

Chapter 3

Robot Bodies

Much of what is distinctive about human intelligence is due to the special kinds of knowledge and representation necessary for sensorimotor problem solving with a human body. Among the most distinctive human behavior, the ability to use our hands to manipulate tools and to interact manually with the environment requires an array of cognitive faculties that may not be necessary to solve locomotion tasks alone - bipedal or otherwise. Manual skills require coordinated control of fingers and arms, but frequently engage trunk motions and locomotion. Moreover, fine motor skills rely on the ability to make fine distinctions in tactile, kinesthetic, proprioceptive, and visual percepts.

The discussion surrounding Figure 2.8 in Section 2.3.2 spoke about the subtle biomechanical differences between the human hand and hands of other primates and made the case that these seemingly small differences dramatically improved manual dexterity. The anthropological record suggests that this new hand followed bipedalism in Lucy, but preceded or co-evolved with innovation in the brain as well. Apparently, as the hand changed, new cortical area was devoted to recognizing associations across proprioceptive, haptic, kinesthetic and visual phenomena and to coordinate multiple serial and parallel kinematic chains (Chapter 5).

In this chapter, we will look at machines that have been designed specifically to study *dexterity* using robot hands and arms. Because the biomechanics of muscle influence the dynamic response of our limbs, we will introduce several synthetic analogs of muscle that are used in robot systems. Next, we will look in some detail at mechanical hands and hand/arm systems that provide an experimental framework for studying control issues. These systems can incorporate proprioceptive feedback and tactile sensing capabilities. Many existing platforms include (or depend on) control inputs derived from humans via a teleoperator interface. Visual feedback is a critical part of manual skill in human beings. Regardless of whether the robot is teleoperated or meant to behave autonomously, manual dexterity will require deft control of hand-eye relationships. Therefore, we will review some of the off-the-shelf stereo visual systems that can possibly serve this role.

Our goal is to characterize the ability of important technologies to support a computational study of developmental processes in robots. As we proceed, the discussion will focus more on the physics of sensorimotor

systems. A brief introduction to some of the physical quantities that characterize all moving bodies is provided in Appendix B.1.

3.1 Actuators

Actuators are the physical devices that transform electrical, chemical, or thermal energy into mechanical energy. In this section, commonly used actuators are presented briefly to give the reader some insight into the range of design alternatives underlying dexterous machines. Each choice presents different challenges with respect to power, dynamic range, packaging, and passive properties.

Roboticians have been considering how to exploit the characteristics of various motors/drivetrains to facilitate low-level control of dexterous robots and walking machines. These machines will bump around in the world, like we do, so they can be distinguished by their passive properties - that is, by the intrinsic compliance of the limb. The mechanical *impedance* of a limb is the ratio of the applied force to the mechanical deflection in the limb. In addition to kinematic effects, the mechanical impedance of the robot depends on properties of the actuator and transmission. We will describe these issues analytically when we discuss the DC motor/gearbox combination, since it is the most commonly used robot actuator.

Passive properties involve the limb and its actuators, but do not refer to active control of limb compliance. Active control requires that an external force is measured and compared to a desired force. The difference will be used to compute a limb deflection that approximates the desired limb impedance. One school of thought regarding manipulator design holds that passively compliant (or *backdrivable*) limbs are important for interacting with an uncertain environment. Such a robot will comply naturally to contacts that it did not predict. Moreover, the response of the limb is appropriate regardless of whether a tactile sensor, for instance, was positioned correctly to observe the unexpected bump. Most importantly, a limb that is passively backdrivable can observe a disturbance as a significant and abrupt change in the actuator effort - a motor current for example.

In this section, we will review several traditional actuator technologies as well as a new generation of actuators that are under development for dexterous machines.

3.1.1 Hydraulic Actuators

One of the most common actuator technologies involves the transmission of power using hydraulic fluid. When properly designed and in working order, a hydraulic system - like the brakes in your car - transmits pressure signals at roughly the sonic velocity in the fluid. The fluid is essentially incompressible so work is transmitted from foot pedal to brake pad in a fraction of the time it takes our nervous system to recognize the events that recommend braking.

The stroke of the brake pedal may be several centimeters in order to actuate the brake caliper through millimeters. The mechanical advantage created can apply much greater clamping pressure on the caliper than our foot and leg alone could muster. Moreover, if the motor runs a small compressor, as in cars with power brakes, then caliper forces can be amplified even more. When large compressors provide high pressure hydraulic sources, and when pistons of various sizes create mechanical advantage, hydraulic systems are among the very best actuators in terms of power-to-weight ratio. Significant mechanical advantage means that backdrivability must suffer, however. In the example of the automobile braking system, for instance, to backdrive the brake peddle, we would have to apply huge forces to the brake caliper. As a result, these types of actuators are appropriate when large force amplification is desired at the expense of backdrivability. For example, Figure 3.1 illustrates a backhoe - a device the incorporates hydraulic pistons to dramatically amplify the human user's ability to move earth effectively.



