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Two Miniature Pan-Tilt Devices

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Abstract

This paper investigates two small robotic pan-tilt devices that differ from the conventional motor-on-motor design. The Platform Pantilt is based on a parallel linkage actuated by two small DC linear stepper motors. The Spherical Pointing Motor (SPM) is a two-axis actuator built using three orthogonal motor windings. The SPM is controlled open-loop and is capable of panning and tilting a load of 15 grams, for example a CCD image sensor, at rotational velocities of up to 600°/sec. *It is* 4 × 5 × 6 *cm and weighs 160 grams. We have also built a subminiature camera consisting of a single CCD sensor chip and a lens assembly that fits on the rotor of this motor.*

1 Introduction

A pan-tilt mechanism is a computer-controlled actuator designed to point an object such as a camera sensor. For applications in active vision, we would like a pan-tilt mechanism to be accurate, fast, small, low-power and inexpensive. We have constructed two actuators meeting these requirements: one based on a parallel linkage actuated by two identical, small stepper motors (Figure 2); the other incorporates both pan and tilt into a single 2-axis actuator (Figure 1). We call the parallel linkage the Platform Pantilt, because it is similar in some respects to the Stewart platform [10,15,16], familiar to many in its application as a flight simulator. The second device, called the Spherical Pointing Motor (SPM), consists of three orthogonal motor windings in a permanent magnetic field, configured to move a small camera attached to a gimbal.

The simplest and most obvious pan-tilt mechanism is the two-stage motor-on-motor (MOM) design. The first motor turns the mechanism through one degree of freedom, usually pan, and the second through the other d.o.f, usually tilt. The second motor must be powerful enough to move the camera sensor. The first must move both the camera and the second motor. The MOM design therefore usually consists of one larger motor and one smaller one. Such a design is inefficient because, as we show, it is not necessary to carry one motor on top of another one.

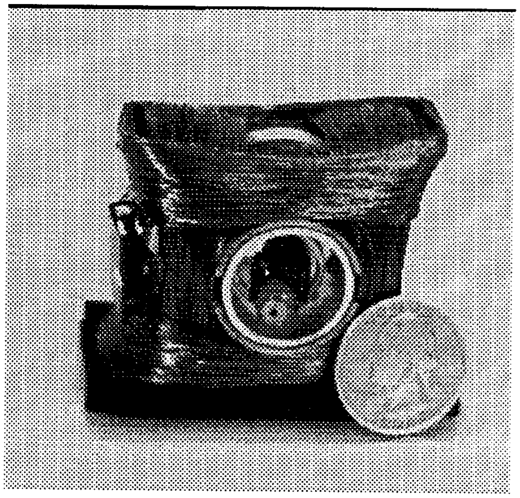

Figure 1: The Spherical Pointing Motor. At the center is a miniature camera consisting of a single CCD sensor chip and a lens assembly that fits on the rotor of this motor.

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2 Background

Pan-Tilt mechanisms have been a source of inspiration and frustration to computer vision researchers. The source of inspiration is nature, where humans and animals rely on their pan-tilt apparatus to achieve wide field-of-view visual sensing. In addition, higher primates such as cats, monkeys, and humans use a strongly space-variant image representation where the resolution of the image is high in the center and falls off sharply in the periphery. Researchers using this type of image [5,17] must be able to select where in the workspace the high resolution part of the image is pointing.

The argument from nature is not by itself a compelling reason to build robot eyes that pan and tilt. The alternative to mechanical pan-tilt action is electronic scanning, i.e. computer control of a fixed set of cameras having a combined wide field-of-view. Selective attention can be implemented by a variety of addressing methods, for example the inverted pyramid of Burt [6]. Such "software pan-tilt" mechanisms are considerably more convenient and reliable than their motorized counterparts, but we argue that they will be ultimately more expensive.

