Increasing Mission Reliability By Using Open-Loop Control

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Key Words — Mission reliability, Feedback sensor failure, Modified bang-bang control, Open loop control

Reader Aids —

General purpose: Widen the state of the art
Special math needed for explanations: Probability and statistics
Special math needed to use results: Same
Results useful to: Reliability engineers, Control designers.

Summary & Conclusions — Reliability of some 1-degree of freedom servo systems can be increased by providing a degraded mode of operation in the event of feedback sensor failure. Mission reliability is increased because redundancy is introduced. The numerical value of increased reliability is neither estimated nor predicted; rather, a general computer software approach is provided that appreciably increases the reliability.

The servo system is comprised of a computer-controlled motor-driven mechanism which repositions a given mass. The servo motor is controlled by real-time computer software/hardware which generates a digital-to-analog voltage proportional to motor force. Feedback from the mechanism provides real-time position & velocity information. Using feedback to determine required motor torques according to some control law leads to closed-loop control. An open-loop controller, on the other hand, requires no feedback information but must rely on predictions of the entire motion cycle with no updating of the current state.

Normally, the mechanical system operates in a closed-loop feedback mode. During normal operation, additional information is continuously gathered on the disturbing forces encountered and their statistical variations from cycle to cycle. Disturbing forces are non-motor generated forces, *eg*, friction, gravity, and inertial coupling. These forces can be estimated after completion of a closed-loop cycle by analyzing the history of position, velocity, and motor forces. This disturbing-force information is used to design an open-loop controller that can instantaneously take over the repositioning task in the event of feedback sensor malfunction.

An ideal and relatively general closed-loop control law that was used in these studies is the modified bang-bang (MBB) controller. There are many other control laws but the MBB controller is amenable to design of the open-loop approach in this paper. The main reason is that the operating cycle of the MBB controller is readily divided into 3 motion sections: acceleration, constant velocity, and deceleration. Disturbing forces can be readily estimated in each section. The measured mean & standard deviation (StdDev) of the disturbing forces are used to design a conservative open-loop cycle. The cycle is conservative in that the target position for open loop is chosen to be less than the actual desired target position by an amount that yields a specified small probability of exceeding the target at some specified confidence level during any given random cycle. The goal is to prevent excessive overshoot or inadvertent crashing of the mechanism into its end stops whenever open-loop control is used. At the end of the open-loop cycle, the mass should be short of its final goal. The total open-loop cycle

is then finished using a constant or cyclic motor force or other technique depending on the specific application.

The key to success of this open-loop procedure is the theoretical derivation of the mean & StdDev of final position as a function of the statistics of the measured disturbing forces. A simple equation permits real-time application of the results.

These techniques were successfully applied to the loading cycle of a large-caliber tank ammunition autoloader. After operating the autoloader for many normal closed-loop cycles, the feedback loss was simulated and then these open-loop techniques were used. The primary disturbing force encountered during these successful trials was high random friction.

1. INTRODUCTION

The main objective of our work is to increase the mission reliability of a 1-degree of freedom computer-controlled servo system. This is to be accomplished by providing an acceptable degraded mode of operation that can take over functioning of the system in the event of feedback sensor failure. The failure mode can be either the total loss of position/velocity feedback or unacceptable instability resulting from such effects as high backlash, partial loss of signal, or sudden high feedback noise. We (at US Army Benet Labs) have experienced all of these failure modes in our development of a large caliber tank autoloader. The degraded mode of operation to be used in the event of feedback failure is open-loop control [1,2]. Open-loop control eliminates many controller-based instabilities and permits operation of a servo mechanism with minimal or no feedback.

1.1 Review of Servo Control

Figure 1. Elementary 1-Degree of Freedom Control Problem

The main objective in servo control is to move a given mass using motor forces. Figure 1 shows a simple 1-degree of freedom force-mass system. A mass m is subjected to a total force u_t which can be a function of time, position, and/or velocity. This force is comprised of a motor force u and a disturbance force u_d . The disturbance force is comprised of all other forces (*eg*, friction, gravity, and inertial coupling) that are not motor forces. One objective of servo control is to drive a mass

m from one position to another, say x_r , as shown in figure 1, using the motor force u , overcoming any disturbing forces u_d that might be encountered during the motion cycle.