Figure 3.1 *The hydraulic backhoe extends the strength and reach of its human user using high pressure hydraulic actuators.*

To control such large forces, a hydraulic servo valve like that pictured in Figure 3.2 is employed.

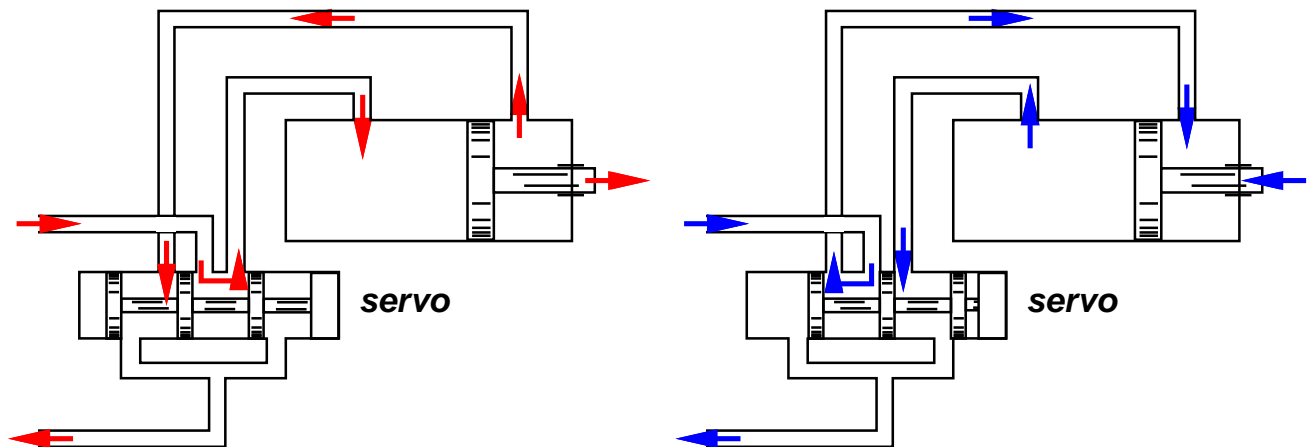


Figure 3.2 *The hydraulic servo valve directs high pressure hydraulic fluid to drive a piston. The flow for extending the linear actuator is illustrated in red, flow for retracting the actuator is shown in blue.*

Servo valves like this can be run by solenoids in a “bang-bang” mode or controlled continuously with high precision linear actuators.

The Sarcos GRLA (for General Large Robot Arm) is illustrated in Figure 3.3. It runs hydraulic actuators at up to 3000 psi to drive a robot arm that is 1.75 meters long from shoulder to wrist. The robot can be driven by an exoskeletal master worn by a human teleoperator. As in the backhoe, the geometrical scale and the work output of the human are amplified dramatically by managing the high-pressure hydraulic fluid flow rather than relying exclusively on human muscle power.



Figure 3.3 *The Sarcos GRLA (General Large Robot Arm)*

This class of actuator can be used in open-loop control frameworks, relying on the human user to close the control loop using vision. This is the way that fork lifts and backhoes are usually configured. Hydraulic actuators can be quite useful in environments where electric motors may not be recommended, like explosive environments. But they can be messy, the servo valves can be quite expensive and they can be expensive to maintain. Hydraulic fluid transmits relatively high frequencies (up to about 5 KHz) and servo valves can reverse the direction of flow in as little as 5 msec. This bandwidth makes it possible to implement clever active controllers on top a passively stiff actuator. For example a small embedded controller can enhance the braking input of a human driver by superimposing a high frequency control input to keep the wheel from skidding as in ABS braking systems.

Nature has devised ways for animals to use hydraulic actuators as well. It has been known for long that spiders cannot extend their legs by activating muscles alone - they generally have no extensor musculature that is adequate for the task. To solve this problem, spiders use their blood as hydraulic fluid. The blood pressures in spiders are typically very high compared to related animals. It is believed that special valves and muscles that compress their forebodies act as actuators for their legs. Some jumping spiders create huge leaps (of up to 10 times their body size) using hydraulic forces created in a specialized fourth pair of legs.

3.1.2 Electric Motors

Electric motors now permeate our lives and are hands-down the most widely used actuator in robotics applications as well. These motors all share the use of electromagnetic fields to transform electrical current into torque. The most common electric motor is the permanent magnet DC motor. They are most efficient at high speeds and, therefore, are often designed to run fast and to reduce the velocity of the output shaft using a gearhead. We will see that this has direct implications on the passive impedance of the actuator.

