Proceedings SPIE, Telemanipulator and Telepresence Technologies
Symposium, pp 55-61, Boston, October 31, 1994

Hard Disk Actuators for Mini Teleoperation

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ABSTRACT

Hard disk drives have evolved rapidly with computer miniaturization into highly compact and integrated electromechanical systems. Hard drives contain many precision mechanical parts which may prove useful in the design of small precision robots. The advantages of parts taken from hard disks include low cost, miniaturization, high quality, and for some applications, cleanliness. We report the results of engineering tests on flat coil head positioning actuators taken from hard drives of sizes ranging from 5.25” to 1.8” media diameter. We also perform a simple analysis which suggests that requirements for torque per unit mass are lower for small robot arms. The results suggest ways that hard disk actuators can be utilized in mini robotic designs and points the way towards improved versions of these designs for robotic purposes.

Keywords: robotic, telerobotic, teleoperation, actuator, miniaturization, hard disk drive

1. INTRODUCTION

Interest has recently grown in the potential for small robotic and telerobotic devices. One objective of researchers is to develop high fidelity scaled force reflection between a human operator and a miniaturized slave robot (Hannaford, 1991, Colgate, 1991, Kobayashi and Nakamura, 1992). Accurate force reflection can be accomplished without force sensors if highly back drivable robots are developed such as direct drive robots (Lawn, 1992). Direct drive robots have also been found to excel at full-sized tasks which involve long duration contact between the robot end effector and the environment (Asada & Kanade, 1983, Asada & Youcef Toumi, 1987).

Hard disk drives have become ubiquitous in the developed world. Virtually all personal computers are equipped with hard drives, including the smallest portable models. This huge manufacturing volume makes the unit cost of the underlying technologies extremely low and justifies large engineering efforts in their design and optimization. Furthermore, the magnetic information storage industry is under pressure from semiconductor technologies to rapidly increase storage densities. As a result, the industry has been introducing a series of smaller and smaller drives based on standard media diameters.

Media diameter has decreased at an average rate of 10% per year since the 1970’s (Marbot & Hannaford, 1991). By scaling arguments, this leads to a decrease in volume and mass of about 30% per year. As a result, precision mechanical components in a wide range of sizes are readily available in the disk drives which are on the market today. Drives ranging in media diameter from 5.25” to 1.3” are currently available. This 4:1 range of linear dimensions corresponds to a 64:1 range of volumes and therefore masses.

We have built a small three-axis direct drive robot for biomedical applications using voice-coil actuators from hard drives (Marbot & Hannaford, 1991). This robot achieved high precision (5-10 microns) within a workvolume of about 32 cm^3 while retaining full backdriveability in response to applied forces.

Using recycled components from existing products is something of a novelty in considering formal robotic design. However, there are many advantages in using these devices for prototyping advanced designs. Low cost is an obvious advantage because many drives fail in ways that are not practical to repair. These failures are usually in the media or electronics. As a result, repair shops receive large quantities of “dead” disk drives whose inner mechanical parts are fully functional. Secondly, since the interior of a hard drive is a very clean environment, these parts are usually in very good condition regardless of the age of the drive. Finally, there is a large variety of actuators readily available through this route in contrast to a relatively small number of models offered by vendors of small voice-coil actuators. In comparison to catalog prices, we have seen actuators and bearings in hard drives which would justify the purchase of a brand new drive just for the mechanical parts inside! Fortunately, obtaining “dead” drives from repair depots and manufacturer’s rejects is substantially less expensive.

Disk drives use several different types of actuators for positioning their heads. The main types are stepping motors, voice coil motors, rotary voice coil motors, and flat coil motors. Flat coil motors (Figure 1) work by forming a single coil of wire wound around an axis parallel to the axis of rotation of the actuator. The coil is wedge shaped, and placed in a gap formed by two oppositely polarized magnets in such a way that one arm of the coil is always adjacent to one magnet and the other arm to its opposite. This configuration produces a net force because each leg of the coil lies in a magnetic field of opposite polarity. Because of this configuration, the motion range of these actuators is typically limited to 20-40 degrees.

