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Design of a Plate Type Multi-DOF Ultrasonic Motor and its Driving Characteristics

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Abstract

Multi-DOF actuators have become more useful in the field of robotics, thanks to the increasing number of DOFs of systems. General features of ultrasonic motor are suitable for constructing a direct-drive multi-DOF actuator. However, those previously developed do not have advantages in volume and weight against the multi-DOF motion unit composed of several electromagnetic motors. In the present study authors develop a novel multi-DOF ultrasonic motor with a plate stator and a spherical rotor. First, a new driving principle of the motor is proposed. Next, the stator geometry is designed in detail using finite element method, and the prototype of the multi-DOF ultrasonic motor with plate stator is produced. The stator is relatively compact against the rotor. Then, vibration characteristics of the stator and driving characteristics of the motor have been measured, respectively. The result confirms that the motor successfully provides the multi-DOF motion of rotor around orthogonal axes by single plate stator. Finally, self-oscillation driving circuit for the motor is proposed.

INTRODUCTION

Robots are now widely used in the field of industry, amusement, extreme work, medicine, and so on. In those applications, the number of degree-of-freedom (DOF) of the systems increases to achieve dexterous motions, because the targets mentioned above came to have much more relations to our lives, and some of robots are handled not only by specialists but also by public. According to the situation, generating dexterous motion like human is one of the most important subjects in the field of robotics. Dexterous multi-DOF motion is generally built by combining single-DOF motions of electromagnetic motors with reduction gears. In this case, however, it is difficult to construct a

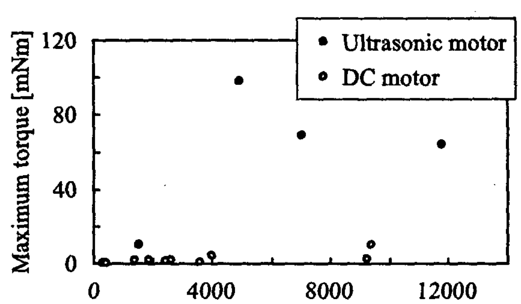


Figure 1. Comparison of maximum torque

compact multi-DOF motion unit, since the total volume and weight of the system become large and heavy. There can be two ways for engineers to solve this kind of problems. One is to make a small, high-power actuator with single-DOF motion. The other is to develop an actuator with several functions like multi-DOF actuator. The former is the extension of the present concept. Then, the system geometry and control scheme are kept to be the same as those of conventional system. On the other hand, if we take the latter, the new type of system configuration can be developed using the different concept from those of the conventional system. Accordingly, some multi-DOF actuators have been proposed and developed, which can generate multi-DOF motion using only single stators. As examples of multi-DOF electromagnetic actuator, Roth *et al.* proposed a three-DOF variable reluctance spherical wrist motor [1], and Yano *et al.* developed a spherical stepping motor [2]. There also are several studies on multi-DOF electromagnetic motors [3-5]. Structures of their motors, however, are so complicated that they cannot be compact. On the other hand, ultrasonic motors have excellent characteristics such as high torque at low speed, high stationary limiting torque, absence of electromagnetic radiation, less noise, and simplicity of design. Some of the characteristics are very much suitable for making multi-DOF actuator, which can be used as a direct-drive actuator. For instance, Figure 1 compares maximum torque of ultrasonic motors and electromagnetic motors. The figure suggests that an ultrasonic motor can potentially be a direct-drive actuator. Therefore, multi-DOF actuators based on the principle of ultrasonic motors have been proposed as follows: Bansevicius developed a piezoelectric multi-DOF actuator [6]. Amano *et al.* developed a multi-DOF ultrasonic actuator [7]. Toyama constructed a spherical ultrasonic motor [8]. Sasae *et al.* developed a spherical actuator [9]. Authors have also developed a new type of multi-DOF ultrasonic motor [10], which generates multi-DOF rotation of a spherical rotor using three natural vibration modes of a bar-shaped stator.

For ultrasonic motors generally have superior features as mentioned above, the multi-DOF ultrasonic motors [6-10] have potentials to replace general multi-DOF motion units composed of single-DOF electromagnetic motors. However, most of the multi-DOF ultrasonic motors mentioned above have rather large stators compared with the rotors; the actuators seem to have a little advantage in volume and weight to multi-DOF motion unit composed of several electromagnetic motors.

