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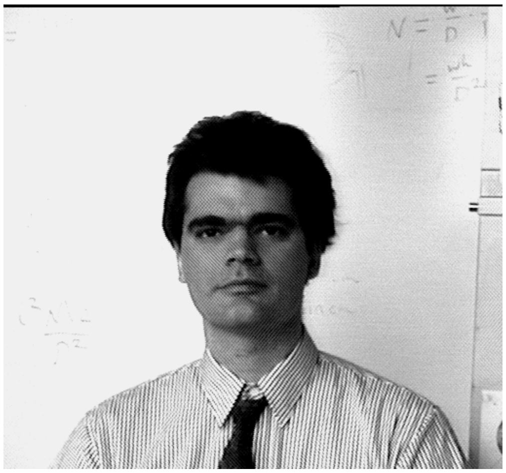

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process technologies to produce multiple actuators in small batches.

Some of the other problems we face are coil overheating, demagnetization, and magnet safety hazards. Current I passing through a coil inductor causes it generate heat proportional to I^2. Previous DD arms suffered from coil overheating as well [1] [4]. Heat and mechanical wear cause permanent magnets to demagnetize, and we have yet to face this problem squarely. Finally, the size and power of our motors make them inherently safer than powerful industrial robot actuators. But there are some hazards associated with very powerful magnets. In one incident, a researcher holding a magnet in his hand attracted a razor blade from several centimeters away on a tabletop. Fortunately, the blade landed on its dull side.

5 Conclusion

We have demonstrated the feasibility of using small direct drive DC motors as actuators for miniature robot limbs, for example the fingers of a hand or the legs of a small walking machine. Small permanent magnet DC motors are economical actuators and have a parts cost close to that of mass-produced DC brush motors of the same size.

The very low cost[4] of miniature DD motors makes them attractive for education as well. Students in our robotics lab, including secondary school interns, build mini DD motors as a lab assignment. This gives the students practical first-hand experience with the principles of electromagnetic actuation and control problems such as calibration and damping. In particular, some students build a two link manipulator like the "Nov 11 92" pair. They then relate its kinematics, statics and dynamics to the simple two-link manipulator theory (see e.g. [7] [8] [12]) they learn in class.

We expect to see growth in human interface applications of robot devices. Current commercial examples of this trend include camcorders with image stabilization and autofocus still cameras using automated eye tracking. We are building force feedback input-output devices based on miniature DD motor technology. The component cost of robot systems is falling rapidly, clearing the way for their introduction into the human environment.

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[4] All the new actuators described in this paper contained less than $10 in parts.