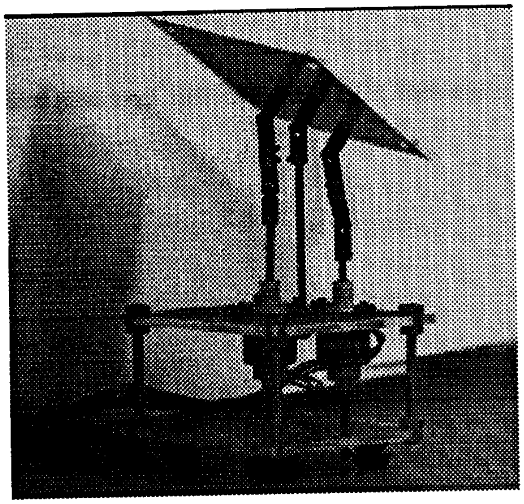

Figure 2: The Platform Pantilt. This stepper motor based actuator is capable of positioning a load of 80 grams, for example a small video camera.

The source of frustration with pan-tilt devices is acquiring or building, then calibrating and controlling, the mechanism itself. Until recently, no manufactures have provided devices specifically designed for computer control of robot cameras. Low-speed inexpensive motorized pan-tilt camera platforms are available, for example from Edmund Scientific (catalog number F38,485), but these have no computer controls. Remote control pan-tilt devices intended for security camera applications, for example the the Graystone Model V370PT, tend to be too slow (6 degrees per second) and too heavy (8 kg) for many robotic applications. Few of these devices have computer controls or position feedback information other than visual. The motion picture industry has developed computer controlled pan-tilts. One example is the Kaleidoscope Hothead II, made by Shepperton Film Studios. Although a digital interface is available, this device is intended to carry a large load such as a 35mm motion picture camera, and although it achieves relatively high speed ($140^o/sec$), it is very expensive. Another source of pan-tilt mechanisms is the lighting industry, which applies them to stage lighting, exhibition and advertising. A high-speed computer controlled pan-tilt mechanism for stage lights is available from Multiline, but its bracketing and high cost make it unappealing for robot vision. A number of manufacturers (for example Aerotech, Daedel, Unislide, and Klinger Scientific) make computer controlled components that can be assembled into pan-tilt devices. In general, these device are fast (up to 500 degrees per second) and easily interfaced to computers, for example via the RS-232 serial port. Better suited for manufacturing and optics applications, the high resolution of these devices (better than 1 arc minute) makes them overkill for many computer vision applications and contributes to their high cost.

Perhaps because of their familiarity and availability, if not their generality and programmability, robot arms have often been the method of choice for vision researchers trying to actuate their cameras. Baloch and Waxman used a 5-axis robot arm as a camera pointing mechanism, mounted on top of a mobile robot [3]. Allen reported mounting a TV camera on a robot arm. [2]. Raviv used a cartesian manipulator to implement camera pan, tilt, roll and translation [14].

Finally, a number of researchers including ourselves have embarked on building their own pan-tilt devices from scratch. Krotkov built what is now recognized as the first robot head, a computer controlled mechanism for moving two cameras [13]. Abbot and Ahuja report an 11 degree of freedom mechanism to control pan, tilt, vergence, horizontal translation, and lens parameters [1]. From Osaka University, Kawarabayashi et. al. report building an active vision "head" to control pan, tilt, vergence, zoom and focus parameters of a pair of cameras [12]. The pan-tilt mechanism in all three of these designs is a MOM design. Dickmanns also reports a "fast" two-axis pan-tilt device carrying two cameras, one with a wide-angle view and the other telephoto, mounted in their robotic automobile [9]. At Harvard, Clark and Ferrier constructed a seven degree-of-freedom "head" to control pan, tilt, and the vergence, focus and aperture of two cameras [8]. At lest one two-eye system, the Rochester Robot, contains independent pan controls for two cameras on a tilting platform, in contrast to other systems in which vergence is coupled [7].

Although many vision researchers are also interested in controlling parameters other than pan and tilt, we have restricted our attention in this paper to these two degrees of freedom. We only mention here that pan-tilt mechanisms are not the whole story. We would like to build inexpensive computer controls for such camera parameters as focus, zoom, and aperture. In some cases it may be desirable to control camera roll and XYZ translation as well. With two or more cameras present, as in a stereo vision system, we would like to control the vergence angle between the camera as well as their baseline separation. These interesting subjects, however, will remain outside the scope of this paper.