Figure 2. Feedback Servo Control

We can control the motor force using a computer and electronic hardware which converts & amplifies computer commands into motor forces. Position & velocity sensors can provide real-time information to the computer controller as shown in figure 2. We can now use various control laws to determine the motor force u as a function of time and feedback signals x and $\dot{x}$ [1,2]. If the feedback information of position and/or velocity is used in the control law, it is closed-loop control. If no feedback is used, it is open-loop control.

1.2 1-Degree of Freedom

This paper only considers the problem of positioning a 1-degree of freedom system.¹ The basic idea is to run the system normally using closed-loop if there are no feedback-sensor failures. In many servo systems, the most important cycle-to-cycle unknowns are the disturbing forces such as friction, gravity, and motion coupling. In the closed-loop system the unknown disturbing forces are automatically taken care of as part of the control law and feedback process. The disturbing forces and their statistics can be estimated during normal operation of the closed-loop system by observing actual motor forces vs response. The calculated statistical means & StdDev of the disturbing forces can then be used to design a conservative open-loop controller using BOLC². Then in the event of feedback failure, the conservative open-loop controller can take over to drive the system short of, but as near as feasible, to its final position with low probability of excessive overshoot or collision. The cycle is then finished using a constant or cyclic force or some other means depending on the application.

¹Decoupling a multi-degree of freedom system will be considered in the future.

²Editors' note: We have assigned the acronym, BOLC (Benet - Open-Loop Control), to the work in this paper, to make references to this work simple and clear.

1.3 BOLC Application

An ideal closed-loop controller amenable to designing an open-loop system is the Modified Bang-Bang (MBB) controller [3-6]. In its simplest configuration, MBB has 3 basic phases: acceleration, constant velocity, and deceleration. An open-loop system can be designed using these 3 motion-phases. Disturbing forces in the 3 phases are estimated from previous closed-loop runs and used to determine constant motor-force levels & times of application to complete the required motion for open-loop operation.

Figure 3. Schematic of XM98 140mm Tank Autoloader

We successfully applied BOLC to a large-caliber tank-cannon autoloader [7]. Figure 3 is a schematic diagram of the XM98 140MM tank autoloader. This autoloader is comprised of a 17-cell carousel ammunition storage & repositioning system (only 2 cells are shown in the figure) and a loading mechanism. The loading mechanism is comprised of 2 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 and into the gun tube. Both servo systems use MBB. Data from cycling the ramming mechanism were analyzed to determine the unknown disturbing forces, primarily friction, in the 3 main control phases. An open-loop system was then successfully run using the generated data. Test details are discussed in section 6, "Experimental Results".

The other sections in this paper are:

2. Problem Description
3. Designing an Open-Loop System
4. Statistics of Final Position & Velocity (for open-loop control)
5. Measurement of Disturbing Forces (from closed-loop MBB control data)

6. Experimental Results (for large caliber autoloader).

Acronyms & Abbreviation

BOLC	Benet open-loop controller (the method in this paper)
MBB	modified bang-bang (controller)
PD	proportional-derivative (controller)
StdDev	standard deviation

Notation

-	implies average value of a r.v.
-	implies a sample outcome of a r.v.
C	s -confidence level
F	friction force
k_1, k_2	positional and velocity gains
m	mass
t	time
t_p	non-central Student t parameter
u, u_d	[servo motor, random disturbing] force
u_g	gravity and/or coupling force
m	subscript: implies a specified maximum
o	subscript: implies open loop
i	subscript: implies a section (see figure 7)
u_t	total force acting on mass m
x, v	[position, velocity] of mass m
x_r	desired or command position of mass m
v_m	specified maximum velocity of mass m
σ_{var}	standard deviation of r.v. var.