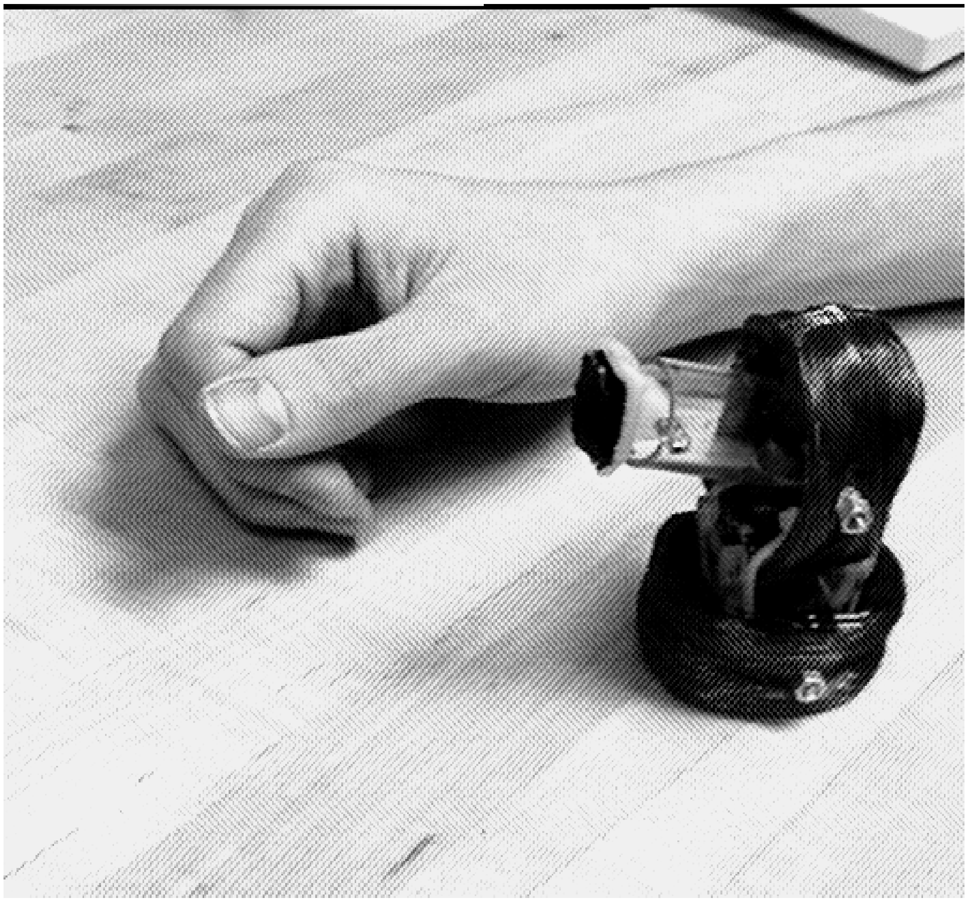

Figure 2: The two-link “Nov 11 92” motor pair.

questions we'd like to pose to the simulator is the placement of permeable materials to make efficient magnetic return circuits for the DD motors.

Control of our DD motors is so far only open-loop. We have programmed simple walking gaits for the two-link actuator using the Motorola MC68HC11 micorcontroller to create a $5V$ pulse-width modulated signals, which a Unitrode LM293 current driver amplifies to deliver up to 1 Ampere to the actuators. The closed loop control of this motor family is a topic not yet explored, although earlier DD arm builders have studied the control problem carefully for their designs [4] [1] [3] [2] [10].

There are interesting DD motor manufacturing questions as well. We make our motor coils by forming a wax mold, wrapping the coil with magnet wire having a layer of thermally activated bonding material, then heating the coil with a heat gun. The heating both melts the wax mold and bonds the coil so that the wire forms a rigid solid mass. The motor rotors consist of plastic or brass magnet housings, a rotor bearing shaft, and a plastic or brass limb which may be connected to a second link. We have only just begun to think about efficient

Device ID	Res. Ω	Rotor config.	Stator config.	Range *deg*	Mass *gm*	Coil height *cm*	Coil width *cm*	Max speed *deg/sec*	Torque *Nt-m*
Oct 15 92	24	$4L$	$1S$	60	80	4	5		0.10
Oct 31 92	145	$6L$	-	100	280	6	7	500	0.07
Nov 11 92 Hip-A	20	$4L$	-	20	90	5	5	100	0.07
Nov 11 92 Knee-A	31	$3L$	$1S$	70	90	5	6	2240	0.08
Dec 9 92	22	$3L$	-	25	70	3	3	500	0.09

Table 1: Specifications and measurements of 5 mini DD motors. We used two sizes of Nd-Fe-B permanent magnets. L refers to the number of "large" cylinderical magnets, 1/2 inch diameter and 1/4 inch height. S refers to "small" magnets, 1/4 inch diameter and 1/4 inch height. The Nov. 11 motors are linked to form a two-link actuator.

result of its slightly smaller coil and higher tolerance fabrication.

The "Nov 11 92 Hip-A" and "Nov 11 92 Knee-A" motors are connected together to form a simple two-link mechanism. The small range of angles (20°) in "Nov 11 Hip-A" resulted from the use of the large shaft necessary to mount the second motor at the end of the first link.

The wide variation in measurable speeds between "Nov 11 92 Knee-A" and "Nov 11 92 Hip-A" results from their significantly different loads. The "Hip-A" motor carries the "Knee-A" motor in a two-link actuator. We measured speed by placing a high alternating current sine wave into the coils and increasing the wave frequency until the full workspace could no longer be covered. In the case of the "Knee-A" motor the workspace is 70° and the highest frequency is 16Hz, resulting in an average velocity of $2 \times 70 \times 16 = 2240°$/sec. Unfortunately, the "Oct 15 92" motor broke before we completed the apparatus for speed tests.

The motor "Dec 9 92" differs from the others in three ways: First, its rotation axis does not pass through the rotor permanent magnets, but instead is slightly in front of them. At its maximum deflection, the magnet assembly hits the surface of the coil, whereas in the others there is always a gap between the magnet and the coil. Second, its coil has a round rather than a rectangular cross section, and the rotor magnets are always completely inside the coil. Third, the motor is substantially smaller than the others. The mass of the Dec 9 motor is close to the mass of the others, but this results from the fact that the rotor assembly is brass, whereas it is plastic in the others.

4 Discussion

There are a number of other topics yet to be investigated in connection with miniature DD motors. The existence of many magnetic fields in close proximity makes the formal analysis of actuator characteristics quite complex. We plan to build a software simulator to help answer questions about the forces and torques generated by magnets and coils in various configurations. Commercial CAD packages exist, but are quite costly, so we plan to build our own. One of the motion control. The size of the motors varies somewhat (see table in section 3) and rotor shafts extend 2.5-7.5 *cm*.

