Control and Design of the Spherical Pointing Motor

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Abstract

We have built a new miniature pan-tilt actuator, the Spherical Pointing Motor (SPM). The SPM is an absolute positioning device, designed to orient a small camera sensor in two degrees of rotational freedom. It is $4 \times 5 \times 6$ *cm and weighs* 160 *grams. The operating principle of the SPM is to orient a permanent magnet to the magnetic field induced by three orthogonal coils by applying the appropriate ratio of currents to the coils.*

This paper describes the open-loop control and design of the SPM. We report physical characteristics and velocity measurements of the prototype. We modeled the SPM with a simple second order system. Without control, it oscillates substantially when a single impulse is applied. By applying a second impulse without feedback, the oscillation can be reduced by as much as a factor of ten.

1: Introduction*

The Spherical Pointing Motor† is an absolute positioning device, designed to orient a small camera sensor in two degrees of rotational freedom (Figure 1). The SPM is a part of a miniature space-variant active vision system [3].

The basic operating principle of the SPM is to orient a permanent magnet to the magnetic field induced by three orthogonal coils by applying the appropriate ratio of currents to the coils. A simple way to understand this device follows: the net magnetic field of the three coils may be visualized as defining a vector (dipole) oriented at angles (Θ, Φ) on the unit sphere. The angles (Θ, Φ) are determined by the three coil currents. The rotor dipole then aligns itself with the net coil field to provide the actuation.

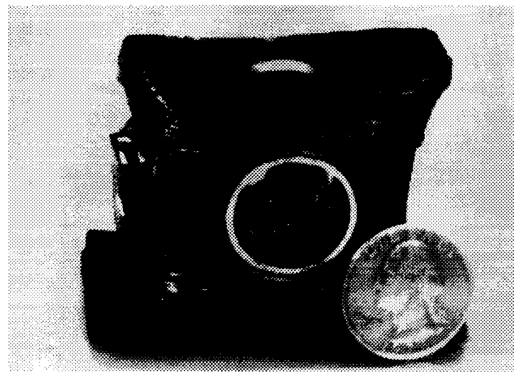

Figure 1: The Spherical Pointing Motor (SPM). At the center is a miniature camera consisting of a single CCD sensor chip and a lens assembly that fits on the rotor of the motor.

The torque on the rotor comes from the basic electromagnetic principle that there is always an induced force on a current-carrying wire loop in a permanent magnetic field in such a direction that the loop will move to make the normal to the plane of the loop align with the magnetic field.

2: Control of the Spherical Pointing Motor

We modeled the dynamics of the SPM with a simple second order system. When a new set of currents are applied to the coils, a torque is created that moves the rotor to the new position. We modeled this with a single impulse (Figure 2). We were interested in finding a way to reduce the oscillatory response without resorting to a closed-loop system.

We model the ringing of the SPM based on the fact [1] that the torque on the rotor is proportional to the sine of the angle between the current position and the destination position. Let us call this angle Ψ. The motor will accelerate towards the destination position with the torque decreasing

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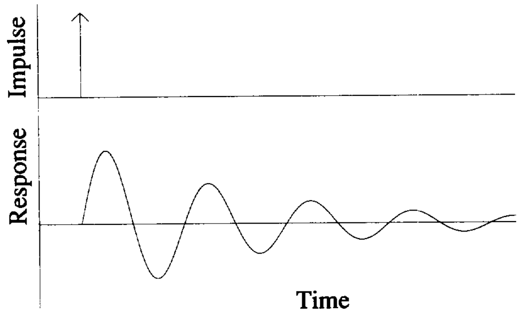

Figure 2: Model of response to a single impulse.

as it is reached. However, it will overshoot and ring around the final position. The torque on the rotor is $\tau = \kappa \sin\Psi$, for some κ. If we use the approximation $\sin\Psi \approx \Psi$, then the position of the motor will follow Equation 1

$$-\kappa\Psi - c\frac{d\Psi}{dt} = r\frac{d^2\Psi}{dt^2} \quad (1)$$

where c is the damping constant and r is the rotational inertia of the rotor [4]. An approximate solution to Equation 1 is

$$\Psi(t) = Ce^{-\frac{ct}{2r}}\cos(\omega t + \beta) \quad (2)$$

where C and β are constants, and the exponential function describes the magnitude envelope of the ringing. The frequency of the ringing is $\omega \approx \sqrt{\kappa/r}$.

