PRACTICAL IMPLEMENTATION OF A DEAD ZONE INVERSE ON A HYDRAULIC WRIST

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ABSTRACT

This paper presents practical aspects of implementing a dead zone inverse on a hydraulic wrist. A dead zone occurs over a range of small input values for which the system does not respond. It was desirable to use the most straightforward method available to achieve improved system performance while requiring the least amount of modification to the controller. Thus a fixed parameter dead zone inverse (DZI) was added to an existing proportional-integral (PI) controller.

First, the parameters of the dead zone were characterized from open loop testing. These parameters are the break points, or input values between which the system does not respond at all, and the slope of the system's response just outside the break points. The DZI augments the PI signal input to the plant, effectively adding or subtracting a constant equal to the size of the dead zone break points and scaling the input by its slope.

Simulations predicted perfect system tracking, but implementation on the hardware revealed several practical issues. First, the dead zone slope parameters vary throughout the robot's workspace. Overestimation can lead to non-ideal system performance, but the more extreme problem is underestimation, which effectively increases control loop gain and can lead to system instability. However, performance is not affected significantly unless these parameters are off by an order of magnitude. Overall the system performance is relatively robust to modeling errors in the slope parameters.

The second issue is that noise can be magnified by the dead zone inverse and cause chattering. This problem was very noticeable in the wrist when the estimated dead zone break points were used in the DZI. This problem can be eliminated by reducing the dead zone break points or reintroducing a small artificial dead zone back into the control loop to envelope the expected noise level.

The requirements for successful implementation of the DZI were found to be a basic characterization of the dead zone and an understanding of practical system issues that can be accentuated by its use. The effectiveness of the technique was tested through simulations and experiments on the wrist.

INTRODUCTION

Dead zones are common nuisances that exist in many systems. For example, some motors do not respond at low voltages due to friction forces. This particular issue arose when an IBM 7565 wrist (Figure 1), donated to Ga. Tech in the 1980s, was added to an experimental testbed used for vibration control research. The wrist is a three degree of freedom hydraulic robot. It is operated via servovalve mechanisms that control the rate of flow of oil into rotary vane pumps that actuate each of its three rotational joints.

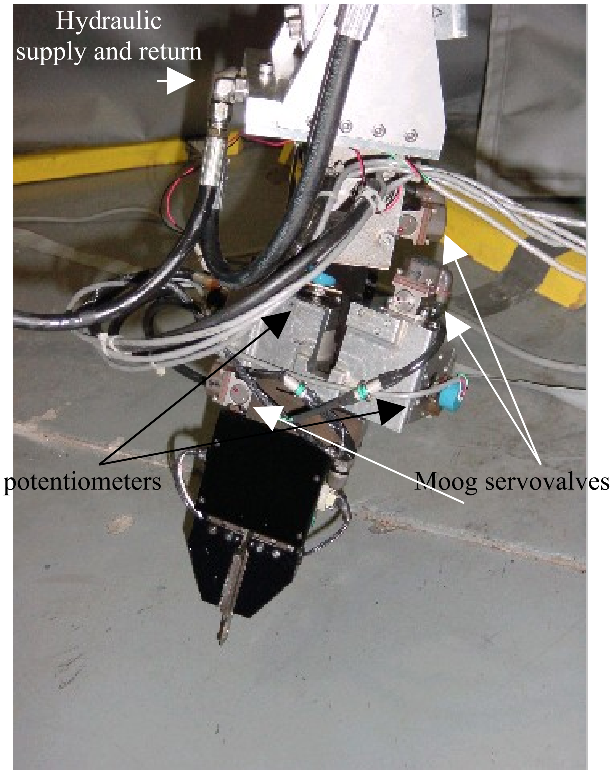

Figure 1
Hydraulic Wrist

The dead zone occurs because the servovalves do not respond to small input currents. The dead zone region was relatively large compared to the normal operating range. The need for good position control about a nominal operating point, i.e. at small input values, necessitates the use of some dead zone compensation technique.

There are several researchers who have addressed dead zones along with various other types of actuator and sensor nonlinearities in detail. The Tao and Kokotovic textbook [1] provides very useful information on how to model these nonlinearities and proposes adaptive control methods to address them [1,2]. Although adaptive control may be the ideal way to address this issue, the goal here was to make an easily implementable yet effective modification to the control scheme to achieve improved system performance. This minimized the time and cost involved and allowed more time to focus on the primary goal of the work.

