20
Camera positioner

PictureTel needed a fast and precise camera positioner for video conference applications, and built a camera controllable in zoom, tilt, and pan axes using servoed DC motors. PowerCam (Figure 20.1) moves a 0.5 kg color video camera through a pan (horizontal) axis rotation of 180° in 1 s, and a tilt rotation of 45° in 1/2 s. The motion control design uses a capacitive sensor for smooth and accurate position control in two axes, and illustrates the use of capacitive sensing for high-performance, low-cost closed loop servo systems.

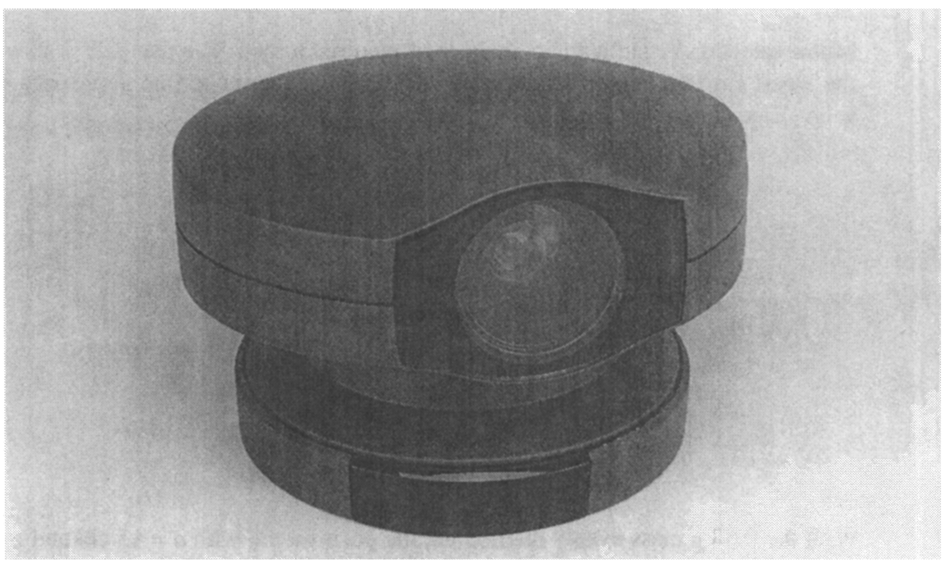

Figure 20.1 PowerCam (patent pending)

20.1 SPECIFICATIONS

PowerCam's lens can be controlled in zoom from 7.5° to 75° field of view. At the narrow 7.5° field of view, the camera must be moved very smoothly to avoid perceptible jerkiness in the video; conservatively, jitter of a quarter of a pixel can be seen with very slow motion. With its 768-horizontal-pixel imager, a single pixel at maximum zoom is 7.5/768 = 0.01° of pan motion. The resolution requirement is more than $4 \times 270/0.01 = 108{,}000{:}1$, or 17 bits. If a digital system is used, perhaps 19 bits of resolution would be needed to avoid limit cycle behavior at the LSB level.

Motion specifications

Pointing accuracy	1.5°
Pointing repeatability	0.25°
Pan axis range	270°
Pan axis speed	180° rotation in 1 s
Tilt axis range	45°
Power	12 V, 1 A

Other design parameters are low cost and low acoustic noise.

20.2 MOTOR

Motor selection began with an analysis of required torque. The pan axis is shown, as it is the worst case for motor torque. The camera polar inertia can be approximated by this solid shape (Figure 20.1a).

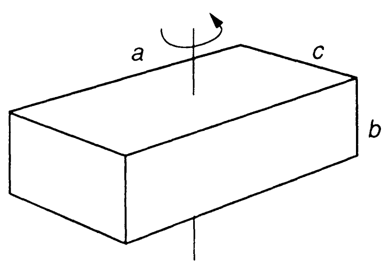

Figure 20.1a Camera inertia

With the 0.5 kg mass evenly distributed, the polar inertia with a = 13 cm and c = 9 cm is calculated as

$$J = mk^2 = 0.5\left(\frac{a^2 + c^2}{12}\right) = 0.001 \text{ kg-m}^2 \qquad 20.1$$

Assuming the acceleration profile has no coast, the motion looks like Figure 20.2.