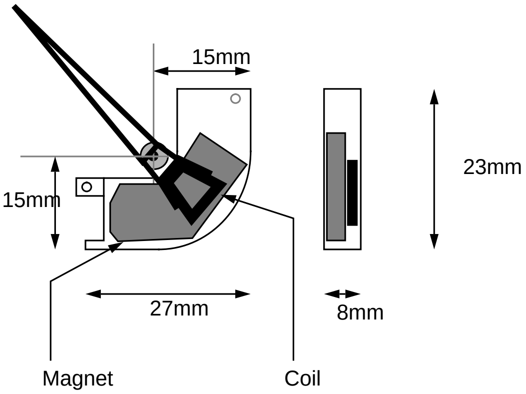

Figure 1.

Dimensions of a flat coil head positioning actuator from a 1.8” disk drive. the magnet (hatched region) has two regions of polarity so that each leg of the coil generates force in the same direction.

What is the significance of a prototype device which incorporates recycled technology? A device incorporating technologies from mass-market devices is one which will require less investment to eventually bring to market, because the recycled technology elements are clearly manufacturable in high volumes and at low cost.

One drawback of this approach is the lack of engineering data on recycled components. In this paper we report electro-mechanical properties of 5 flat coil actuators from disk drives with media diameters of 5.25”, 3.5”, 2.5”, and 1.8”. We made measurements on three versions of the 1.8” drive, one with a single magnet above the coil, another with magnets above and below the coil and a third in which we filled the magnetic gap with ferrofluid (Ferrofluidics Corp, Nashua NH, 03061-2009). In addition to measurements of maximum operating torque, Rtherm, friction, and electrical parameters, we derive measures such as motor constant, and specific torque (torque per unit of mass), and compare them with similar measures for macro-scale motors obtained by Hunter and Hollerbach (1992).

2. METHODS

Hard disk drives were obtained from local repair shops and manufacturers. We measured coil temperature with type “E” thermocouples bonded to the coil surface with thermally conductive epoxy. Electrical variables were measured using digital volt-ohm meters. We measured torque using a digital force gauge at a known lever arm from the axis of motion. All temperature measurements are reported in the steady state. The devices had thermal time constants on the order of 5-10 minutes.

2.1. Maximum Torque

For these motors, the torque produced is linearly proportional to coil current. The “maximum” torque is really a thermal limit determined by the temperature at which the insulation will fail. A usual standard is to measure torque with a current sufficient to raise the temperature of the coil to a specified value. We measured coil temperature as a function of coil current twice; once with the actuator coil in free air and once with the actuator installed in the drive.

The motor torque constant, Kt could be derived from the torque and current measurements.

2.2 Friction

Using the torque constant, Kt, it is possible to estimate the static friction level for the actuators. We started from zero and gradually increased current without an external load until a deflection of the actuator was observed. The torque required to visibly deflect the actuator was a function of position. Our measurement reports the average value of this torque for three positions across the range of motion.

Mass was obtained by weighing the coil, actuator body, magnets and frame. The drive case, media, heads, and head arms were not included.

Volume was measured by wrapping these parts tightly in plastic, immersing them in water, and observing displacement.

3. RESULTS

The first measurements were the temperature vs. current curve (Figure 2). These measurements establish the current and thereby the torque which can be maintained in the steady state with a given allowable temperature. Current was applied in steps, and the temperature recorded when its rate of change was less than about 1% per ten seconds.