A fixed parameter dead zone inverse was added to an existing proportional-integral (PI) controller. The overall control scheme is shown in Figure 2 where:

θ_d = desired joint position
θ_a = actual joint position, measured via potentiometers
G_{PI} = proportional and integral controller
G_P = plant transfer function
DZ = Dead zone
DZI = Dead zone inverse

The PI controller was designed separately for good system performance based on model estimates acquired through open loop testing. The dead zone parameters were also easily identifiable from open loop testing. Two issues became apparent in implementation of the DZI. First, the slope parameter directly affects the control loop gain. The system performance varies little unless the slope is drastically over or underestimated; however if it is underestimated too much the system can be driven unstable. Second, the DZI tends to accentuate noise in the system. Regardless of whether a fixed parameter or adaptive compensator is used, these implementation issues will still apply. In fact, these could become more of a problem if the DZI parameters are allowed to vary, as an adaptive scheme may prescribe.

MODEL AND CONTROL SYSTEM DESIGN

The physical system is controlled by PC via a Motorola 68040 microprocessor and Acromag D/A and A/D boards (Figure 3). The processor interfaces with VxWorks real-time control system with control routines written in C code. The wrist is actuated via three Moog series 30 valves, each of which control vane actuators. The control output, τ, from the PC (+/- 2047) is converted to +/- 10 V output via the D/A board, then sent through voltage to current amplifiers to send a constant current output to the valves. The resulting joint motion is measured by potentiometers.

The first task was to develop a model of each joint and design appropriate independent PI controllers for each. A simplified first order approximation was used for the valve model, which is reasonable for relatively low frequency operation (<50 Hz) [3]:

$$\frac{Q(s)}{i(s)} = \frac{K}{as+1} \tag{1}$$

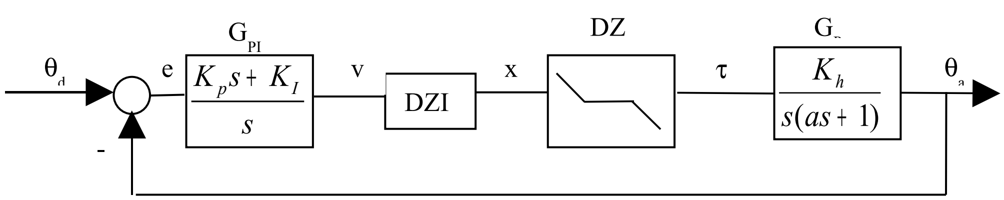

Figure 2
Control Loop with PI Control, Dead Zone Inverse, and Dead Zone

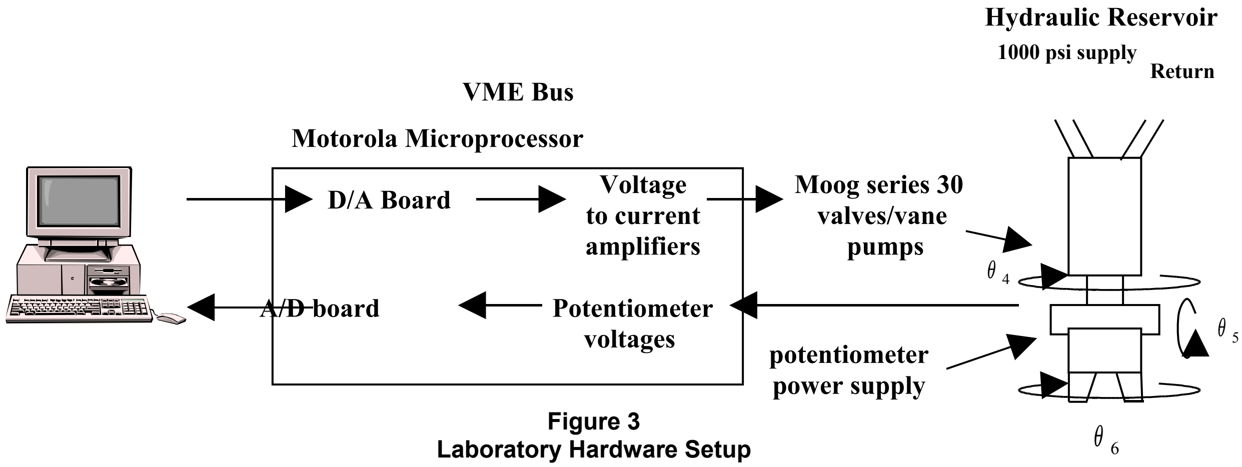

Figure 3
Laboratory Hardware Setup

where:

Q = flow rate (cubic inches)
i = current input (ma)
K = servovalve static flow gain at zero load pressure drop (cubic inches/ma)
a = apparent servovalve time constant (sec)

However, the relationship between the commanded output from the control output, τ, to the resulting joint motion, θ_a, was needed. Since the current input is proportional to the controller output signal. This relationship takes the form:

$$\frac{\theta_a(s)}{\tau(s)} = \frac{K_h}{s(as+1)} \tag{2}$$

where:

θ_a = resulting joint motion (rad)
τ = control signal output (unitless)

The constants K_h and a had to be determined experimentally. Open loop tests were performed on each joint, where a constant control output was sent to each valve and the resulting joint velocity recorded. This allowed estimation of the unknown parameters in equation 2. The proportional and integral gains were selected based on the model estimates for the system when well outside the dead zone. These were based on a root locus approach for the linear system and further refined by tuning the closed loop system for good performance. The resulting system parameters and selected PI gains are shown in Table 1.

Table 1
Model and Controller Properties

	K_h	a	K_p	K_I
Joint 1	0.0085	0.248	1200	720
Joint 2	0.0038	0.3134	1400	420
Joint 3	0.006	0.0248	1500	1350

However, over approximately 9% of the full range of commanded output, the wrist either did not respond at all or operated much more slowly than in other regions.

Dead Zone Model

The hydraulic valves demonstrated classic dead zone behavior with easily identifiable parameters. The velocity of joint one in response to the control output signal, proportional to the input current to the valve, is seen in Figure 4. For low positive and negative values of forcing current, the velocity is zero, thus any input between the break points b_l and b_r will result in zero motion. Another important parameter is the slope of the response just outside the dead zone. The slopes m_l and m_r are not necessarily equal, constant, or equal to the gain of the open loop system in other regions (K_h). These gains might also be different for positive and negative motion, for motion due to different input values, or at different locations throughout the robot's workspace.

Using the notation introduced in Tao and Kokotovic [1], the mathematical model of the dead zone shown in Figure 4 is:

$$\tau(t) = DZ(x(t)) = \begin{Bmatrix} m_r(x(t) - b_r) & if \quad x(t) \geq b_r \\ 0 & if \quad b_l < x(t) < b_r \\ m_l(x(t) - b_l) & if \quad x(t) \leq b_l \end{Bmatrix} \tag{3}$$

For the sake of implementation the slopes were averaged such that:

$$m_{avg} = \frac{m_r + m_l}{2} \tag{4}$$

The cutoff values and slopes were determined by a linear fit and are shown in Table 2.

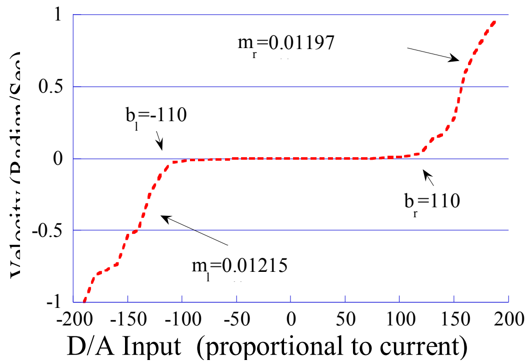

Figure 4
Dead Zone Characterization for Joint 1

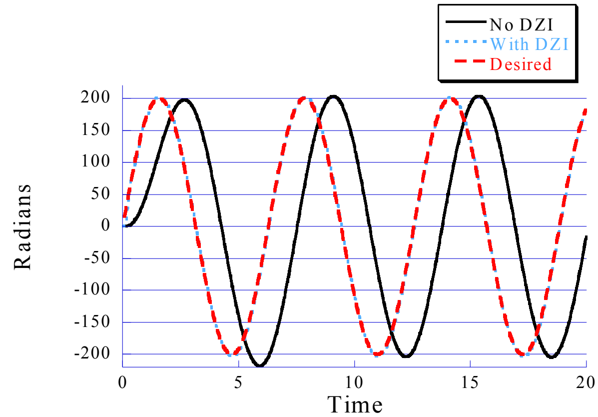

Figure 5
Simulated System Response With and Without DZI

Table 2
Dead Zone Properties

	b_l	b_r	m_l rad/sec	m_r rad/sec
Joint 1	-110	110	0.01205	0.01197
Joint 2	-260	270	0.010526	0.02352
Joint 3	-190	150	0.007377	0.00646