Direct drive pointing actuators are electromechanically equivalent to old fashioned analog Ammeters, in which the angular deflection of an indicator needle depends on the input current. The existence of high $BH_{\max}$ magnets makes it possible for a pointing motor to carry a load much more massive than an indicator needle.

Permanent magnet pointing actuators have three additional desirable properties for robot limbs. First, the shaft orientation is an easily calibrated function of the input current. Second, the stator permanent magnet acts as a brake that holds the rotor at a fixed orientation, even without current in the coil. Third, the pointing actuators have built-in compliance analogous to a spring based remote center of compliance wrist.

The range of the workspace is limited by the mechanical constraint of the coil and the size of the rotor shaft. The rotor arm literally slams into the coil at its maximum deflection. The coil is a hard mechanical limit. But the maximum impact force is far less than the force needed to break the coil or the rotor.

Most significantly, one motor generates enough torque to lift another one of roughly the same size, without resorting to the use of a counterweight. In one of the two link devices we built, the distance between the axis of the first joint and the second joint is about 5 *cm*, and the diameter of the motor coils is also about 5 *cm*. Each motor weighs about 90 *gm*. Given an arbitrary orientation of the first motor with respect to gravity, it can lift and move the second motor (and both rotor links) through the whole range of its workspace (20°). Although the rotor magnets are roughly balanced on the rotor shaft, the mass of each successive link is not counterbalanced.

3 Experiments

We built a series of 15 rotary direct drive actuators (see figure 2). All of the motors basically rotated a shaft through a range of angles. The largest range we built was 100° and the smallest was 20°.

To measure maximum torque, we used a constant current power supply with the voltage set nominally to $40V$ and the current held at 1 Ampere. We placed a Mark-10 digital force meter normal to the end of the shaft, and found the deflection angle giving the highest force value. As the shaft length was always constant, we calculated the torque as the product of the force measurement and the shaft length. The highest torque achieved was 0.1 *Nt-m*, more than enough for one motor to lift another.

Table 3 summarizes the results obtained with five of the motors. The coil wire length determines the resistance of each coil. We used AWG 30 magnet wire, which has resistance of about 3Ω per meter. Most of the coils were basically rectangular, so the table gives the dimensions of the coil in width and height. The minimum gap is the minimal distance between the rotor magnet and the stator.

The motors called "Oct 15 92", "Nov 11 92 Hip-A" and "Nov 11 92 Knee-A" are all approximately the same. The torque generated by the Oct 15 motor is slightly higher as a

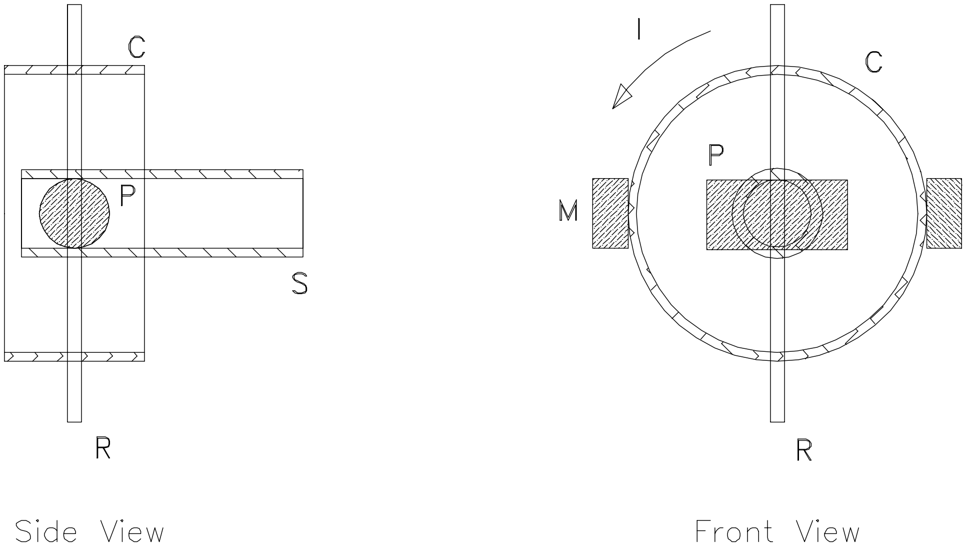

Figure 1: Principle of direct drive: The motor stator holds a coil C and a rotor bearing R. The rotor consists of a permanent magnet P and a shaft S. Current I in the coil results in motion around the axis R in a direction given by the sign of I. An optional second stator magnet M transforms the pure revolute actuator into a pointing actuator.

the commercial arena, radio control (RC) hobby servomotors are the closest in size, power, workspace and ease of control to our DD motors. These RC "servos" combine low-cost high-speed DC motors with a gear assembly linked to a rotor, which typically travels up to 180°. Our DD motors have a more limited workspace, but operate at higher speeds ($> 2000°$/sec) with almost no friction, and of course no gear backlash.