We were able to measure the velocity of the SPM as it was ringing by recording the induced voltage of the permanent magnet on a pickup coil of magnet wire that was placed adjacent to the SPM. The recording was made by amplifying the induced voltage and digitizing this through the audio port of a Sun Sparcstation at a sample rate of 8 KHz. Because the SPM is controlled with Pulse-Width Modulation (PWM), the pickup coil not only records the ringing (at approximately 60 Hz), but also records the PWM signal (at 1 KHz). The recorded signal is filtered with an FFT in software to isolate the ringing from the PWM in the induced signal. Although we actually wanted to measure the position, the velocity (Equation 3) is a scaled and delayed approximation of the position.

$$\Psi'(t) = -C\left(\omega\sin(\omega t + \beta) - \frac{c}{2r}\cos(\omega t + \beta)\right)e^{-\frac{ct}{2r}} \quad (3)$$

This ringing can be greatly reduced by various open-loop control methods. Perhaps the simplest strategy is to move the motor from the initial position to the destination position in small decreasing increments at fixed time intervals. This way, maximum motor velocity is traded off for control. Including the time it takes for ringing to stop, this controlled approach yields a faster average velocity. This method is implemented by moving a fixed percentage of the distance between the current position and destination position at each step. This will decrease the motor movement with each step. The motor velocity can then be controlled with either the percentage movement of each step, or the time interval between steps. We use a constant time interval, and vary the percentage movement of each step to experiment with different speeds. We call this the fixed percentage control method.

A second slightly more complicated open-loop control strategy based on traditional stepper motor control theory, and also examined by Singer and Seering [5], yields better results than the fixed percentage method. The idea, called the two step method, is based on the fact that the SPM rotor oscillates with an approximately constant period. Although the motor has two degrees of freedom, we model only one degree of freedom. We give two impulses (Figure 3) 180^o

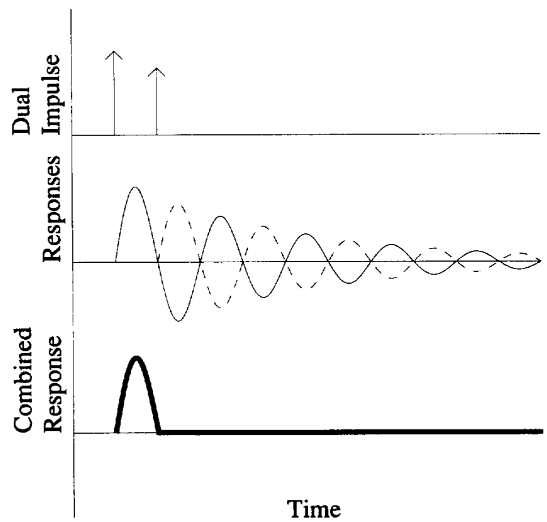

Figure 3: Ideal model of response to a dual impulse.

out of phase with each other in order to cancel the ringing. We implement this by first stepping the motor to a point midway between the initial and destination positions determined from the motor calibration [2]. We then wait for the moment where the rotor velocity is zero at which point we apply a second step to hold the rotor at this position. The energy of the ringing will be largely dissipated, and the rotor will be at the destination position. Although we don't know exactly when to apply the second step, we can estimate it by waiting half the period of oscillation. Because we model the system with a one-dimensional pendulum when it actually is a two-dimensional problem, our estimation is not exact, but is a close approximation. In practice, because neither the midpoint nor the time at which the currents are changed are exactly correct, not all of the ringing energy is dissipated, and a little ringing of the same period remains, but with greatly reduced amplitude (Figure 4).