Dead Zone Inverse

In order to deal with the dead zone, the control technique of dead zone inversion, DZI, can be found described in [1]. The dead zone inverse attempts to augment the signal input to the plant so that the dead zone is canceled. This is done by adding a constant equal to the size of the dead zone break points to the input and then scaling the input by the slope of the dead zone. The equations for the inversion relating the old input v to the new input x are:

$$x(t) = DZI(v(t)) = \begin{cases} \dfrac{v(t) + \hat{m}_r \hat{b}_r}{\hat{m}_r} & if \quad v(t) > 0 \\ 0 \quad if \quad v(t) = 0 \\ \dfrac{v(t) + \hat{m}_l \hat{b}_l}{\hat{m}_l} & if \quad v(t) < 0 \end{cases} \tag{5}$$

where ∧ denotes an estimated parameter. The effect of the slopes m_l and m_r in the inversion is similar to proportional gains in the control loop. The dead zone inverse does not require feedback to work, but if feedback is used the inverse and the controller work in series.

RESULTS

Simulations of the hydraulic wrist were created in Matlab Simulink with the models and PI controller given in Table 1 and dead zone properties given in table 2. Studies to determine the effect of the dead zone as well as implementation of the DZI were performed. In addition, the DZI was added real-time to the control loop for the wrist. The cases considered here were the robot holding a constant position and tracking a low amplitude sine wave input about a desired position. Both cases tested the operation of the wrist at relatively low amplitude input, i.e. in and around the dead zone region. Hardware implementation brought to light several issues that are discussed further here.

Dead Zone Effects

The effect of the dead zone phenomenon is to add phase lag as well as a magnitude change to the system. If the response of the wrist including the dead zone is compared to the case without it, the results show this problem clearly. The simulated result can be seen in Figure 5 with the gains and model parameters for joint 1.

When closed loop tests were performed on the wrist the results were similar, although the impact on magnitude was more dramatic. Figures 6 and 7 show the desired and actual responses of the wrist joint 1 in two different configurations; the other joints behaved in a similar manner. Figure 6 shows the wrist in a configuration of $[90,90,0]^\circ$, the configuration shown in Figure 3. No comparison for the wrist can be made for the case without the dead zone since it cannot be turned on and as it can be in the simulation. Notice the configuration dependent change in undershoot.

Dead Zone Inverse and Implementation Issues

The dead zone inverse effectively eliminates the effects of the dead zone in simulation. If a sinusoidal input is simulated with exact parameter knowledge, that is the dead zone inverse and dead zone have the same values, the result is shown in Figure 5. However if the parameters for the inverse are incorrect errors will occur.

Figure 8 shows three experimental cases of varying the DZI slope parameter m_{avg}. If the slope is too shallow, i.e. m_{avg} is too large, the tracking is poor and a large