3 Platform Pantilt

The Platform Pantilt is a two-motor actuator designed to overcome the limitations of a motor-on-motor pan-tilt design. Both its motors are identical, and operate in parallel. Both motors are mounted to a fixed base, so the moving platform does not have to carry any motors. As shown in Figure 3, the Platform Pantilt consists of the two fixed motors connected by a somewhat complex linkage to a rotating platform. With such a linkage it is not obvious that the kinematics are unique. That is, does this mechanism maintain a 1-1 correspondence between motor and platform positions? We show that it does.

Referring to Figure 3, we define a coordinate system such that the origin lies at the corner of the platform base, and the x axis extends to the right. The point A lies along the y axis at the top of a fixed shaft extending upward from the origin. The point C lies on in the xy plane and moves along a line parallel to the y axis depending on the value of h_1. The point E lies in the yz plane and moves along a line parallel to the y axis depending on the value of h_2. The stepper motors are connected to shafts that translate the points C and E. The platform is at the top, attached by three short rigid shafts to the points D, A and B. All of the joints at the points A, B, D and E are passive universal joints. The joint at point C is a pin joint, capable of rotating only around the z axis.

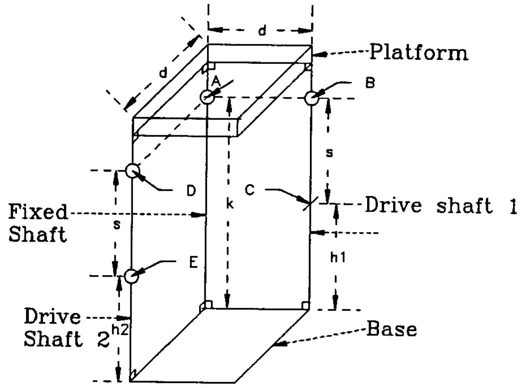

Figure 3: The Platform Pantilt. Note that circles at points A, B, D and E denote universal joints with two degrees of freedom while the line at point C denotes a pin joint with only one degree of freedom.

There is a fixed relationship between the pan and tilt angles Φ and Θ and the points B and D. The pan and tilt angles define a vector parallel to $\overline{(B-A)} \times \overline{(D-A)}$, indicating the orientation of the platform. Conversely, when the pan and tilt are zero, the vector $\overline{B-A} = (d,0,0)$ and $\overline{D-A} = (0,0,d)$. The pan angle rotates these vectors around the z axis and the tilt angle rotates the result around the rotated vector $\overline{B-A}$. Therefore, we reduce the forward kinematics problem to finding B and D given h_1 and h_2, and the inverse kinematics problem to finding h_1 and h_2 given B and D. The algebra of the kinematic solution is a bit tedious, so we outline here a geometric argument based on the solution of several intersection problems.

The forward kinematics problem can be solved by first obtaining the point B. The point B lies on the intersection of two circles in the the xy plane, one centered at A having radius d and the other centered at C having radius s. The intersection problem has two solutions, only one of which is mechanically possible. Once we obtain B, we find D, which lies on the intersection of three spheres: one centered at A having radius d, one centered at E having radius s, and one centered at B having radius $\sqrt{2}d$.

In the inverse kinematics problem we are given B

and D, and must find find h_1 and h_2. We first obtain the point C. The point C lies on the intersection of a circle and a line, both lying in the xy plane. The circle is centered at B with radius s, and the line is defined by $x = d$. Having fixed h_1, we obtain the point E, which lies on the intersection of a sphere and a line. The sphere is centered at D with radius s and the line is defined by $z = d$.

4 Spherical Pointing Motor

The Spherical Pointing Motor (SPM) is an absolute positioning device, designed to orient a small camera sensor in two degrees of rotational freedom. The basic principle is to orient a permanent magnet in three orthogonal motor windings[1] by applying the appropriate ratio of currents to the three coils. The SPM can either have the coils on the outside with the permanent magnet rotating on the inside, or vice versa. Figure 4 depicts an example of the former.

In this section we look at the transfer function taking input current to pan and tilt angles. We point out some design constraints on the configuration of the coils and the permanent magnets, and discuss briefly calibration and accuracy of the motor. In the derivation, we use the external coil motor, but the derivation for the internal coil motor is almost identical.