2 Mini direct drive actuators

The main difference between the new DD actuators and conventional DC motors is their limited range of rotor travel. Conventional DC motors are designed to rotate 360° continuously, and ours move only within a bounded circular arc. But continuous rotation is an undesirable characteristic for a robot limb. Robot arms generally have cables or control lines running through the joints from one link to the next. If the joints rotate continuously, the cables stress and sometimes break, resulting in the need to use safety limit switches on the actuator motors.

Our miniature DD motors are of two broad types: pointing motors and pure revolute motors (see figure 1). Both types consist of a rotor, which carries a permanent magnet, and a stator, which houses a wire coil. Pointing motors have an additional magnet or coil on the stator, the function of which is to create a reference magnetic field from which the rotor is deflected, or pointed. If the extra field comes from a permanent magnet then the pointing rotor has a passive orientation, and it holds this position even with no power in the stator coil. This property makes pointing motors useful for camera aiming, and also facilitates compliant

> "To manufacture artificial workers is the same thing as to manufacture motors." - Harry Domain, *R.U.R.*[2]

1 Introduction

We [3] have recently built a set of miniature rotary direct drive (DD) actuators, based on strong Nd-Fe-B rare earth permanent magnets and controlled by low-cost embedded microcontrollers. This motor family is an offspring of the Spherical Pointing Motor (SPM), a two-axis pan-tilt actuator we built to point a miniature CCD camera [14] [6] [5]. In the present work we wanted to determine how large a torque an SPM-type motor could generate, and whether it would be possible to use these actuators as robot fingers, legs and force-feedback human interface devices. The affirmative answer to these questions could be determined with simpler single-axis actuators, and in any case the 1-dof actuators are suitable for many tasks as well.

Direct drive DC motors have many advantages as robot limb actuators: high speed, very low friction, simplicity of design, low design and construction costs, and extended wear. They have no gear backlash, and they simplify the implementation of advanced control strategies such as force and torque control and compliant motion [4] [1] [3] [2] [10]. Our new actuators have all of these advantages and more: they have very high speed (we have measured 2240°/sec), moderate torque (e.g. 0.1 $Nt\text{-}m$), small mass (e.g. 70 gm), small size (e.g. $3 \times 3 \times 3cm^3$) two leads per axis, limited self-braking, and they actuate limbs safely without the use of a limit switch. The new devices have permanent magnet rotors, so there are no brushes or commutation, and no torque ripple.

The Adept series of SCARA robots is one of the most successful commercial applications of DD robot actuators. In the SCARA configuration, the base DD motor is fixed and the elbow motor moves only in a plane orthogonal to gravity, so the load on the base motor is almost constant. This basic design has been implemented by others as well [4]. More anthropomorphic designs required the use of counterweights, or pantograph linkages to connect the elbow with shoulder-mounted motors. The latter configuration is allowed under the definition of "direct drive" that says only that there is no gear reduction between the motor and the joint it actuates. Our definition is more strict: "direct drive" to us means that the motor is physically aligned with the axis it drives.

In addition to the earlier large scale direct drive robot arms, there are several other technologies related to our DD actuators. Six-dof magnetic levitation is possible using Nd-Fe-B magnets, but at present levitated platforms are limited by their small workspace [13]. Magnetic gears based on rare earth magnets are interesting frictionless motion transducers [9]. For pointing applications, the spherical stepper motor [11] is a possible alternative to the SPM, though its pointing precision is limited by the packing density of magnets and coils on a sphere. From

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[2] from the play by Karel Capek, 1921.

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Miniature direct drive rotary actuators[1]

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Abstract

This paper reports the development of direct drive DC motor actuators for miniature robots. The motors are based on Nd-Fe-B rare earth permanent magnets and controlled by low cost microcontrollers. The motors have low friction, small size, high speed, low construction cost, no gear backlash, operate safely without limit switches, have limited self-braking, and generate moderate torque. Significantly, one motor can generate enough torque to lift a second motor of about the same size against the force of gravity, at a distance approximately equal to the size of the motor, without resorting to the use of a counterweight. We demonstrated the feasibility of using these actuators to make a two-link robot finger or leg.

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