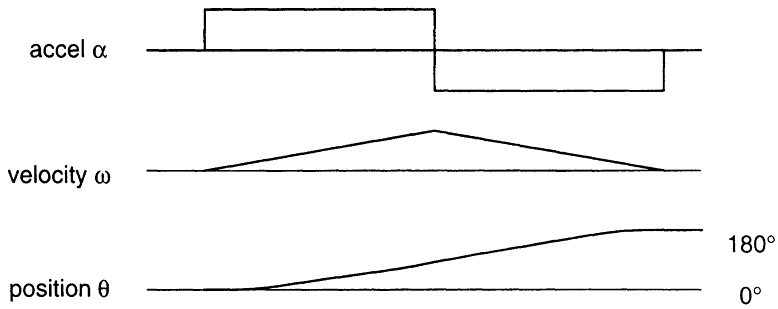

Figure 20.2 Camera motion profile

The minimum acceleration α to meet the 180°/s speed specification is calculated from

$$\theta = \frac{1}{2}\alpha t^2 \tag{20.2}$$

so that

$$\alpha = \frac{2\theta}{t^2} = \frac{\pi}{0.5^2} = 12.56 \quad \text{rad/s}^2 \tag{20.3}$$

And the torque to accelerate the load is

$$T = J\alpha = 0.01335 \quad \text{N-m} \tag{20.4}$$

or 1335 g-cm. Assuming a 75% transmission efficiency, a relatively low 50:1 gear ratio to keep motor noise low and a safety factor of 2, peak motor shaft torque, ignoring motor inertia, is 71 g-cm at 1500 rpm.

Of the many types of motors which could be considered, four were closely compared (Table 20.1).

Table 20.1 Motor comparison

	DC brush	DC brushless	Stepper PM	Stepper hybrid
Cost, 10K qty.	$1.25	$6.00	$5.00	$18
Efficiency	0.6	0.65	0.25	0.35
Life	>1500 h	>10,000 h	>10,000 h	>10,000 h
Friction	2–5 g-cm	lowest friction; depends on bearings		
Size, length × diam.	3 × 2 cm	3 × 2 cm	4 × 3	5 × 4
Max. speed	8000 rpm	8000 rpm	1500 steps/s	5000 steps/s
Drive	power amp	Hall-effect commutate	microstepping drive is needed for smoothness	

20.2.1 DC brush motor

DC brush motors have high efficiency and very low cost, and are the easiest to drive. DC brush motors designed for servo use have low inertia rotors, five or more commutator segments for smooth torque, a large diameter shaft so shaft resonance does not affect servo stability, and they are well characterized for servo use. Unfortunately, the price reflects this additional sophistication.

Small mass-production DC brush motors are available in the \$1–5.00 price range, from vendors like Mabuchi, Canon, Chinon, Pittman, and Kollmorgan with three-segment commutators, sleeve bearings, and smaller (1–1.5 mm) shaft diameters.

EMI radiation can be a problem with DC brush motors, as sparking at the commutator generates broadband noise. A ceramic capacitor close to the brushes will help. Some models, such as Mabuchi's RF series, handle EMI with an internal varistor.

Torque ripple

Two motor design details affect smooth torque delivery. One is the higher torque ripple with a three-segment commutator (Figure 20.3).

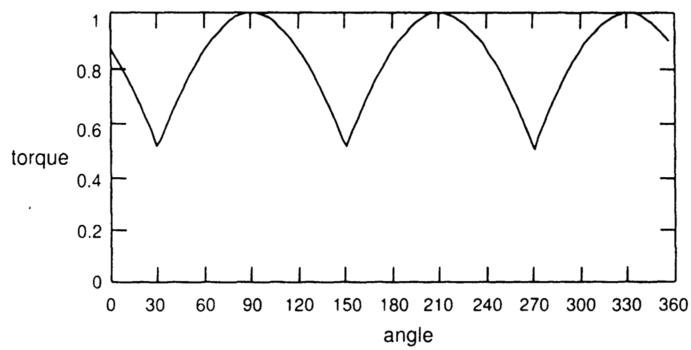

Figure 20.3 Three-segment torque ripple

The three-segment commutator has a 50% torque ripple. If the motor is enclosed in a high-gain servo loop, this may not be a problem. With five segments, the torque ripple improves to 82% (Figure 20.4).