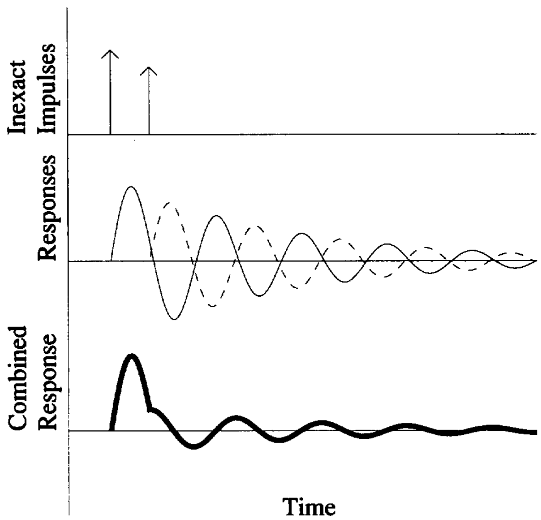

Figure 4: Model of system response with inexact timing to a dual impulse.

This approach is unusual in that it takes a constant time to move any distance, where the time is half the period of oscillation. A sample result of this approach is shown in Figure 5.

A problem with the two-step control strategy is that the system response is not very robust, i.e., a small uncertainty in the midpoint or delay timing results in relatively large uncontrolled ringing. We compensated for this imprecision by various combinations of the previous two control strategies. The first approach is to apply the two-step method twice, first moving to the midpoint, and then to the destination point. This method theoretically also takes constant time, which is twice as long as the two-step method. We call this approach the dual two-step method.

A final variation, called the multi two-step method, is to apply the two-step method multiple times with logarithmically decreasing steps. The motor is always moved half way between its current position and the destination position with the two-step method. This takes time $O(\log\Psi)$ where Ψ is the total angular distance travelled.

We are currently investigating other control approaches advocated by Singer and Seering involving three impulses to make a more robust strategy. Results from the open-loop control strategies we tested are presented in Section 6.

One of the motivating factors behind the development of the SPM was to make a motor that could be run by an

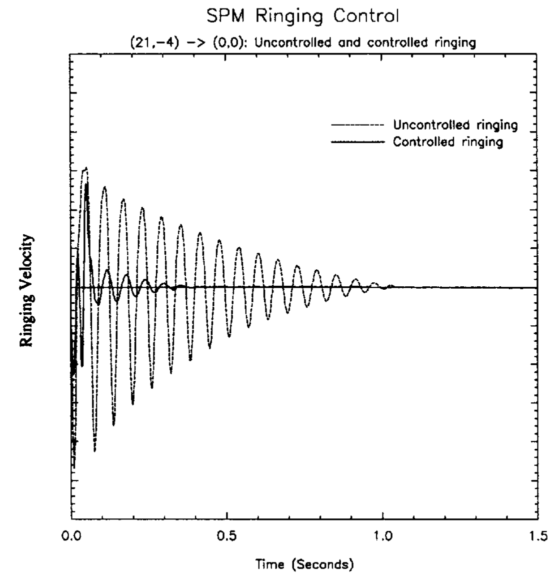

Figure 5: Measurement of two-step open-loop control strategy to reduce ringing. Results are shown for movement of 21^o with and without control.

open-loop controller, and we have accomplished this task. However, if higher performance is needed, a velocity or position sensor could be added to run the motor with a closed-loop control strategy. This would allow the two-step control strategy to be applied more accurately, as the zero-velocity point would be known exactly. Not only would this increase the speed of the motor, but it would also increase its accuracy. The motor's supply currents could be 90^o out of phase with the position, as with traditional DC motors. This would result in always driving the motor at its maximum torque and thus the torque would no longer be dependent on the difference between the current and destination position. No closed-loop control strategies have been implemented yet.