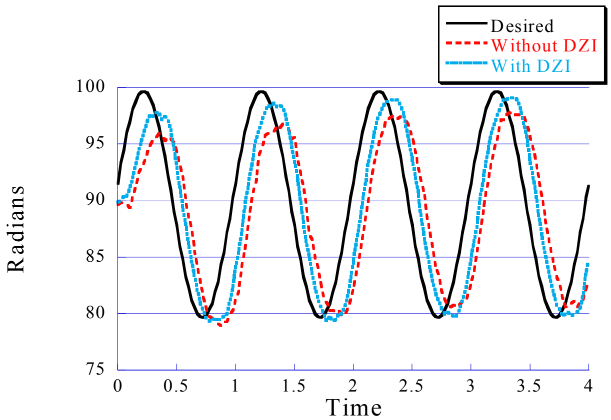

Figure 6
Wrist Response With and Without DZI at [90,90,0]°

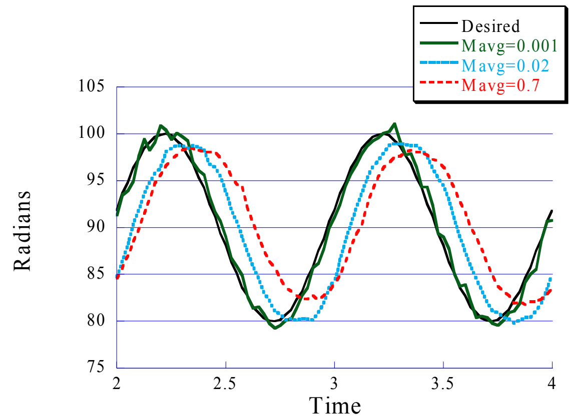

Figure 8
Experimental Effect of Changing DZI Slope

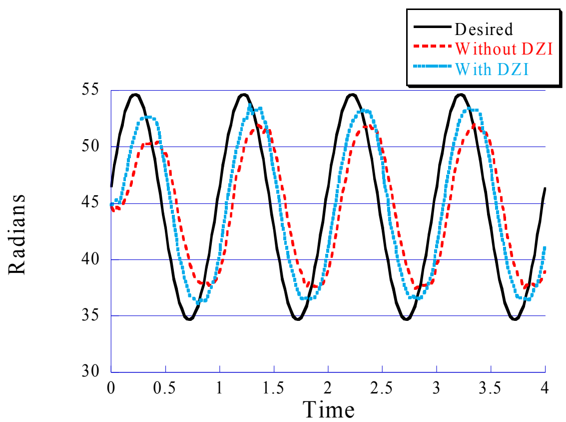

Figure 7
Wrist Response With and Without DZI at [45,45,0]°

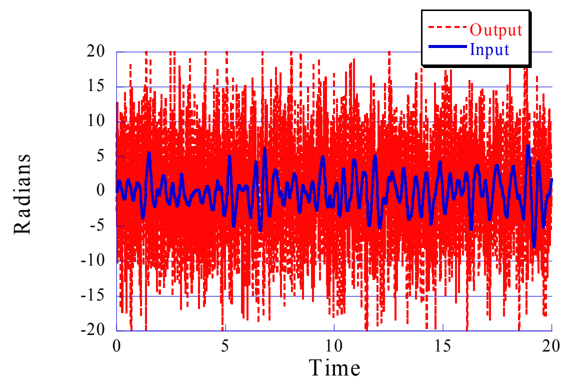

Figure 9
Simulated Chatter Result

overshoot occurs, however if the slope is too steep then high frequency oscillations occur about the trajectory. This happens because the slope of the inverse is effectively a proportional gain. A low gain has a slow response while a high gain or steep slope causes vibration. It is important to note however, that these effects are predominantly seen for very large changes in parameter values for m_{avg}. A 100% variation does not change the response drastically; instead, the values must change by an order of magnitude to see significant results.

This indicates that as long as approximate estimates are available for the dead zone slopes, improved performance will result from simply implementing the DZI with those estimates. In fact, there is little risk in doing so provided the slope estimates are not off by an order of magnitude or vary by orders of magnitude throughout the workspace.

The use of the break point parameter estimates in the DZI introduces another problem. The augmented input essentially has an offset added the size of these break points. If noise (or discretization error) is in the system, this offset will magnify the noise. Thus, noise that previously did not affect the system due to the dead zone now causes the system to respond. This was especially a problem on the wrist because the joint positions are measured using potentiometers, which are well know to be inherently noisy. If noise of low amplitude is input to the simulated system, mimicking the robot holding a desired stationary position with sensor noise, error occurs of magnitude greater than the noise as seen in Figure 9. The noise is effectively magnified by the dead zone inverse.

When the wrist was commanded to hold a desired fixed position, the same chatter was seen as shown in Figure 10. To correct this the DZI break points, b_l and b_r, were reduced to the values shown in Table 3. This indicates the DZI break points have to be carefully chosen to avoid magnification of noise in the system. Even if the exact break point values are known, as in the simulation, it may not be possible to use them in the DZI if noise exists in the system.