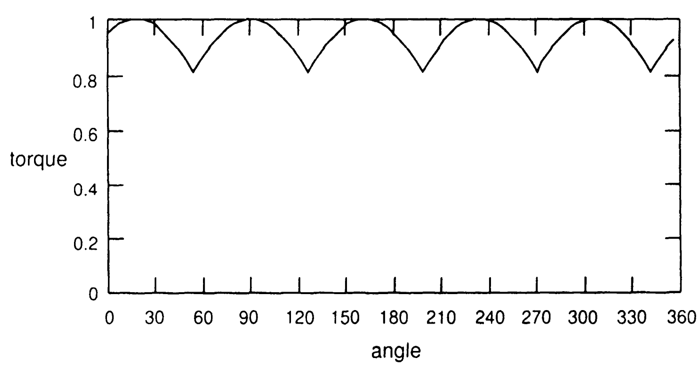

Figure 20.4 Five-segment torque ripple

Several three- and five-pole motors were tested for torque vs. shaft angle performance. Torque curves were similar to above predictions, except magnetic gap variations produced a 5–20% variation of peak torque as a function of angle.

Neutral commutation

Commutation in a brush-type DC motor at slow speed should switch the armature current from one coil to the next just as the coils are equally positioned around the magnetic pole, so the active coil is switched out just as the next coil is in position to produce an equal torque. This is called neutral commutation, and a motor designed for low speed or bidirectional operation will have neutral commutation. At high speed, the inductance of the armature slows the rate of armature current change, and the brushes would need to be advanced slightly to avoid a torque transient and arcing at the switch point. Motors with this feature have a preferred speed and direction and should not be used for servo actuators.

Commutation transient

Another potential problem with DC motors is the momentary torque transient which can be generated at the commutation point if the brushes are not correctly positioned, or if the magnetic circuit or the windings are not accurate, or when a brush bridges two commutator segments momentarily. This problem is reduced with five-segment armatures, and with current drive circuits instead of voltage drive.

20.2.2 DC brushless motors

DC brushless motors have excellent efficiency, longer life than brush motors, and are reasonably low in cost. One potential problem for smooth, low-speed positioning servos is the commutation transient. While the relatively slow torque ripple of a three-segment commutator can usually be attenuated by a high-gain servo loop, a quick transient caused by inaccurate commutation cannot.

More detail on DC brushless motors is found in Section 9.4.

20.2.3 Permanent magnet step motors

Permanent magnet, or PM, steppers are reasonably priced, in the $5.00 range for medium quantity, and have 3.75, 7.5, and 15° step angles. A large range of sizes is available, down to about one cm diameter. The smaller sizes are capable of faster stepping, so maximum output power does not scale directly with size, but smaller sizes are limited to the coarser step angles. The step sizes are much too coarse for smooth motion in the current application, but microstepping drives can improve this.

Microstepping replaces the usual square wave drive with sine waves in quadrature, and in theory can produce arbitrarily smooth motion. The difficulty in practice is that the PM stepper is not accurately constructed, and several effects conspire to degrade smooth low speed motion:

1. Quadrature relationship. The nominal 90° relationship of the two windings may be several degrees misaligned.
2. Quadrature amplitude. The two windings may need different current amplitudes for good accuracy.

3. Detent torque. The rotor is detented by the magnetic circuit to each step angle. Increasing the size of the magnetic gap improves microstep width at a cost of efficiency.
4. Hysteresis. Remnant magnetism near winding current zero cross causes small nonlinear effects when current is reversing.
5. Resonance. The magnetic restoring torque and the combination of motor and load inertia form a mechanical resonance, usually in the 200–500 steps/s range. As the motor passes through this resonance, the operation can be rough.

These effects can be considerably ameliorated by careful shaping of the drive signals, and adjusting their phase relationship and amplitude. The ideal drive waveform often becomes a cusp shape, reversing the expected sine shape, to repair detent torque effects. The improvement afforded by these methods is limited, however, as imperfections in the rotor magnetization cause each step's ideal drive current to be slightly different. A practical limit is 8–10 microsteps/step. Other drawbacks with stepper drives for this application are poorer efficiency and relatively noisy operation. Performance is improved by using feedback from output shaft position to the motor driver to compensate for these nonlinearities, but the stepper in this system has little to offer compared to brush or brushless DC motors.