In this study, we develop a novel multi-DOF ultrasonic motor with a plate stator and a spherical rotor and its novel driving circuit. In the present paper, first we describe the basal design of vibration mode shapes of the stator and the driving principle. Then, we introduce the detailed design of stator using finite element method and the produced prototype of the motor. Procedures for drive experiments are explained. Additionally, a self-exiting driving circuit of the ultrasonic motor is newly introduced. Finally, we describe the conclusions of this study.

DRIVING PRINCIPLE

An ultrasonic motor is a frictionally driven motor, which is generally composed of a stator (vibrator) and a rotor. A typical ultrasonic motor uses two natural vibrations of the stator to drive the rotor. The vibration energy of the stator is transmitted to the rotation of the rotor by frictional force between the rotor and the stator. In case of the general single-DOF ultrasonic motors [11], the two natural vibration modes make points on the stator move on oval trajectories around specific axis. Then, the rotor, which is in contact with the points on the stator, rotates around the axis.

In order to develop a multi-DOF ultrasonic motor, we must extend the driving principle. That is, multi-DOF motion of the rotor can be realized when the axes of the oval trajectories are arbitrary varied. So, frequencies of three natural vibrations, which are orthogonal each other, must correspond to produce the arbitrary-axis trajectory. Namely, the stator for multi-DOF ultrasonic motor must meet following conditions;

- Natural frequencies of three vibration modes correspond,
- Vibrating directions of the vibration modes are orthogonal to each other,
- Geometry of the stator must be simple for easy production,
- The three vibration modes must be lower natural vibrations not to excite other unwanted modes.

As mentioned above, there have been several types of stators, whose vibration modes almost meet the conditions above. Most of the stators, however, are not compact to alleviate the size problem.

We adopted a basal design of vibration modes of the plate stator to solve the problem. As there are a great number of modes' shapes for plate, we carefully considered the above-mentioned conditions to select adequate vibration modes. We performed finite element analysis to confirm the modes' shape (cf. Figure 2). As a result of the analysis, we have chosen three natural vibrations shown in Figure 3. The reference frame in Figure 3 is common in use throughout the paper. "+" and "-" in diagrammic illustrations of these modes' shape represent the spatial phase along with the z-axis.

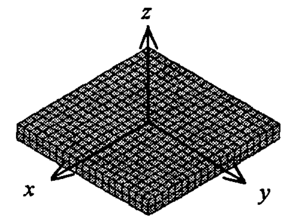
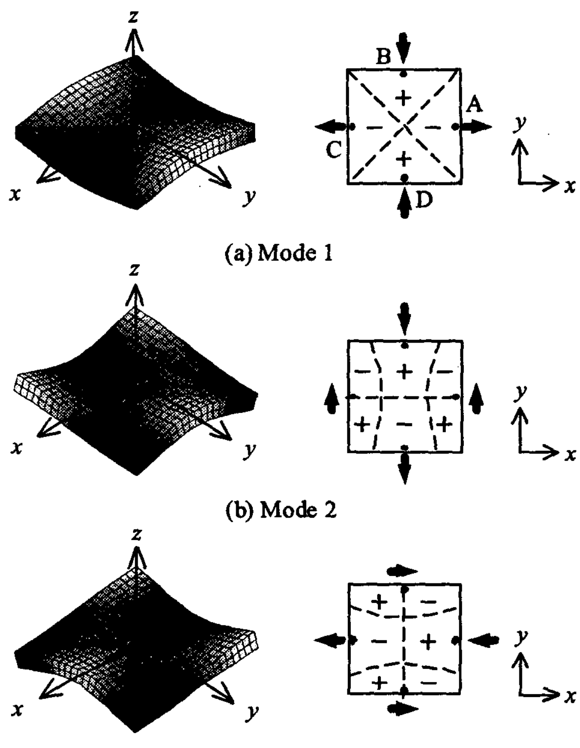


Figure 2. Finite element model of plate



(a) Mode 1

(b) Mode 2

(c) Mode 3

Figure 3. Natural vibration modes of plate

When the contact points against the rotor are located at the black dots A, B, C, and D in Figure 3, their vibration directions according to each natural vibration are:

- Mode 1: along the z-axis
- Mode 2: along the y-axis
- Mode 3: along the x-axis

Then, arbitrary oval trajectory of the points can be formed if the natural frequencies of the three vibrations correspond. Fundamentally, if the mode 1 and 2 (3) are combined with the phase difference of $\pi/2$, the points rotate nearly around the x- (y-) axis. If the mode 2 and 3 are combined, the points rotate around the z-axis. It implies that the rotor, which is in contact with the points, can selectively rotate around the x-, y-, and z-axis.