Other, standard notation is given in "Information for Readers & Authors" at the rear of each issue.

2. PROBLEM DESCRIPTION

Consider the positioning problem of a 1-degree of freedom system using MBB control. Eq (1) is the equation of motion for a typical simplified system:

$$u + u_d = m\ddot{x} \quad (1)$$

The closed-loop control approach used in this study is the MBB controller (switching zone controller [3-7]). The MBB controller is based in part on bang-bang theory in which maximum allowable torques are applied both to accelerate and decelerate a mechanism to move from one position to another in near minimum time. Essentially, the MBB controller is comprised of bang-bang control with a boundary layer away from the desired target position and then a transition to PD control near the target position [1-2]. A maximum velocity is often specified as a design requirement.

Figure 4 is the schematic diagram for the MBB controller; the dynamic system is that in (1).

Notation

a	nonlinear function selected to guarantee sufficient force for deceleration: $(u_m - u_{dm})/u_m$
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b	constant selected to guarantee no overshoot, $2a \cdot u_m / k_1$
ξ_1	$b + m \cdot v_m^2 / (2a \cdot u_m)$

Figure 4. Block Diagram of MBB Controller

Figure 5. Example of an Ideal MBB Control Case

Figure 5 shows position, velocity, and motor force as a function of time for an example ideal control case where no

feedback noise exists. Figure 6 presents actual data for the ramming cycle of a tank autoloader, where acceptable noise effects are present in the feedback and hence in the motor forces.

Figure 6. Experimental Data for Large Caliber Autoloader Ramming Cycle

Main Problem

If there is a loss or degradation of feedback, can a positioning cycle be completed using another control mode? For the autoloader, can ammunition be loaded and the firing mission completed? BOLC uses open-loop control which doesn't require feedback information. The motor force vs time histories of the closed-loop system are used to generate a motor force profile that can be used in an open-loop mode if required.

3. DESIGNING AN OPEN-LOOP SYSTEM

Figure 7 shows an ideal open-loop profile; constant motor force is applied in each of the 3 sections shown. The time intervals for force application depend on the disturbing force and other fixed parameters of the system. Ideally, the system is accelerated in section 1 to v_m . The motor force is then reduced to a value which just overcomes the disturbing force in section 2 to maintain a constant velocity. Finally a negative constant force is applied to decelerate and stop the system at the desired target position with the velocity going to zero.

In the actual case, the disturbing forces in the 3 main sections are random variables. From many closed-loop trials, we can estimate the mean & StdDev of the disturbing forces in the 3 sections. The average value of the disturbing forces are then used to estimate the t_i for the 3 sections. However, since the disturbing forces are random variables, the actual final posi-

tion and velocity for open-loop control of the system is random. We therefore choose a conservative target position $x_{ro} < x_r$. This new target position is chosen so that the probability of exceeding x_r in any given random cycle using open-loop control is some small acceptable value, eg, 5% or 10%, at some given s -confidence level. At the end of the open-loop cycle, some other procedure might need to be initiated to finish the total cycle. For example, a constant positive force can be applied for a given period of time or until a switch is tripped indicating completion. For the autoloader, there are hard stops at the end of a loading or unloading cycle. Some final docking velocity is acceptable as long as it's not too large. Also, there is some desired final docking force which can be applied at the end of the total operation. The final procedure depends on the system to be controlled and on experimentally determined acceptable final velocities and forces.

Figure 7. Ideal Open-Loop Profile of Constant Motor-Forces

We are concerned here only with designing the original open-loop cycle portion of the total operation. From several closed-loop trials, we estimate the random disturbing forces in the 3 sections of figure 7 as discussed in section 1.2, "1-Degree of Freedom". For a large enough sample size we can estimate the s -means & StdDevs of the disturbing forces. From the statistics of the frictions and other disturbing forces, we estimate the statistics of the final random position x_f for open-loop operation. We do this by assuming the s -normal distribution for disturbing forces and then using either Monte Carlo simulation or theoretical derivations (see next section). Once we know the statistics of the final position we can estimate x_{ro} using the sample mean and StdDev of x_f .

$$x_{ro} = x_r - t_p \cdot \sigma_{x_f}. \quad (2)$$

In (2) t_p can be determined from the non-central t-distribution for a given p and C [8,9]. For example, for $p = 10\%$, $C = 90\%$, then $t_p = 2.065$ and 1.657 for sample sizes of 10 and 30 respectively.