3: Design Issues

We want to design the SPM to maximize its torque while minimizing its size and power usage. There are several parameters that we have control over in this design. The diameter of the wire and the area, number of turns, and voltage across the coil as well as the magnetic return path are the parameters that most affect the design, and are the ones that we will discuss here.

The first issue is the magnetic return path. A magnetic circuit consists of a permanent magnet that generates magnetic field lines with a geometry dependent on the type of material in its immediate vicinity. A simulation of the magnetic circuit for the external coil SPM with and without an iron return path is shown in Figure 6. This shows that adding the iron return path would increase the efficiency of the magnetic field by nearly 50%.

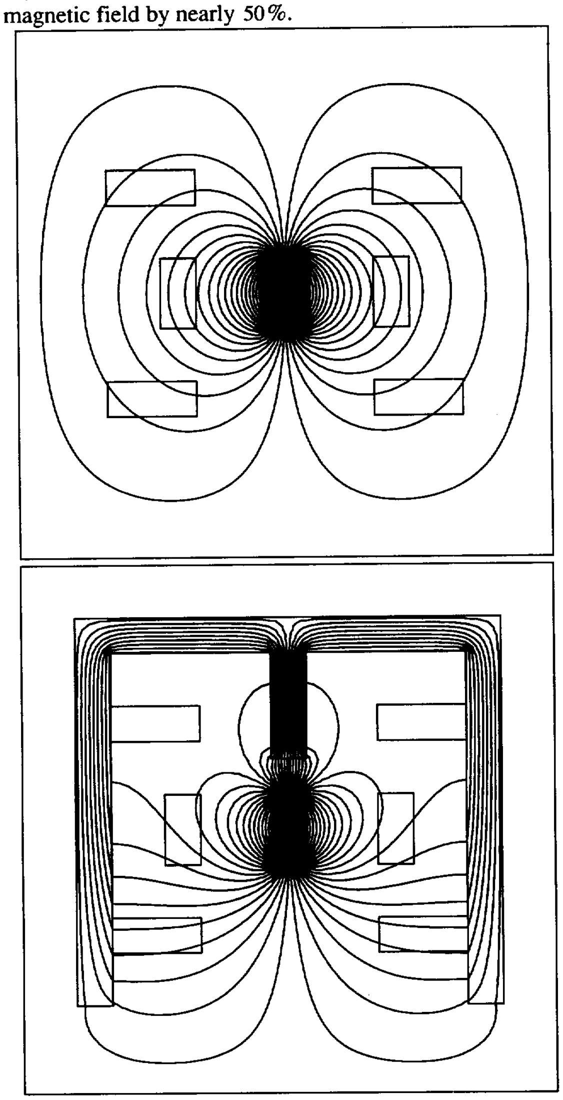

Figure 6: Simulation of magnetic circuit for the SPM (above) without and (below) with an iron magnetic return path. The permanent magnet is in the center. The rectangles represent the coils of the motor.

Now let us investigate the parameters of voltage (V), the number of turns in the coil (N), the area of the coil (A), the diameter of the wire (D), and the permanent magnetic field strength (B). We know that the torque, $\tau \propto NiAB$, and power, $P = Vi$. We want to maximize the ratio τ/P while maintaining a minimum acceptable torque and maximum acceptable power. We use the relationships $i = V/R$, and $R \propto (N\sqrt{A})/D^2$ to derive the equations for torque, power and their ratio using only the input parameters:

$$\tau \propto VD^2B\sqrt{A} \tag{4}$$

$$P \propto \frac{V^2D^2}{N\sqrt{A}} \tag{5}$$

$$\frac{\tau}{P} \propto \frac{BNA}{V} \tag{6}$$

From these relationships, we can see that we want to maximize B, N, and A while minimizing V. In doing so, we must also maintain our torque and power requirements and adjust V and D accordingly. The parameter values for our prototype SPM are reported in the next section.