Stepper Motors

A very common electromagnet actuator is the stepper motor. It uses a programmable stator (the outer ring and four electromagnets in Figure 3.4) to advance a rotor (the innermost element with rigidly placed permanent magnets). The equilibrium position shown in Figure 3.4 (A) is transformed by a sequence of stator controls into three discrete displacements (frames (B), (C), and (D)) in the clockwise direction. This actuation scheme depends on a property of electric motors called “cogging” - when the rotor sees regularly spaced minima in the magnetic field. In continuously controllable DC motors, cogging is considered a bad thing (as we shall discuss later in this Section), but it is the feature of a stepper motor that permits it to be used as an open-loop position control device. The controller simply sequences the programmable electromagnets in the stator so as to count off the right number of discrete rotations. These motors are relatively low torque and if the load inertia is too great or the motor is clocked too quickly, the actual position can slew past setpoints and ruin the motor’s positional accuracy. Moreover, the motor can actually resonate (typically between 50 and 150 *steps/sec*), which could likewise cause the rotor to escape from local magnetic wells and loose track of its angular position.

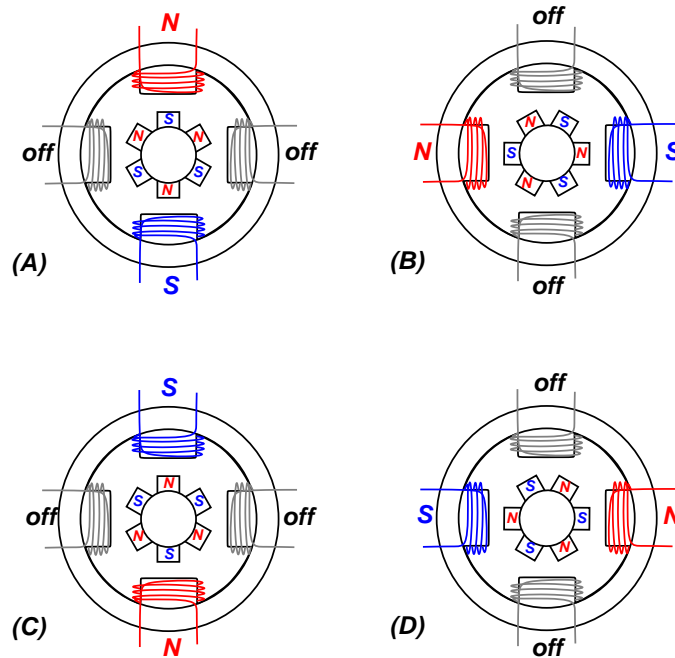


Figure 3.4 The stepper motor provides for accurate position control without the need for feedback.

Permanent Magnet DC Motors

Electrical energy can be transformed into mechanical energy by pushing an electrical charge through the loop (or armature) in the presence of a directed magnetic field. The physics of virtually all electric motors is described in terms of the Lorentz force, $qV \times B$, where q is the electrical charge moving at velocity V through a conductor that is placed in a magnetic field B (Figure 3.5). The force produced is the vector product (or cross product) of current (qV) and magnetic field strength, B , which means that the direction of the Lorentz force is perpendicular to both of these quantities by the right hand rule. Therefore, the conductor in Figure 3.5 will experience a force that is directed into the plane of the paper.

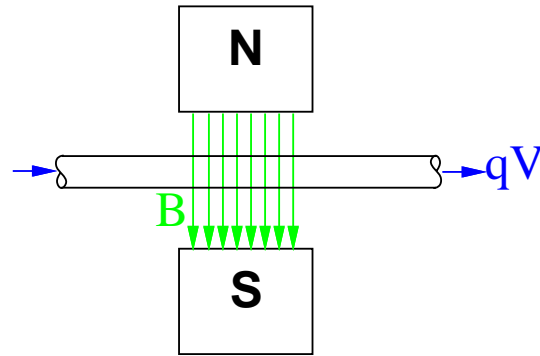


Figure 3.5 A charge q moving along a conductor at velocity V through a magnetic field, B , from north to south magnetic poles.

A particularly popular actuator for robot systems is based on the Lorentz force produced when a current loop is placed in a magnetic field. The force perpendicular to the plane of the rotor in Figure 3.6 causes the conductor loop to revolve around the dotted axis shown. This is the fundamental configuration of the permanent magnet DC motor. Instead of pushing current (electrical energy) into this system to produce a rotation (mechanical energy), if we input mechanical energy to rotate the conductor loop, then this velocity

in the presence of a magnetic field will force create a current output.