4. STATISTICS OF FINAL POSITION & VELOCITY

In order to estimate the statistics of final position and velocity under open-loop control, we need to make some simplifying assumptions. The consequences of these assumptions need to be assessed carefully in each application. For the autoloader, these assumptions seem reasonable.

Assumptions

1. The disturbing forces in each of the 3 open-loop sections of figure 7 are s -independent random variables; they are constant in each individual section during any given cycle. These forces vary randomly, however, from cycle to cycle.

2. The disturbing forces are a friction term which depends on the sign of the velocity and another constant force term such as gravity or motion coupling. This assumption implies:

$$\bar{u}_{di} = \bar{u}_{gi} - \text{sign}(\dot{x})\bar{F}_i = \text{disturbing force for section } i. \quad (3)$$

3. The random disturbing forces are s -normally distributed. They are to be estimated for a system during closed-loop MBB operation.

Hypothetical Assumption

4. The disturbing forces are constant at their average values. The t_i are calculated by applying (1), within each open-loop section. These representative times and the associated constant motor force u are:

$$t_1 = mv_m/[u_1 - (\bar{F}_1 - \bar{u}_{g1})]; u = u_1$$

= maximum acceleration motor force

$$t_3 = mv_m/[u_3 + (\bar{F}_3 - \bar{u}_{g3})]; u = -u_3$$

= maximum deceleration motor force

$$t_2 = \frac{x_r}{v_m} - \frac{1}{2}(t_1 + t_3); u = u_2 = -\bar{u}_{g2} + F_2$$

= force required to maintain constant velocity v_m (4)

If in any given run, assumption 4 were true, then the times in (4) would yield the ideal response in figure 7; the final position is x_r and the final velocity is 0. However, using the times in (4) when the disturbing forces are random yields random values for final position and velocity. Being able to estimate the statistics of the final position and velocity for the random case would permit the design of a conservative open-loop controller (*conservative* is explained in Summary & Conclusions).

The statistics of final position and velocity can be estimated using Monte Carlo simulation.

Explanation of Monte Carlo Simulation

Sample outcomes of the disturbing forces are generated randomly assuming the s -normal distribution. The position and velocity at the end of each section of figure 7 are calculated by solving (1) for constant forces. By generating many samples in this manner, the mean & StdDev of the final position & velocity are calculated. One need only solve (1) over and over again using different random values of disturbing forces and then calculate the statistics of final position and velocity.

Derivation of Estimates

For any given sample outcome, let the disturbing forces be $\bar{F}_i$ and $\bar{u}_{gi}$ for $i = 1, 2, 3$. The calculation of positions and velocities at the end of the sections in figure 7 are:

Section 1

$$\begin{aligned} \bar{v}_1 &= \frac{t_1}{m} [u_1 - (\bar{F}_1 - \bar{u}_{g1})] \\ \bar{x}_1 &= \frac{t_1^2}{2m} [u_1 - (\bar{F}_1 - \bar{u}_{g1})] \end{aligned} \quad (5)$$

Section 2

$$\begin{aligned} \bar{v}_2 &= \frac{t_2}{m} [u_2 - (\bar{F}_2 - \bar{u}_{g2})] + \bar{v}_1 \\ \bar{x}_2 &= \frac{t_2^2}{2m} [u_2 - (\bar{F}_2 - \bar{u}_{g2})] + t_2 \bar{v}_1 + \bar{x}_1 \end{aligned} \quad (6)$$