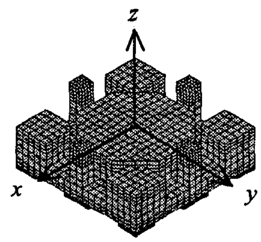


Figure 4. Finite element model of stator

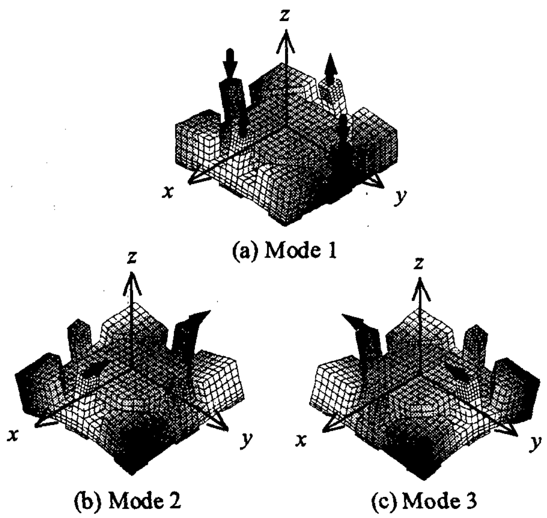


Figure 5. Natural vibration modes of stator

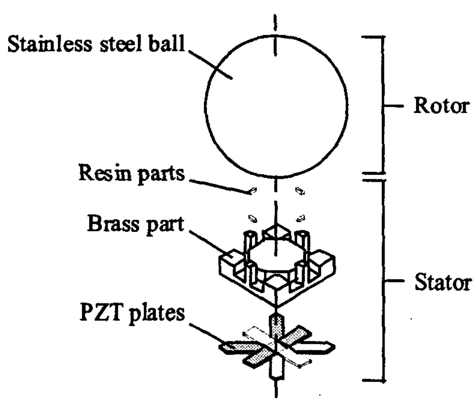


Figure 6. Geometry of multi-DOF ultrasonic motor (Polarized direction of PZT plates colored in gray and white are opposite. Diameter of rotor is 40 mm)

DESIGHN AND PRODUCTION

We have just discussed the motion of the points. It is important, however, to make the natural frequencies of the vibrations correspond. In this chapter, we design the actual stator in detail using finite element analysis.

Figure 4 shows the finite element model of the designed stator. The vibration modes are illustrated in Figure 5. All the natural frequencies nearly correspond at 24 kHz. According to the finite element model, we design the geometry of multi-DOF ultrasonic motor as shown in Figure 6. The multi-DOF ultrasonic motor consists of a spherical rotor made of stainless steel and a plate stator. The stator is composed of a brass part, resin parts, and PZT plates. Concave portions in the brass part adjust frequencies and enlarge vibration amplitude at contact points. The resin parts are located at the contact points against the rotor. The PZT plates are appropriately located to excite each natural vibration. Figure 7 and Table 1 show the inputs for the PZT plate in order to generate each vibration. Figure 8 shows the prototype of the multi-DOF ultrasonic motor with plate stator. The volume ratio of the rotor against the stator is about 152 %. The ratio of our previous multi-DOF ultrasonic motor [10] was about 22 %.