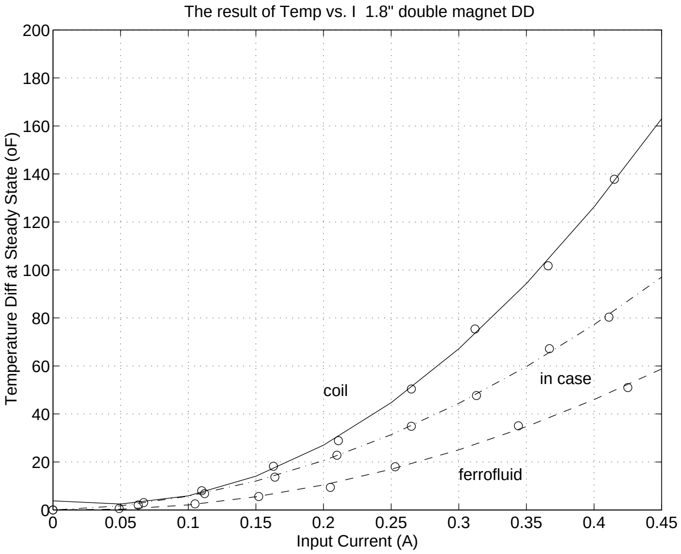

Figure 2

As current was increased, the temperature rose parabolically as expected from a linear model of heat dissipation in response to electrical power. The coil’s electrical resistance was a linearly increasing function of temperature. Although space limitations preclude a derivation, it can be shown that this curve can be approximated by

$$T = R_{THERM} R(T) I^2$$

However, the thermal resistance depended on whether the flat coil temperature was measured in the disk drive case, or in free air. Surprisingly, the thermal resistance was lower in the case. This was apparently due to conduction of heat through the bearing to the relatively large radiating surface of the case. The Rtherm value for each drive is given in Table 1.

To obtain a value for “maximum” torque output, an operating temperature must be selected. This should be based on the temperature rating of the insulation material which was unavailable to us. We used an arbitrary value of 200 degrees Fahrenheit (111 deg C) above ambient temperature. This temperature did not cause any observable change in the actuators. This corresponded to an absolute coil surface temperature of 137 deg C, comparable to the value used by Hollerbach et. al., (1992). The data we obtained are consolidated in Table 2. Maximum torques varied from $57.4\text{x}10^{-3}$ Nm to $6.8\text{x}10^{-3}$ Nm from the largest to the smallest actuator.

Minimum torque, the lowest torque which caused observable displacement, varied from a high of 0.33x10^{-3} Nm for the 5.25” actuator, to 0.05x10^{-3} Nm for the 2.5” actuator. It is interesting that friction did not vary monotonically with size. One possible explanation for this is that we did not take great pains to keep the devices free of dust. Of the drives we tested, the 2.5” drive was the one with the least elapsed time between breaking the seal and testing. This may account for its very low friction level.

Table 1: Thermal Resistance

Size Coil	R_T in case [^{o}F/Watt]	R_T coil only [^{o}F/Watt]
5.25”	20.8	28.1
3.5”	28.4	39.5
2.5”	58.6	90.0
1.8” dm	43.1	77.0
1.8” sm	39.7	88.3

3.1 Derived Measures

Following Hollerbach et.al, 1992, we computed the specific torque by dividing maximum torque by mass. These values ranged from 0.242 Nm/kg for the 5.25” drive to 0.50 Nm/kg for the double magnet 1.8” actuator with added ferrofluid. These values are low with respect to the approximate theoretical limit of 6.0 derived in Hollerbach et.al. because of the flat coil geometry. In the flat coil geometry, only a fraction of the total magnetic flux is used to generate force (Figure 1). The ratio of magnet area to coil area in the actuators tested was between 4:1 and 5:1. If new coils were wound to use the entire magnet area, they would increase the torque by this ratio without significantly increasing mass. This would give specific torques in the range of 1.0 to 2.5 Nm/kg.

Because of the application of the smaller disk drives in portable devices, torque per unit of volume was also calculated. This measure ranged from a low of 519 Nm/m^3 to a high of 1233 Nm/m^3 for the 1.8” double magnet design with added ferrofluid.