Section 3

The $v_3(t)$ can go negative in this section. When it does, the friction force changes sign. The u_t acting on m consequently changes:

$$\begin{aligned} u_t &= u_t^+ = [-u_3 - \bar{F}_3 + \bar{u}_{g3}] \text{ for } v_3(t) \geq 0.0 \\ &= u_t^- = [-u_3 + \bar{F}_3 + \bar{u}_{g3}] \text{ for } v_3(t) < 0.0 \end{aligned} \quad (7)$$

For a given run we calculate the time $t = \tilde{t}_c$ when $v_3(t) = 0.0$ where up to this point $u_t = u_t^+$: Crossover time = $\tilde{t}_c = m\bar{v}_2/[u_3 + (\bar{F}_3 - \bar{u}_{g3})]$.

$$\begin{aligned} \bar{v}_3 &= \frac{t_3 u_t^+}{m} + \bar{v}_2; \text{ if } \tilde{t}_c \geq t_3 \\ &= \frac{(t_3 - \tilde{t}_c)u_t^-}{m}; \text{ if } \tilde{t}_c < t_3 \\ \bar{x}_3 &= \frac{t_3^2 u_t^+}{2m} + \bar{v}_2 t_3 + \bar{x}_2; \text{ if } \tilde{t}_c \geq t_3 \end{aligned}$$

$$= \bar{x}_c + \frac{(t_3 - \tilde{t}_c)^2 u_t^-}{2m}; \text{ if } \tilde{t}_c < t_3 \quad (8)$$

$$\bar{x}_c = \frac{\tilde{t}_c^2 u_t^+}{2m} + \tilde{v}_2 \tilde{t}_c + \bar{x}_2$$

Section 4

This section is added to open-loop operation because the velocity at the end of section 3 is generally not zero. The motor force is set to zero but motion continues until friction eventually stops the motion. If the friction force in section 4 is equal to its value for section 3, $\bar{F}_3$, we get the following final position and velocity:

$$\bar{v}_f = 0.0$$

$$\bar{x}_f = \bar{x}_3 - \frac{m \bar{v}_3^2}{2 u_t} \quad (9)$$

$$u_t = -\bar{F}_3 + \bar{u}_{g3}; \bar{v}_3 \geq 0.0$$

$$u_t = +\bar{F}_3 + \bar{u}_{g3}; \bar{v}_3 < 0.0$$

We conducted many Monte Carlo trials using these equations on our own computer program. Each set of Monte Carlo trials involved the following steps:

1. Fix the system parameters m , u_m , v_m , $\bar{F}_i$, $\sigma_{F_i}^2$, $\bar{u}_{gi}$, $\sigma_{u_{gi}}^2$, x_r .
2. Generate random sample outcomes of the disturbing force terms $\bar{F}_i$, $\bar{u}_{gi}$ for each of the 3 open-loop sections, using a random number generator.
3. Calculate $\bar{x}_f$ using (4) through (9).
4. Repeat steps 2 & 3 n times; eg, 1000 times.
5. Calculate the mean & StdDev of $\bar{x}_f$ for the n trials.

This Monte Carlo simulation is time consuming. Consequently, it cannot be readily conducted in real time during system operation. We need an acceptable faster solution. We derived such a solution by making some additional simplifying assumptions to those made for the Monte Carlo approach. We then compared these solutions to the Monte Carlo results.

Additional Assumptions

1. The velocity remains positive (or of constant sign) throughout the cycle. The fact that it can go negative near the end of the cycle is negligible. Thus we can treat disturbing forces as constants throughout.
2. Residual velocity $\bar{v}_3$ at the end of the operating cycle is negligible so that $\bar{x}_f = \bar{x}_3$.

