6. Concluding Remarks

Following materials have been developed under this project:

- A prototype "Educational Robot:" ED I.
- Manuals: Laboratory Manual and Developer's Manual. Manuals for the `VxWorks`^{tm} based real-time system.
- An undergraduate robotics textbook authored by Li, Murray and Sastry.

The primary benefit to our institution has been through the establishment of a permanent robotics course sequence that is accessible to undergraduates from both New York University and Stevens Institute of Technology. Also, the creation of a multifunctional laboratory has helped us to form a coherent sequence of experiments for many different courses that the student can get involved in with a minimal overhead. Secondarily, it has also helped our research work in robotics and manufacturing, by sharing a common software development platform and by acting as a testbed for some of the miniature actuators developed in an unrelated project.

The primary contribution to the computer science community is through a body of well-trained computer scientists who have a strong hands-on understanding of robotics. Also, over the period of the project, we have invited several visitors from other computer science departments to guide and share our work. This dissemination effort is hoped to influence the way robotics and manufacturing classes are taught currently.

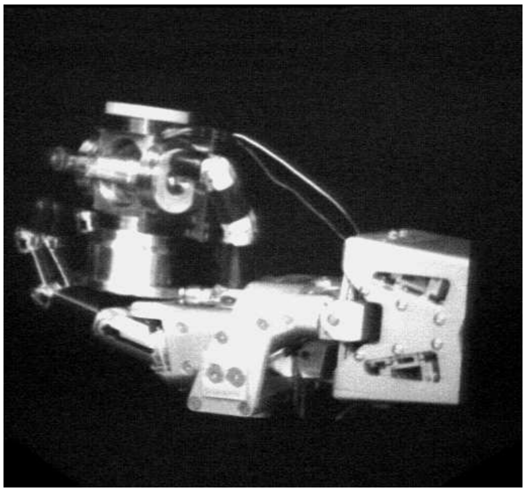

Figure 8: **A direct drive pointing device.**

6.1 The Future

In parallel with the ED I project, we have also explored alternate technologies that are suitable for teaching robotics. One approach has been developing miniature direct drive robots that are ideal for teaching as they are easy to configure (e.g., we have been able to build mobile robots, robot fingers

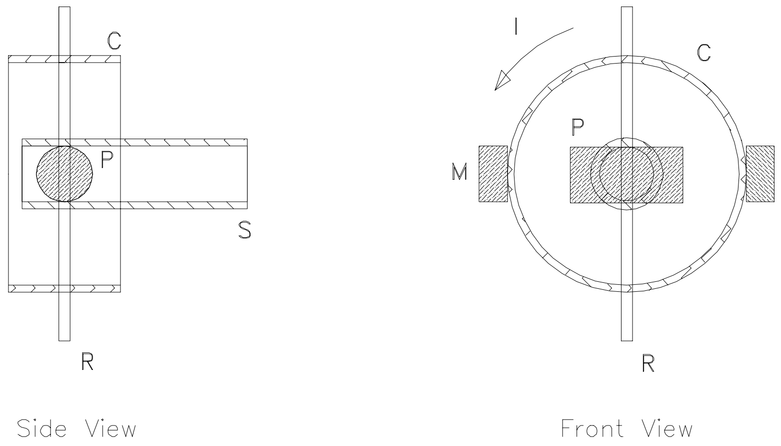

Figure 9: **Principle of direct drive: The motor stator holds a coil C and a rotor bearing R. The rotor consists of a permanent magnet P and a shaft S. Current I in the coil results in motion around the axis R in a direction given by the sign of I. An optional second stator magnet M provides a reference field from which the rotor may be deflected or pointed.**

or miniature arms, grippers and multi-fingered hands from simple parts), they are safe and they are easy to program. Several student projects based on these robots have been carried out under the guidance of Richard Wallace.

The key components are very low cost direct drive DC motor actuators. 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 developed a prototype three link finger direct drive which can exert a force of up to 1.0 Nt at the finger tip (see Figure 8). The finger joints are primitive permanent magnet DC motors consisting of a single stator coil and a single rotor magnet, which provide a means of direct joint torque control by varying current through the coil. The joints of the DD finger contain no gears or transmission mechanism (see Figure 9), which results in very low friction and eliminates gearbox control problems, and facilitates force control strategies such as compliance.

The very low cost (about $10) 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 theory. In particular, some students built a small two link direct drive manipulator. They then related its kinematics, statics and dynamics to the simple two link planar manipulator theory (see e.g. [7, 25]) they learn in class.

In future, we plan to incorporate these robots into the regular class experiments and report our experience.