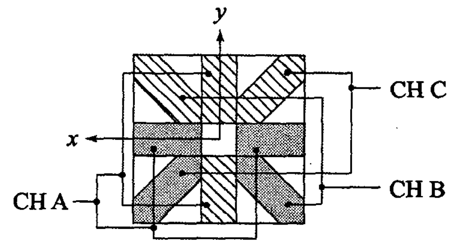


Figure 7. Input lines for PZT plate

Table 1. Inputs phase for PZT plate

Vibration mode	Channel A	Channel B	Channel C
Mode 1	0	—	—
Mode 2	—	0	0
Mode 3	—	0	π

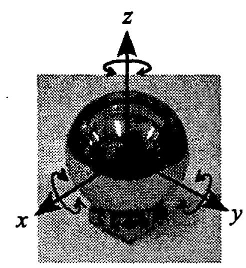


Figure 8. Prototype of multi-DOF ultrasonic motor

Table 2. Natural frequencies of virations

Vibration mode	Natural frequency [kHz]	
	Measured	Calculated
Mode 1	22.45	24.43
Mode 2	22.17	24.88
Mode 3	22.17	24.88

EXPERIMENT

Vibration Characteristics

It is necessary to confirm the natural frequencies and shape of the three vibrations from finite element analysis by experiments. This section describes the result of the vibration experiments.

First, the natural frequency of each vibration was measured. Table 2 shows the results of the measurements. For comparison, the results from eigen value analysis using finite element method are also shown in the table. Differences between measured/analyzed natural frequencies are around 10 %. The measured frequencies are lower than those analyzed, because the boundary between parts are not modeled in the finite element model, which lowers the stator stiffness. However, the natural frequencies of the vibrations are close enough for driving the rotor as the driving principle described in Chapter 2.

Next, in order to confirm the mode shape, we measured the motion of the contact points when each vibration is excited on the stator. Table 3 shows the results of the measurements. The frequency and amplitude of the alternating input to the PZT plates are about 23 kHz and 20 V, respectively. The signs in Table 3 represent the spatial phase of the point motions. Figure 9 shows the conceptual illustration of the vibration modes, which are expected from Table 3. Comparing Figure 9 and Figure 3, we can say the excited vibrations are different from expected ones. For mode 1, the overall shape is similar, except that the vibration direction has a little difference. The production tolerances and material isotolopy cause the difference. However, the vibration directions of the points almost agree with the expected ones. On the other hand, modes 2 and 3 have completely different mode shapes from those in Figure 3. With careful consideration, however, you can find that the modes 2 and 3 in Figure 9 are the combination of those in Figure 3. For instance, if the modes 2 and 3 in Figure 3 are simultaneously excited on the stator, the stator vibrates like the mode 2 in Figure 9. Namely, the vibration modes are essentially the same modes. A mode combining is conceptually illustrated in Figure 10.

From the results mentioned above, the phase relation of input signals to drive the rotor around each axis of reference frame is summarized in Table 4.

Table 3. Motion of contact points

Point		Displacement [μm]		
		Mode 1	Mode 2	Mode 3
A	x	18.21	10.47	-12.29
	y	2.28	-4.10	-5.01
	z	1.96	1.52	-1.10
B	x	-17.30	8.19	-7.28
	y	-3.19	-4.55	-5.92
	z	2.84	-1.26	1.86
C	x	4.10	-4.55	5.92
	y	-16.39	11.38	10.92
	z	-1.16	1.40	1.80
D	x	-3.64	-3.64	6.83
	y	19.57	11.84	9.10
	z	-3.26	-1.72	2.02

Driving Characteristics

The input signals for the ultrasonic motor are three alternating inputs, whose parameters are common frequency, independent amplitudes and phases. It is important to confirm the driving characteristics against each parameter. Since varying the frequency causes the vibration amplitudes change, we only measured the rotational speeds around each axis against frequency and phases as basic driving