Combining (4) through (8), using these additional assumptions, we calculate $\bar{x}_f$ directly as a function of the disturbing forces and t_i :

$$\bar{x}_f = \bar{x}_3 = x_r + c_1(\bar{u}_{d1} - \bar{u}_{d1}) + c_2(\bar{u}_{d2} - \bar{u}_{d2})$$

$$+ c_3(\bar{u}_{d3} - \bar{u}_{d3}) \quad (10)$$

$$c_1 = \frac{1}{m} \left(\frac{t_1^2}{2} + t_1 t_2 + t_1 t_3 \right)$$

$$c_2 = \frac{1}{m} \left(\frac{t_2^2}{2} + t_2 t_3 \right)$$

$$c_3 = \frac{1}{m} \frac{t_3^2}{2}$$

For this case $\bar{x}_f = x_r$, the target position and for s -independent disturbing forces in the 3 open-loop control sections,

$$\sigma_{x_f}^2 = c_1^2 \sigma_{u_{d1}}^2 + c_2^2 \sigma_{u_{d2}}^2 + c_3^2 \sigma_{u_{d3}}^2 \quad (11)$$

Autoloader Example

Table 1 lists some results for a particular autoloader example derived from both Monte Carlo simulation and using (11).

- a. The F_i are the only disturbing forces
- b. $m = 80$ lbs/g, $g = 386$ in/sec²

$$v_m = 120 \text{ in/sec}$$

$$x_r = 115 \text{ inches}$$

$$u_{\max} = 75 \text{ lbs.}$$

For the Monte Carlo trials, a sample size of $n = 1000$ was used for each case.

From the results shown in Table 1 and other results not shown here, we conclude that (11) can be used to approximate adequately the Monte Carlo results. Real-time estimation of open-loop parameters and conservative target positions can therefore be readily obtained in real-time during operation of a given system. Specifically, given the estimates of the statistics of the disturbing forces, we can quickly estimate the statistics of the final position for open-loop operation. From this information we can calculate a conservative set of open-loop parameters by calculating a new $x_{ro} < x_r$ which yields acceptable probability that $\bar{x}_f \leq x_r$ for any given cycle run.

TABLE 1
Monte Carlo Simulation and Calculation of StdDev of Final Position

$\bar{F}_i$, lbs	σ_{F1} , lbs	σ_{F2} , lbs	σ_{F3} , lbs	σ_{x_f}	
				Simulation	(11)
10	1.0	1.0	1.0	2.875	2.732
20	1.0	1.0	1.0	2.924	2.887
30	1.0	1.0	1.0	3.260	3.201
30	1.0	0.0	0.0	2.896	2.871
30	0.0	1.0	0.0	1.442	1.410
30	0.0	0.0	1.0	0.139	0.135
30	2.0	2.0	2.0	6.739	6.402

The conservative open-loop controller described here is intended to be used only as a degraded mode of operation in the event of feedback sensor malfunction. Closed-loop MBB control is the normal mode of operation.

5. MEASUREMENT OF DISTURBING FORCES

In measuring disturbing forces, we first accumulate motor force, position & velocity vs time data during closed-loop MBB system operation. We process these data to determine the beginning & end points of each of major motion *sections*: acceleration, constant velocity, and deceleration. We then estimate the disturbing forces in each *section*. Ideally, we would determine an equivalent constant disturbing force, perhaps representing an average, for each *section* so that we can estimate a constant motor force to be used in the open-loop mode.

Assumption

1. Disturbing forces are constant in each *section* but can differ in each section. ◀

We calculate the disturbing forces using the following relations:

$$\bar{u}_{di} = \frac{m(\Delta\dot{x})_i}{(\Delta t)_i} - \bar{u}_i \quad (12)$$

$$\bar{u}_i = \frac{1}{N_i} \sum_{k=1}^{N_i} u_k$$

Notation

u_k motor force for increment k
 N_i number of sample time increments in *section i*
 $(\Delta\dot{x})_i$ velocity change within *section i*.

In *section 2*, the velocity change should be near zero; thus disturbing force $\approx$ average motor force.

6. EXPERIMENTAL RESULTS

Figure 8 shows a typical closed-loop cycle for the autoloader rammer; we have indicated the 3 major control *sections*. The maximum force is 75 lbs except for the first 12 inches of travel where 110 lbs is required to overcome high initial friction forces. Besides friction, there are coupling disturbing forces between the rammer and telescoping cell which results in the more complicated motion profile of figure 8.