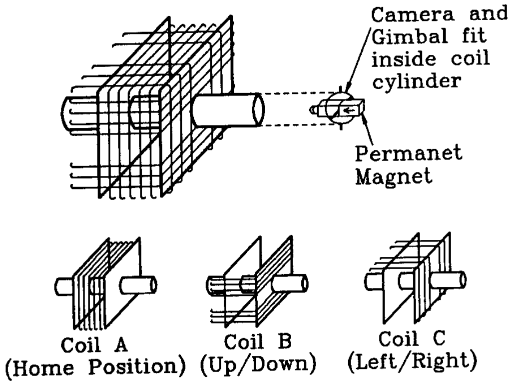

Figure 4: Illustration of the external Spherical Pointing Motor shown in its home position with labels for the three coils.

Both designs are constrained by two principles that affect the range of motion of the motor. The SPM is meant to be used as a pointing device. As such, it has a "home position", defined as the initial resting position from which the motor can make pan or tilt excursions of limited extent. Assuming that we want the home position to be centered within the possible excursions, we are led to the following constraints:

1. The permanent magnets must be positioned so that the field they define is orthogonal to both axes of rotation of the gimbal when it is in home position.
2. The camera must be positioned on the rotor so that its optical axis is orthogonal to both axes of rotation of the gimbal when it is in home position. Note that this is equivalent to being aligned with the magnetic field if the first design constraint is satisfied.

These design principles arise because the motor is limited to two mechanical degrees of freedom and because the motor rotation can not be controlled about an axis aligned with the permanent magnetic field.

We assume that the two rotational axes of the gimbal are orthogonal and intersect at a point, so that the kinematics of the SPM are trivial. That is, Φ and Θ are both the input and output variables. Our problem is to determine the variables Φ and Θ as a function of currents i_A, i_B and i_C in the three coils A, B and C.

Given a coil of wire in a magnetic field $\mathbf{B}$, the torque $\boldsymbol{\tau}$ exerted on the coil is the cross product

$$\boldsymbol{\tau} = \boldsymbol{\mu} \times \mathbf{B} \tag{1}$$

where $\boldsymbol{\mu}$ is the magnetic dipole moment having direction perpendicular to the coil and magnitude

$$|\boldsymbol{\mu}| = NiA \tag{2}$$

where i is the current in the wire, N is the number of windings in the coil, and A is the area inside each winding [11]. The orientation of $\boldsymbol{\mu}$ is determined by the direction of current in the wire loop. When a nonzero current i flows through the loop, there will be a torque on the loop so that it will rotate to its minimum energy configuration where $\boldsymbol{\tau} = 0$, i.e. $\boldsymbol{\mu}$ is aligned with $\mathbf{B}$.

In the SPM, the three orthogonal coils A, B and C have magnetic dipole moments $\boldsymbol{\mu}_A$, $\boldsymbol{\mu}_B$ and $\boldsymbol{\mu}_C$ respectively. Writing $K = NA$ as a constant for each of these dipole moments, the SPM rotated to Φ and Θ creates three torques, $\boldsymbol{\tau}_A$, $\boldsymbol{\tau}_B$ and $\boldsymbol{\tau}_C$, one for each winding. When currents i_A, i_B and i_C flow in the

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[1] Strictly speaking, the coils must only be linearly independent, but then the transfer function becomes more complicated.

three coils, we obtain three magnetic dipole moments:

$$\begin{aligned}
\mu_A &= K_A i_A(\cos\Theta\cos\Phi,\ \sin\Theta, -\cos\Theta\sin\Phi)\\
\mu_B &= K_B i_B(-\sin\Theta\cos\Phi,\ \cos\Theta,\ \sin\Theta\sin\Phi)\\
\mu_C &= K_C i_C(\sin\Phi,\ 0, \cos\Phi)
\end{aligned}$$

The SPM rotates so that the sum of the three torques is zero, i.e.

$$\tau_A + \tau_B + \tau_C = 0. \tag{3}$$

We can write Equation 3 as

$$(\mu_A + \mu_B + \mu_C) \times \mathbf{B} = 0 \tag{4}$$

and solve for Θ and Φ:

$$\Theta = \tan^{-1}\left(\frac{-K_B i_B}{K_A i_A}\right) \tag{5}$$

$$\Phi = \tan^{-1}\left(\frac{K_C i_C}{K_B i_B\sin\Theta - K_A i_A\cos\Theta}\right) \tag{6}$$