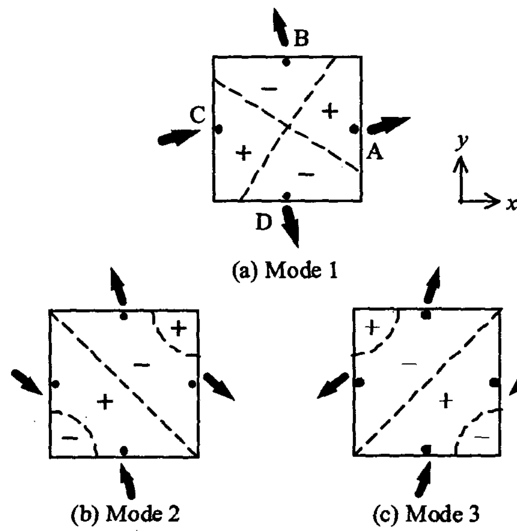


Figure 9. Excited vibrations of stator

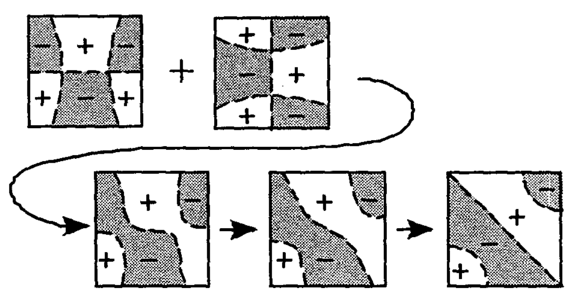


Figure 10. Mode combining

Table 4. Phase relation of inputs for driving

Rotational Axis	Channel A	Channel B	Channel C
x-axis	$\pi/2$	0	0
y-axis	$\pi/2$	0	π
z-axis	—	0	$\pi/2$

Table 5. Driving conditions

Parameter	Channel A	Channel B	Channel C
Amplitude [V]	20	20	20
Phase [rad]	as shown in TABLE 4		

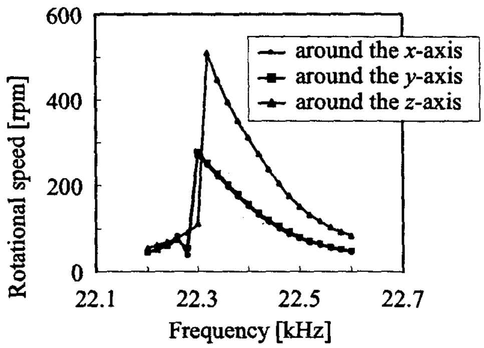


Figure 11. Rotational speed against frequency

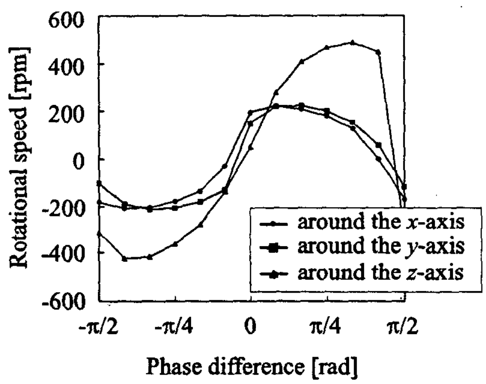


Figure 12. Rotational speed against phase difference

characteristics of the multi-DOF ultrasonic motor.

First, we measured the rotational speed against the driving frequency (Figure 11). The input parameters except for frequency are described in Table 5. The highest rotational speeds around the *x*- (*y*-) and z- axis are about 300 rpm and 500 rpm, respectively, at around 22.3 kHz, which is nearly the same as the natural frequencies of the three vibrations as described above.

Second, we measured the rotational speed against the phase difference. Here the term "phase difference" denotes that the phase difference between two vibrations used to drive the rotor around each axis. Figure 12 shows the measured results. The amplitudes are the same as those in Table 5 with the driving frequency at 22.3 kHz. The sign of rotational speed represents the rotational direction. Each characteristic plot in Figure 12 has a sinusoidal-shape. Theoretically, the rotor stops if the phase difference is equal to 0 rad because the contact points cannot draw the oval trajectories. However, the result shifts to left in Figure 12. The natural frequencies of the vibrations do not exactly correspond. This causes an independent phase delay for each vibration against the input signal. Because of the phase change, the curves are shifted slightly to the left.

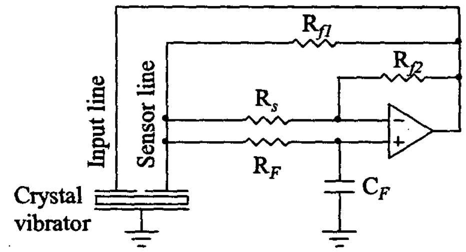


Figure 13. Self-oscillation circuit

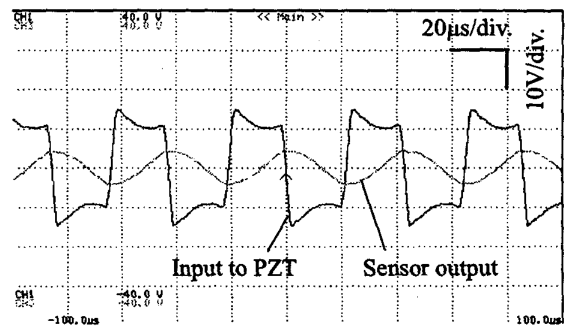
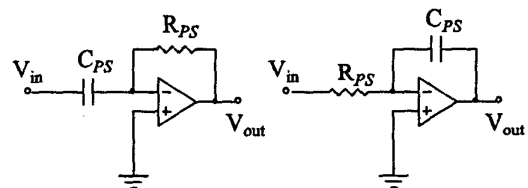


