Using Four Switches

Run #	Velocity (Encoder), in./sec		Velocity (Switches), in./sec		Disturbing Forces, lbs				Total Time, sec	Final Pos., in.
	v_3	v_4	$\bar{v}_3$	$\bar{v}_4$	$\bar{u}_{d1}$	$\bar{u}_{d2}$	$\bar{u}_{d3}$	$\bar{u}_{d4}$		
4-0	31.2	16.8	30.6	12.9	-35.5	-32.8	-19.1	-45.3	0.796	39.99
4-1	28.6	17.7	30.0	13.5	-35.3	-31.0	-20.0	-44.2	0.784	40.00
4-2	32.0	16.0	29.6	13.0	-34.7	-32.3	-20.6	-45.2	0.786	40.01
4-3	30.3	14.3	31.9	10.7	-35.4	-32.7	-17.3	-49.0	0.795	39.99
4-4	33.7	1.7	36.9	0.0	-36.5	-32.4	-9.1	-57.1	0.810	39.29*
4-5	30.3	4.2	35.3	0.0	-37.2	-33.3	-11.8	-57.1	0.828	39.44*
4-6	28.6	16.0	30.8	12.7	-35.3	-33.0	-18.8	-45.7	0.796	39.98
4-7	30.3	15.2	30.4	13.1	-34.4	-33.2	-19.4	-45.0	0.787	40.01
4-8	27.8	15.2	29.4	10.6	-34.7	-32.2	-20.9	-49.1	0.788	39.98
4-9	27.8	17.7	27.6	14.1	-33.9	-32.2	-23.3	-43.0	0.780	40.04
4-10	29.5	14.3	31.3	8.7	-34.5	-31.3	-18.2	-51.7	0.780	39.89
4-11	27.0	16.8	30.6	11.0	34.1	-32.3	-19.1	-48.4	0.780	39.99
4-12	26.1	17.7	25.3	13.9	-34.2	-32.5	-26.1	-43.4	0.789	40.03
4-13	28.6	16.8	30.0	11.7	-34.1	-33.1	-20.0	-47.4	0.785	39.97
4-14	31.2	16.0	29.8	12.7	-34.9	-33.6	-20.3	-45.6	0.797	39.95
Averages					-35.0	-32.5	-18.9	-47.8	0.792	39.90
Standard Deviations					0.9	0.7	4.1	4.5	0.013	0.22

*fourth switch not tripped.

Using the data for $\bar{v}_4$ in Table 4, we calculated the standard deviation of $\bar{v}_4^2$ and compared to the theoretical result, Eq. (12):

$$\sigma(\bar{v}_4^2) = 62.91 \text{ from data;}$$
$$= 56.15 \text{ from Eq. (12).}$$

Again, the agreement is satisfactory.

CONCLUSIONS

A general conclusion is that control using switches shows a lot of promise for certain applications. Two of the immediate benefits of the application to the autoloader were that motor torque feedback noise was eliminated and total cycle time was minimized compared to PID control. It should be mentioned again that a fully definitive control procedure is not claimed in this report. Additional research is required to determine the robustness of the procedures used and to develop additional theory and procedural changes.

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