4: Prototype Spherical Pointing Motor

The prototype SPM (Figure 1) is $4 \times 5 \times 6$ cm, weighs 160 grams and is capable of actuating a 6 gram load. Its total workspace is approximately 60^o in both the pan and tilt directions. The permanent magnetic field is estimated at 1 Tesla with an efficiency of about 5%. The number of turns in the coil is estimated. The maximum torque is computed here, where $\Psi = 90^o$. Table 1 shows the parameters of the motor along with its calculated torque and power usage. The actual torque and power usage have not been measured.

Table 1: Average coil parameters

Parameter	Value
N	515 turns
D	30 gauge (= $0.000254m$)
A	$0.001 m^2$
V	15 Volts
R	23Ω
τ	$0.016Nm$ or $2.0ozin$
P	10 Watts

The SPM is controlled by limiting the amount of current in each coil. This can be done either by regulating the voltage on the coils, by using a constant voltage with a Pulse-

Width Modulation (PWM) technique, or by using a variable current source. The PWM method (which we use) is preferred for ease of use, although the variable current source technique has the advantage that the currents, and thus the motor position, are independent of the temperature of the motor.

The SPM controller we use is based on a Motorola M68332 microcontroller that is capable of creating PWM signals. A Unitrode L293N power driver supplies the current for the motor. PWM means driving the motor with a square wave of constant amplitude and with a period of variable duty cycle, where duty cycle refers to the percentage of the period where the supply is high. A duty cycle of 0 gives no current to the motor while a duty cycle of 100 gives maximum current. The inertia and inductance of the coil effectively smooths the PWM supply. The polarity of the voltage on the coil also needs to be controlled in order to position the motor everywhere on the unit sphere. The power driver allows us to control the voltage polarity.

5: Accuracy and precision measurements

The precision and accuracy of the SPM were measured by reflecting a laser diode off a reflective surface attached to the rotor. The reflected beam's movement is measured on a wall several feet away as described below.

The precision of the motor is defined as the angular distance between adjacent positions. If the controller consisted of an analog variable current source, the motor's precision would be infinite. As we are using a digital PWM controller, the precision with which we can control the motor is limited by the step size of the PWM duty cycle. For our controller, the step size is dependent on the frequency of the PWM. Lower frequencies have more precise control of the step. However, lower frequencies also introduce a choppiness that vibrates the motor. We use a 1 KHz frequency and are able to specify 4,000 steps in the duty cycle (i.e., 4,000 different duty cycles). As the duty cycle of the PWM on a single coil with a specified polarity changes between 0 and 100, the motor will turn at most 45^o. Thus, we can position the motor to steps no smaller than $45^o/4000 = 0.011^o$ or 0.68 minutes of arc.

The accuracy of the motor is defined as the repeatability of the motor. If the motor were balanced so that gravity was not a factor, then its accuracy would be dependent only upon the friction of the bearings. As there is no iron core, there is no hysteresis, and thus it is absolutely repeatable. Because the motor, in fact, is not perfectly balanced, the motor position is not constant at different orientations to gravity, but at a fixed orientation, the accuracy is dependent only upon the friction of the bearings.

We measured the motor's accuracy with a laser setup (Figure 7) and found the motor to be accurate to 0.15^o. The camera mounted in our motor returns 192×165 pixels with a 33^o horizontal field of view, or 0.175^o per pixel. For our camera and lens, the SPM is thus accurate to about one pixel.

The procedure for measuring motor accuracy is as follows. The motor is set at a fixed position with the rotor positioned at the place to be measured. The laser is then oriented so that the reflected beam hits the wall at a right angle. This point on the wall is recorded. The rotor is moved away and then back to the original position. The distance between the new reflected laser position and the original position is measured, and the accuracy of the motor is calculated according to Equation 7.

$$\Phi = \frac{1}{2}\tan^{-1}\left(\frac{e}{f}\right) \qquad (7)$$

The accuracy of the motor is measured by first moving the motor Θ degrees. The distance from the motor to the wall is f, and e is the distance between the first and second laser position on the wall. Φ is the angular difference between the first and second motor positions.