Table 2: Flat Coil Actuator Properties

Drive Size	Mass [gr]	Vol. [cm^3]	R T_o=80^o F [ohm]	R T=280^o F [ohm]	Static Friction [Nm*10^{-3}]	Current ΔT=200^o F [A]	Torque ΔT=200^o F [Nm*10^{-3}]	K_m [Nm*10^{-3}A^{-1}]	P_{diss} ΔT=200^o F [Watt]	Torque/ Mass [Nm/Kg]	Torque/ Vol [Nm/m^3]
5.25”	237	111	21.6	35.6	0.33	0.52	57.4	110.5	9.6	0.24	517
3.5”	65	27	26.9	39.0	0.22	0.43	18.6	43.7	7.1	0.29	688
2.5”	41	28	16.8	24.2	0.05	0.38	18.8	50.1	3.5	0.46	672
1.8” dm	22	9	6.5	10.9	0.07	0.65	8.9	13.6	4.7	0.40	988
1.8” sm	14	9	6.2	10.6	0.07	0.69	6.8	9.8	5.0	0.48	751
1.8” ff	22	9	6.5	10.9	N/A	0.81	11.1	13.6	7.2	0.50	1233

3.2 Smoke Test

To get a rough idea of the maximum permissible operating temperature, we performed a “smoke test” on one of the 2.5” drives. We gradually increased the temperature of the coil by increasing applied current. We observed a small amount of smoke at 155 deg C. With the available power supply, we were able to increase the temperature to about 250 degrees C with 12 watts of power. The smoke rate did not substantially increase. Upon re-cooling the device, no change in resistance was measurable.

3.3 Ferrofluid

Ferrofluidic materials have been used occasionally in voice coils in high frequency loudspeakers. We injected type EMG905 oil based ferrofluid into the magnetic gap of the double magnet 1.8”drive. As a result, the peak torque was increased by about 25%. The added conduction path for heat flow resulted in significantly lower R_{THERM} (see Table 1).

Upon injection, the ferrofluid neatly filled the magnetic gap, immersing most of the coil. After the ferrofluid was added, the actuator showed a noticeable attraction for the ends of its motion range without any applied current. The torque required to move the actuator from the limits was 0.7x10-3 Nm. This was due to the fact that at the extremes of motion, certain parts of the coil frame extended beyond the magnetic gap. Thus at the motion extreme, less ferrofluid was displaced from the gap, and the total system energy was reduced. In a future project, this effect could be eliminated by trimming the coil frame and or extending the magnet size slightly.

4. ANALYSIS

Specific Torque Requirements for DD Arms

It is of interest to see if we can derive requirements for these parameters from one of the most basic functions of a serial robot arm which is to hold itself and its payload up against gravity. A major part of the weight of direct drive robot arms is the actuators which in turn defines torque requirements for the proximal joints. Is there a minimum value of specific torque below which the arm cannot hold itself against gravity?

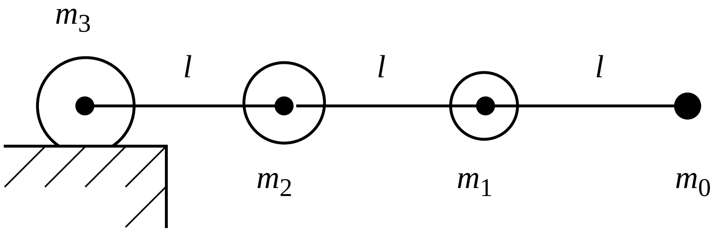

Figure 3

Simplified schematic diagram of a direct drive serial arm resisting gravitational torques

To study this question, consider the schematic planar chain of direct drive actuators and links in figure 3. Assume the link length is l, link mass is zero, and a payload of mass m_0 is attached to the end effector. For this analysis it is convenient to number the links in increasing order from the end effector to the base in contrast to the usual practice. Let u be the specific torque, that is the ratio of torque to mass in the actuators.