We conducted many trials applying the results in this paper. Table 2 lists some of the results obtained for the disturbing forces and their StdDev for closed-loop MBB operation of the autoloader rammer. Eq (12) was used for calculating disturbing forces. The StdDev in table 2 are the s -unbiased sample deviations calculated for the number of trials shown. Some variations exist between different sets of runs. These variations

primarily reflect wear and current condition of the ramming mechanism. It's important when applying open-loop control to use the latest data to reflect updated conditions. The rammer numbers in table 2 indicate the use of 2 rammer mechanisms.

Figure 8. Closed-Loop Cycle for Autoloader Rammer Showing 3 Major Control Sections

TABLE 2
Disturbing Forces and StdDev for Autoloader Trials

Rammer Number	Trial Nos.	u_{d1} lbs	$\sigma_{u_{d1}}$ lbs	u_{d2} lbs	$\sigma_{u_{d2}}$ lbs	u_{d3} lbs	$\sigma_{u_{d3}}$ lbs	σ_{x_f} eq.(11)
1	27-51	48.1	1.37	61.8	1.47	30.8	1.45	4.12
	301-320	52.6	1.23	66.1	2.33	31.2	3.14	4.36
	501-523	56.6	1.95	68.8	1.77	33.9	3.30	6.61
2	101-110	52.2	1.84	66.5	2.22	30.4	3.79	5.98
	301-310	52.5	1.61	64.4	3.11	27.3	1.97	5.74

We conducted many open-loop trials after the closed-loop trials 301-310 for rammer #2. Figure 9 shows some of the results of these trials for 3 values of conservative open-loop target position x_{ro} . x_{ro} for these trials was estimated using (2) for 3 values of $t_p = 1.0, 2.0, 3.0$. Comparison is made in these figures to the last closed-loop trial conducted prior to the open-loop trials.

The main problem in these trials was in matching *section 1*, the acceleration phase. The average open-loop motor force (96 lbs) didn't accelerate the round of ammunition as fast as in the closed-loop trials. It appears that a higher motor force closer to the initial closed-loop 110 lbs needs to be used to match accelerations. However, the maximum velocity was closely achieved in all cases but with a nearly fixed delay time for the open-loop trials. This delay was added to t_2 for the results in figure 9. This yielded satisfactory

Figure 9a. Open- vs Closed-Loop Trials for Autoloader Rammer [$t_p = 1.0$]

Figure 9c. Open- vs Closed-Loop Trials for Autoloader Rammer [$t_p = 3.0$]

Figure 9b. Open- vs Closed-Loop Trials for Autoloader Rammer [$t_p = 2.0$]

results for all of our open-loop trials. Table 3 lists some of the final positions obtained for the open-loop trials.

A satisfactory procedure for finishing the ammo ramming function is to apply cyclic motor force with a peak of about 50 lbs until a switch is tripped (indicating a successful loading). Application of open-loop procedures, both to increase reliability and minimize instabilities will be incorporated into next-generation tank autoloaders.

TABLE 3
Final Positions for Open-loop Control of Autoloader Rammer

Run #	t_p (StdDev)	$\bar{x}_f$ (inch)	x_{ro} (inch)	x_r (inch)
403	3.0	94.5	97.3	115.0
404	2.0	104.5	103.0	115.0
405	1.0	110.8	108.8	115.0
406	1.0	107.9	108.8	115.0

We conclude that these BOLC techniques are sound and apply to real situations. This provides an acceptable degraded mode of operation which can increase the mission reliability by providing redundancy.

Using the modified bang-bang control law makes it easier to divide the motion cycle into the 3 sections of acceleration, constant velocity, and deceleration. However, other control laws can be used as long the disturbing forces can be estimated for the equivalent open-loop sections. It might be possible to run a system in the open-loop mode for a major portion of the motion cycle. The stability advantages of running open-loop could then be realized regardless of reliability considerations.

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