20.2.4 Hybrid step motors

Hybrid steppers use a combination of magnetic hysteresis and a permanent magnet rotor. They feature higher efficiency than PM types, higher speed operation, and smaller step angles to 1.8°, but the price is higher. Low speed smoothness is better than in PM steppers, but decent performance still requires the adjustments above to shape winding current. Drawbacks for this application are large size (1.75 in minimum diameter) and high cost, over $17.

Motor choice: DC

The brush-type DC motor was chosen for this application for its low cost, low power, and simple drive circuits. For more stringent applications which need longer life or higher pointing accuracy, a brushless DC motor or a carefully driven PM stepper would be the choice.

20.2.5 Transmission

A one-pass friction drive was selected for quiet operation, low cost, zero backlash, and freedom from adjustment. A section of the pan axis is shown in Figure 20.5.

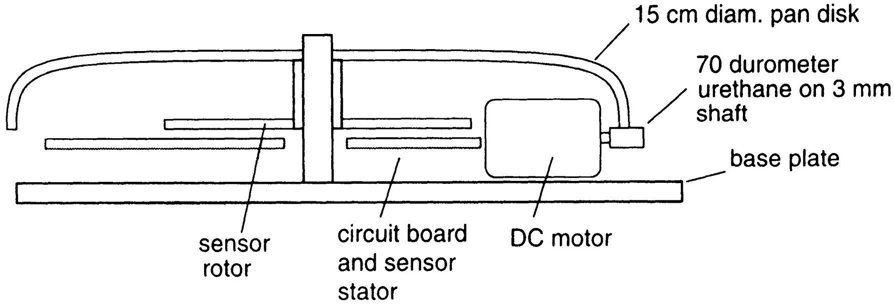

Figure 20.5 Pan axis construction

The gear ratio, 50:1, results in a maximum motor speed of about 3000 rpm. This speed is a little low for maximum motor power output, but helps keep noise low and motor life high. This is not a positive drive, so allover feedback is needed.

20.3 SERVO SYSTEM

The servo uses an output shaft capacitive position sensor and closes a loop with allover feedback from output shaft position to motor drive current. The standard PID (proportional-integral-derivative) loop compensation was chosen after a brief, unproductive romance with fuzzy logic.

The servo loop was built using analog circuits. This makes for a low cost, high performance loop, although it cannot accommodate variations in load inertia of more than a factor of three to four. If the load inertia was not constant, an adaptive digital approach could be used so that the servo parameters could more easily be adapted to match load inertia.

A precision conductive-plastic potentiometer was tried first for position sensing. Its output noise was rated at 0.1% rms which seemed adequate, but when tuning the servo the derivative gain Kd needed to be high for good slow-speed smoothness. This high gain amplified the potentiometer noise enough to swing the power amplifier output rail-to-rail, limiting gain and efficiency.

Position sensor choice: capacitive encoder

The final position sensor used was a capacitive type (Figure 20.6) with 1.6" outside diameter; its noise is less than 0.005% rms. The dual V geometry shown previously (Figure 7.8) was used, but as a rotary pattern rather than linear, with the pickup plate stationary. The wiring to the rotor is free in this design, as travel is limited to 270° and a wire cable is needed for other camera signals. The rotor drive voltages are at 5 V p-p and are low impedance so no special shielding is needed. The fixed pickup location means that this very high impedance point is easy to shield and guard with PC etch, and its connection to the amplifier can be minimum length.

Both rotor and pickup are fabricated from FR-4 0.062 in PC board stock, with bare nickel plating on the electrodes rather than solder mask to avoid triboelectric effects.

The circuit chosen is a 0–180° drive, with feedback-type amplifier for low spacing sensitivity, with an empirically determined positive feedback to make sensor amplitude variation with spacing nominally zero. Because an off-the-shelf operational amplifier has too much input-to-output capacity, which results in low output voltage and excessive spacing dependence, a discrete FET transistor input preamp was added (Figure 10.30). Demodulation uses a 74HC4053 CMOS switch and a lowpass filter with a 580 Hz corner frequency so that its phase shift at the servo zero cross frequency (about 100 Hz) is low.