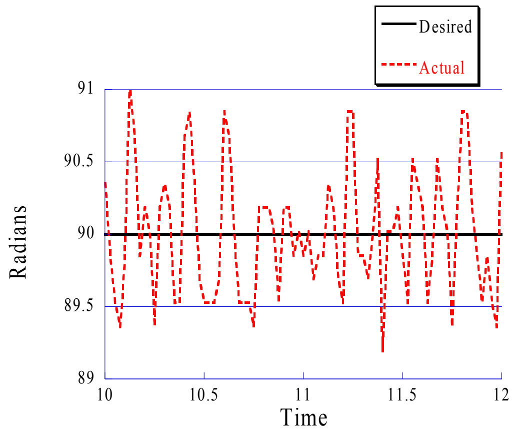

Figure 10
Chatter Witnessed on Wrist

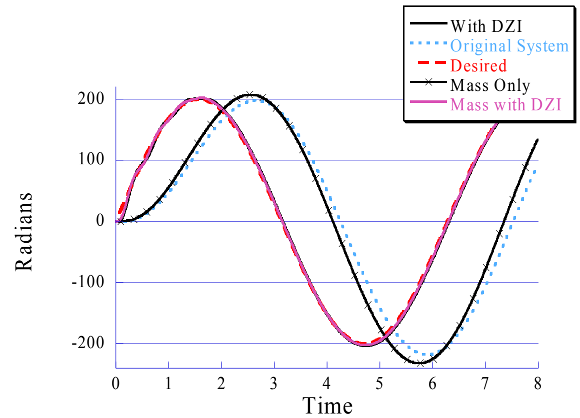

Figure 11
Simulated Result of Model Parameter Change

Table 3
Adjusted Dead Zone Size Properties

	b_l	b_r
Joint 1	-70	70
Joint 2	-150	150
Joint 3	-130	130

These are particularly important considerations if a DZI is used with varying parameters, as an adaptive control scheme might prescribe, or if the dead zone parameters vary widely throughout the operating region. In these cases, a lower limit would need to be established for the DZI slopes to prevent the control loop gain from become too large and compromising system stability. In addition, an upper limit should be placed on the break points at a level to prevent the controller from magnifying system noise. An alternative would be to add an artificial dead zone back into the control loop large enough to "ignore" the noise.

Figures 6 and 7 show joint 1's response with and without the dead zone inverse. The tracking is not perfect as it was for the simulation since it is a real system and the dead zone inverse does not cancel all of the unwanted dynamic effects. Ideal cancellation could not be achieved, primarily due to the noise accentuation problem. However, adding the fixed-parameter DZI to the control system did result in improved system response that varied less throughout the workspace than the system response with no compensation.

Sensitivity

The change in the response of the DZI when subject to a parameter change, in this case an increase in mass, was also examined. Figure 11 shows the simulated effect of increasing the mass. Here the desired trajectory, original system with DZI, and modified system with DZI traces are all nearly identical. It is interesting to note adding the mass

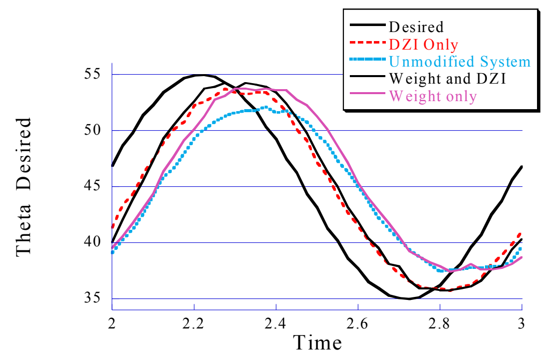

Figure 12
Experimental Sensitivity Test

noticeably without the DZI but the performance with the DZI is nearly identical.

When more mass was attached to the wrist the difference in response was very noticeable as can be seen in Figure 12. This was due primarily to the robot moving against the gravity field, which is why the difference becomes larger at the top of the trajectory. However, as simulations indicated, these differences are reduced when the DZI is used.

The conclusion from this is that a plant parameter change does not substantially alter the performance of the dead zone inverse. However, the same parameter change does change the system performance more drastically when the dead zone inverse is not used. This is especially important for robotics since the model parameters typically vary with the joint configuration. The DZI is relatively insensitive to variations in the plant dynamics.

CONCLUSIONS

The dead zone inverse was successfully implemented in simulation and in hardware and worked well to reduce the dead zone problem encountered by the hydraulic wrist. Although, it did not yield perfect tracking as it did in the simulations, it did improve actual system performance significantly. The DZI technique was found to be robust to changes dead zone slope parameters. However, the designed DZI was found to magnify noise in the system and the break point parameters had to be reduced to eliminate this effect. Finally, the DZI technique was found to be relatively insensitive to changes in the plant parameters.

ACKNOWLEDGEMENTS

Partial funding for this work was provided by the Air Force Institute of Technology U.S. Air Force Academy Faculty Preparation Program.

DISCLAIMER

The views expressed in this article are those of the authors and do not reflect the official policy or position of the United States Air Force, Department of Defense, or U.S. Government.

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