The torques in the actuators are

$$\tau_1 = m_0 g l \tag{1}$$

$$\tau_2 = m_1 g l + m_0 g 2l \tag{2}$$

$$\tau_3 = m_2 g l + m_1 g 2l + m_0 g 3l \tag{3}$$

where g is the acceleration of gravity. These can be written as a series

$$\tau_j = gl \sum_{i=0}^{j-1} (j-i)\, m_i \tag{4}$$

The masses are assumed to be related to the torques by u:

$$m_j = \frac{\tau_j}{u} \tag{5}$$

Substituting this into the torque series,(4),

$$\tau_j = \frac{gl}{u} \sum_{i=0}^{j-1} (j-i)\, \tau_i \quad , \tag{6}$$

with the initial values

$$\tau_0 = u m_0 \ , \ \ \tau_1 = m_0 g l \tag{7}$$

This is a Fibonacci-like series which grows very quickly with j. However, the torques and masses are always finite as long as *u* is non zero.

Thus, no matter how wickedly small *u* is, the arm can in principle be designed to stand up to gravity if the motors are allowed to grow in size rapidly enough from distal to proximal. The non-moving mass of the base motor can be made arbitrarily large to allow enough torque at the base. In a practical case, however, it is desirable to limit the mass and volume of even the base actuator so that a useful measure of performance can be formed from the ratio of the payload mass to the base actuator mass. To study this performance measure, it is useful to consider an example with three links and motors. Using (6), we get

$$\tau_3 = m_0 g \left(3l + \frac{4gl^2}{u} + \frac{g^2 l^3}{u^2} \right) \tag{8}$$

giving

$$\frac{m_0}{m_3} = \frac{1}{g\left(\frac{3l}{u} + \frac{4gl^2}{u^2} + \frac{g^2 l^3}{u^3} \right)} \tag{9}$$

$$\frac{m_0}{m_3} = \frac{1}{3\alpha + 4\alpha^2 + \alpha^3} \tag{10}$$

where

$$\alpha = \frac{gl}{u} \equiv \text{arm index} \tag{11}$$

α is thus a measure of *dynamic similarity* of direct drive robot arms. Since the specific torque, *u*, only appears in a ratio with *l*, for a given level of performance, lower values of *u* are required for smaller direct drive serial robots. Alternatively, small versions of direct drive arms which preserve *u*, will have correspondingly greater performance.

We can consider a few numerical examples:

Table 3: Numerical Examples

u	$l = 0.1m$		$l = 1.0m$	
	α	$\frac{m_0}{m_3}$	α	$\frac{m_0}{m_3}$
15	.065	4.7	0.65	0.25
10	.098	3	0.98	0.12
5	.196	1.33	1.96	$\boxed{0.035}$
.6	1.6	0.05	16	193×10^{-6}
.5	1.96	$\boxed{0.035}$	19.6	109×10^{-6}
.3	3.3	0.012	33	25×10^{-6}

These examples compare the performance of 3-link DD arms with link lengths of 0.1m and 1.0m. We can see that a small robot using $u = 0.5$ has the same performance as a large robot using motors at the theoretical limit, $u = 5.0$.

5. DISCUSSION

This study has measured some basic engineering parameters for actuators from hard disk drives of various sizes (physical media diameters). We suggest that devices of this sort provide a rich source of components for robotic prototyping and experimentation at low cost.

Adding ferrofluid to the magnetic gap appears to be a promising way to get increased torque capability, better thermal properties, and some well behaved damping from these devices. Problems related to non-uniform displacement of fluid can be easily solved with slight modifications.

By analysis of a simple planar direct drive arm under the acceleration of gravity, we showed that smaller direct drive arms should have better dynamic performance than larger ones. This suggests that the benefits of direct drive arms such as better force control and precision should be highly relevant to small robot designs.

6. ACKNOWLEDGMENTS

This work was supported by National Science Foundation PYI grant BCS-9058408, the Washington Technology Center, and the hard disk drive industry.

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