6: Velocity measurements

We measured the average velocity of the motor for point to point motions since we have no ability to measure instantaneous velocity. We recorded the velocity using the technique described in Section 2 for measuring the ringing. The motor controller was programmed to accept motion commands with a specified control strategy over an RS-232 serial port. A program running on a Sun Sparcstation controlled the SPM and automatically recorded and analyzed the results. For each control strategy, ten measurements were made at each of ten different angular movements. The averaged results with error bars showing

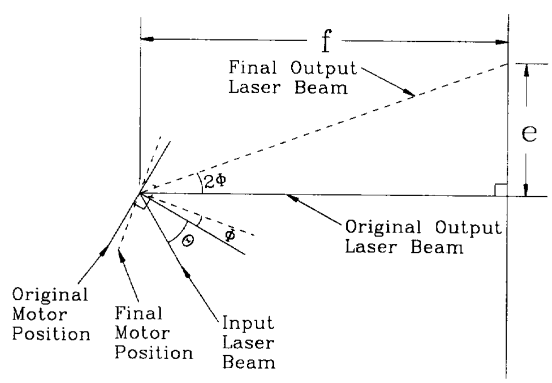

Figure 7: Illustration of our experimental setup for measuring motor accuracy. The solid lines represent the first motor position, and the dashed lines represent the second.

the variance of each experiment are shown in Figure 8, Figure 9, and Figure 10.

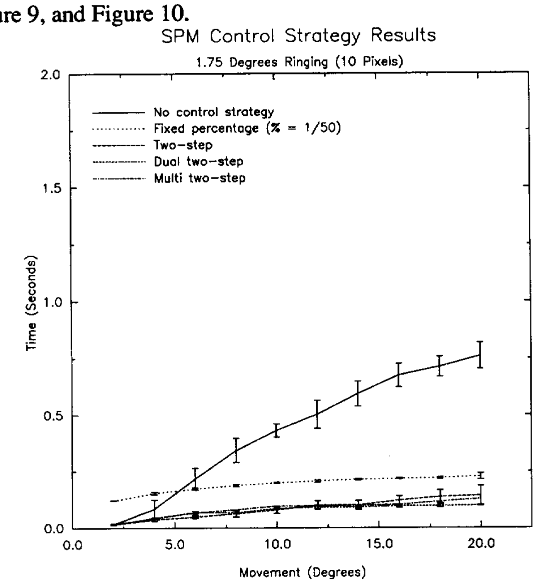

Figure 8: Results of different open-loop control strategies to reduce the ringing of the SPM. Times reported are those after which amplitude of the ringing has been reduced to 1.75^o **(10 pixels in our camera). Control strategies are discussed in the text.**

A summary of the control strategies follow:

- **No control:** Base line for comparing control strategies.
- **Fixed percentage:** The motor is moved a fixed percentage of the distance between its current position and the destination position with a fixed delay between each movement.

By making the percentage of movement per step small enough, the ringing can be completely eliminated at the price of velocity. Results shown here are for a percentage selected such that the total time to move was minimized.

- **Two-step:** The motor is moved to the midpoint between the initial and destination positions. After a delay equal to half the period of the natural motor oscillation, the motor is moved to the destination position.

The midpoint and delay used are an approximation to the ideal values. These result in good results with a fixed time to move any distance, and a small amount of ringing at the end of the movement. The ringing at the end of the motion does not depend on the amplitude of the motor movement. Rather, it depends on the inaccuracy of the midpoint and delay calculations. A calibrated look-up-table approach would be necessary to eliminate the ringing completely.

- **Dual two-step:** The two-step method is used to move first to the midpoint, and then to the endpoint.