With an air gap of 0.5 mm, the demodulated output range is between 0.4 and 4.6 V instead of the theoretically expected 0 to 5 V, representing a stray amplifier input-to-output capacitance of less than 0.16 pF.

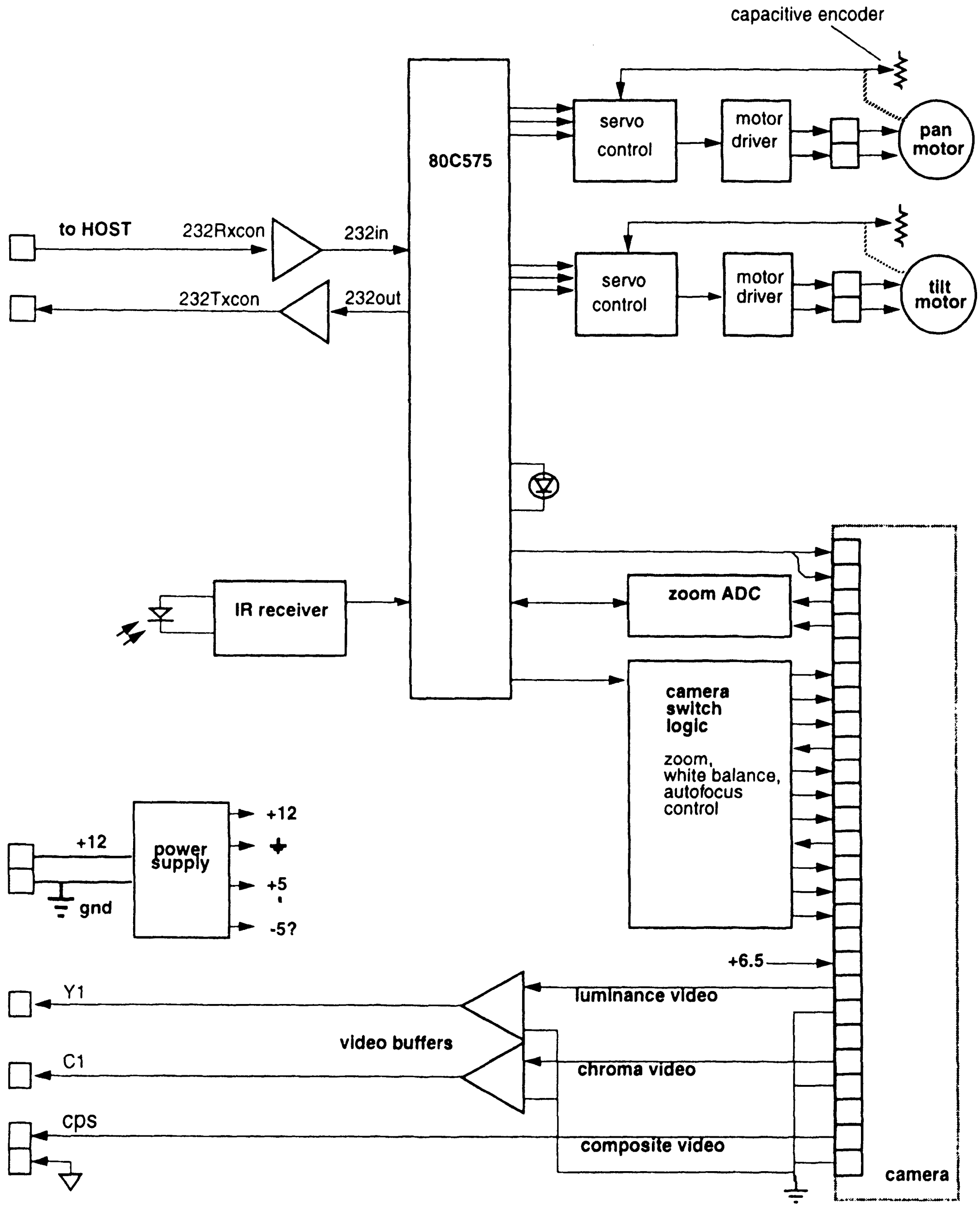

Figure 20.6 Block diagram