Thus we can write the pan and tilt angles of the gimbal as a function of the currents applied to the three coils. We can now prove the first design constraint. When the gimbal is panned so that $\Phi = 90^o$, assuming $i_C \neq 0$, Equation 6 shows that

$$K_B i_B \sin\Theta - K_A i_A \cos\Theta = 0$$

or

$$\tan\Theta = \frac{K_A i_A}{K_B i_B}$$

which can be true along with Equation 5 only when $i_A = i_B = 0$. But by Equation 5, Θ is undefined when $i_A = i_B = 0$. Therefore, when the SPM is panned 90^o, there is no control of tilt.

The calculation of motor position for specified currents would be accurate in the ideal case where all three coils were perfectly symmetrical, had the same number of turns, and were the same size. In general, none of these things are true. Thus the calculated currents gives only an approximation to the resultant position of the motor. Therefore, the motor must be calibrated to associate motor positions with the related set of currents that moves the motor to these positions. A procedure for automatic calibration of the SPM has been developed [4]. It is based on visual feedback from a camera mounted on the rotor of the motor. It assumes that a calibrated image sensor and lens are used, i.e., that it is known how many degrees each pixel subtends, and that this is constant. The basic idea is that a scene of black dots on a white background is imaged. For each motor position that is to be calibrated, the motor is moved approximately to that position using the calculated currents. The image is analyzed, and the position of the dot is used to calculate the actual position of the motor. This position is then associated with the coil currents.

The dynamics of the Spherical Pointing Motor are that of 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. This torque is dependent on the angle between the initial motor position and the destination position. Let us call this angle Ψ.

The motor will accelerate towards the destination position with the torque decreasing as it is reached. However, it will overshoot and ring around the final position. The ringing is described as follows. The torque $\tau = \kappa\sin\Psi$ for some κ. For small angles, $\sin\Psi \approx \Psi$. Then the position of the motor will follow Equation 7 [11, P. 228].

$$-\kappa\Psi - b\frac{\mathrm{d}\Psi}{\mathrm{d}t} = I\frac{\mathrm{d}^2\Psi}{\mathrm{d}t^2} \tag{7}$$

where b is the damping constant and I is the rotational inertia of the rotor. The approximate solution to this is

$$\Psi = Ae^{-bt/2I}\cos(\omega t + \alpha) \tag{8}$$

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

In practice, this ringing can be greatly reduced by moving the motor in small decreasing increments. This way, the motor velocity is traded off for control. The simplest method is to move a fixed percentage of the distance between the initial position and final position. This will decrease the motor movement with each step.

A second slightly more complicated open-loop control strategy based on traditional stepper motor control theory yields much better results. The idea is based on the fact that the motor oscillates with a constant period. Again, the motor is initially moved to an intermediate position. But this time, it is selected so that when the motor overshoots, the maximum position will be at precisely the desired endpoint. Because the period of the oscillation is known, we know when this maximum point will be reached. When it occurs, we change the coil currents to hold the motor at the new position. If either the midpoint, or the time at which the currents are changed are not exactly correct, there will still be a little ringing of the same period, but with vastly reduced amplitude.

The accuracy (or repeatability) of the motor is determined only by the friction of the bearings. As there is no iron core, and thus no hysteresis, if there were no friction, the motor would be infinitely accurate. We measured the accuracy of the SPM by reflecting a laser beam off a reflective surface attached to the rotor, and found the motor to be accurate to 0.15° which corresponds to about one pixel for our camera.

5 Conclusion

We have introduced a new miniature pan-tilt actuator suitable for pointing a camera. The Spherical Pointing Motor (SPM) is comparable in capabilities, yet at least an order of magnitude less in size and cost than other equivalent pan-tilt actuators. It is also extremely easy to use as it is an absolute positioning device and is run open-loop, although it could be run closed-loop if higher speed and accuracy are wanted. A set of currents applied to the coils moves the motor and holds it at a fixed position.

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