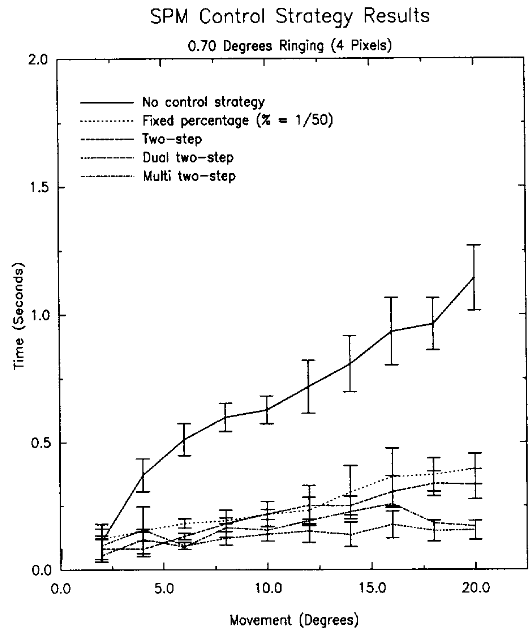

Figure 9: Results of different open-loop control strategies to reduce ringing. Times reported are those after which amplitude of the ringing has been reduced to 0.70^o **(4 pixels in our camera).**

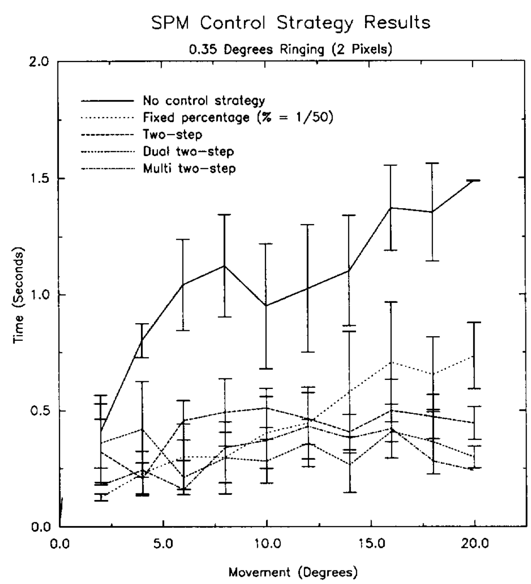

Figure 10: Results of different open-loop control strategies to reduce ringing. Times reported are those after which amplitude of the ringing has been reduced to 0.35^o **(2 pixels in our camera).**

This theoretically takes twice as long as the single two-step method, but actually results in slightly better results because the resultant ringing is somewhat reduced.

• **Multiple two-step:** The two-step method is used multiple times, always moving halfway between the current position and the destination position.

This theoretically takes time $O(\log\Psi)$ where Ψ is the angular distance between the initial and destination positions. In practice, it produced very similar results to the dual two-step method.

Our measuring apparatus was fairly noisy, resulting in the high variance reported. It is clear that all four control strategies provided substantial improvement over the uncontrolled performance. Of these, the two-step methods are a little better than the fixed percentage approach. Because of the noise in our measurements, it is not clear which two-step method is the best.

The results are summarized in Table 2. For each control strategy, the time to move 2 degrees and to move 20 degrees are given for each of three ringing requirements. The times are specified in milliseconds.

Table 2: Control strategy summary

Ctrl Method	0.35^o ringing	0.70^o ringing	1.75^o ringing
No control	408/1480	110/1140	18/1760
Fixed percentage	127/734	120/395	120/227
Two-step	332/445	83/334	16/143
Dual two-step	359/298	96/155	18/100
Multi two-step	179/240	56/171	17/128

It should be stressed that the results from these two-step open-loop control strategies were obtained with approximate calculated values for the mid-point and timing values. We fully expect that with a calibrated look-up-table approach, we will obtain substantially better results.

7: Conclusion

We have built a new miniature pan-tilt actuator, the Spherical Pointing Motor. The motor's dynamics are modeled by a damped second order system. We apply an open-loop control strategy based on standard stepper motor control theory and are able to substantially reduce the settling time of the motor. We believe that we can improve these results even further by implementing an adaptive control algorithm that learns the properties of a specific motor with feedback off-line, and then runs open-loop using this pre-computed look-up-table.

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