Figure 14. Experimental result of self-oscillation



(a) Phase advance (b) Phase delay

Figure 15. Phase shifter

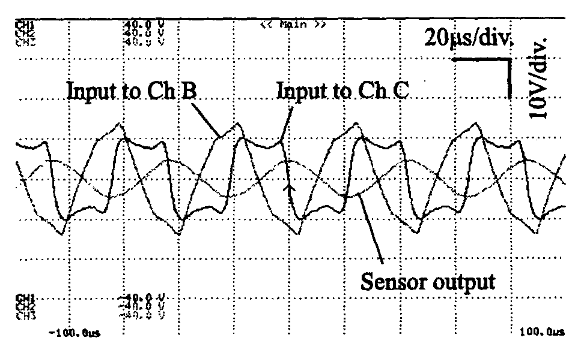


Figure 16. Generated input signals during driving

SELF-OCSILLATION DRIVING CIRCUIT

For driving ultrasonic motors, generation of the desired natural vibration of the stator is one of the most important points. Therefore, we generally use function generator or pulse generator to make alternative inputs for ultrasonic motors. Then, we have to carefully adjust the frequency of the signals so as to excite the desired vibrations, or we have to add another circuit as a resonance detector. It makes the system complicated. Consequently, we introduced a theory of self-oscillation circuit to ultrasonic motor driving circuit. We generate two-phase inputs for the motor by the circuit. There has been developed a self-oscillating ultrasonic motor [12], however, the motor is driven only by single vibration of the stator. Figure 13 shows a general crystal oscillator circuit. The circuit is composed of crystal resonator, resistor, capacitor and operational amplifier. Then frequency of the input signal for the vibrator should become a resonant frequency of the crystal itself. We have substituted the ultrasonic motor's stator for the crystal, and have adjusted the properties of circuit components (Rs = 10 kW, Rf1 = Rf2 = 1 MW, CF = 68 pF). As a result, the desired natural vibration should be automatically excited on the stator.

Figure 14 shows the experimental result of self-oscillation of one vibration, mode 2, provided that a part of one PZT plate in Figure 7 is used as sensor. The input signal seems to be a rectangular wave because the signal is saturated at the operational amplifier so as to obtain enough voltage to drive the ultrasonic motor. The result (sensor output voltage) confirms the vibration has successfully excited on the stator. The stator itself works as a low pass filter.

The self-oscillation circuit does work as mentioned above. In addition, we have to input another phase-shifted alternative signal for driving the rotor around each axis. Accordingly, a phase-shifted signal is generated at a phase shifter (differentiator/integrator) shown in Figure 15, where RPS = 68 kW, CPS = 68 pF.

Using the self-oscillation circuit and phase shifter, we constructed a self-oscillation driving circuit of the motor. Figure 16 shows the generated signals. The signals include high-frequency components, however, the main components are 22 kHz ones. It means the desired vibrations are successfully excited on the stator. The shape difference between the inputs to channel B and C is caused by an independent phase delay related to each frequency component at the phase shifter.

Experimental result confirms the rotor can be rotated using the self-oscillation driving circuit. The maximum rotational speed of the rotor is about 70 rpm, when the input voltages to the operational amplifiers are 18 V.

CONCLUSIONS

In this study, we have proposed the driving principle of the multi-DOF ultrasonic motor with plate stator, and designed the stator in detail using finite element method. Then, we have produced the prototype of the multi-DOF ultrasonic motor. Measuring the vibration characteristics of the stator, we have confirmed that the rotor successfully rotates around three orthogonal axes. In addition, we have developed the self-oscillation driving circuit of the motor.

Future works focus on multi-DOF motion control of the rotor motion, and use the motor to applications, such as multi-DOF robot eye, and leaser orientation.

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