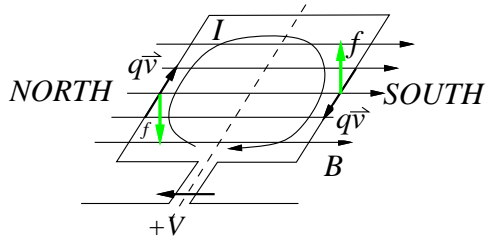


Figure 3.6 A schematic of a single loop in the rotor.

Figure 3.7 shows an induced *current* perpendicular to the axis of the conductor that is the result of the rotor velocity. The right hand rule verifies that the current produced is opposite in direction to the current that generated the motion in the first place. This suggests that the ability of a motor to generate torque will diminish as the motor velocity increases.

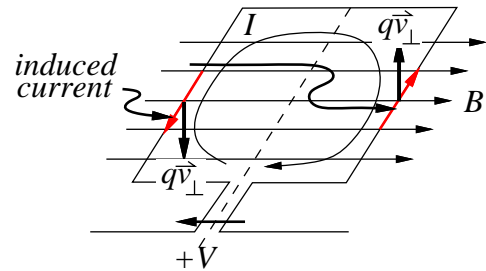


Figure 3.7 Backwards electromotive force due to rotational velocity.

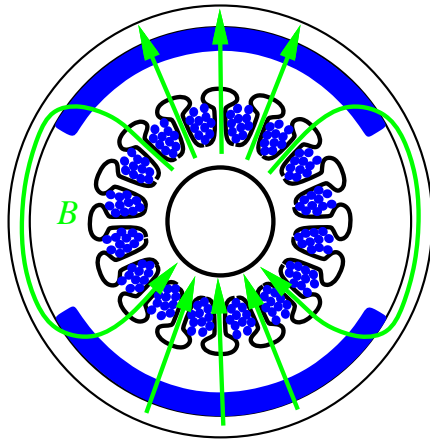


Figure 3.8 The Basic Iron Core DC Motor.

The permanent magnet DC motor is very popular because it is reliable, it has a good power to weight ratio, and can produce relatively large torques. The configuration of the DC motor in Figure 3.8 is extremely reliable and cheap, but inexpensive magnets require that an iron rotor is necessary to columnate the magnet field. Consequently, cheap DC motors can have massive rotors that compromise the motor dynamics. The n -fold rotational symmetry in the rotor also leads to a measurable ripple in the magnet field strength as

A wind turbine works this way - wind energy pushes the conductor through the magnetic field causing electrons to accelerate (i.e., current). In fact, this property effects the DC motor as well since this velocity induced current is in the opposite direction as the current driving the motor. This effect is called a backward electromotive force (or back emf) that is proportional to the angular velocity of the rotor.

This model also suggests that we may expect the steady state torque produced in the motor to be proportional to the amount of current we can push through the loop, and that its steady state velocity will be proportional to the voltage. In practice, this motor runs out of torque as soon as the current loop becomes perpendicular to the magnetic field. At this point, or slightly before, a reversal of the current in the coil can continue to accelerate the rotor in the same direction. This is referred to as commutation and can be accomplished in solid state switching circuits or mechanically using brushes and conducting pads. In this manner, a permanent magnet DC motor can be run continuously in both directions under the management of a closed-loop servo control with position feedback.

the motor rotates. With no current in the coil, cogging produces a discrete set of minimum energy rotor positions - positions that maximize the amount of iron between the north and south poles of the magnets. Stepper motors depend on cogging, but DC motors become difficult to control precisely when cogging effects become too pronounced.

So-called surface wound variants were developed to address this issue that employ more expensive rare earth magnets and eliminate radial fingers on the iron rotor. Consequently, rotor inertia is reduced significantly and cogging can be virtually eliminated at the expense of higher cost. This approach can be extended to produce the *moving coil* DC motor where the coil *is* the rotor. Here the rotor inertia is extremely low and extremely high performance can be achieved. Moreover, these motors can be manufactured in very thin configurations down to 0.02 inches and up to approximately 12 inches in diameter. As result, they are sometimes called printed circuit motors and can be *very* expensive.

DC Motor Electrodynamics

The relationship between torque and current in the motor is a linear function of the number of windings, the magnetic field strength and the current supplied by the motor driver, $\tau = K_t I$, where τ is the rotor torque, K_t is the torque constant for the motor, and I is the current. K_t , the motor's torque constant, is proportional to the number of loops in the motor windings and is published by vendors for use by designers.

Figure 3.9 represents a simple circuit model of the DC motor. A resistance, R , and inductance, L , represents the impedance of the windings.

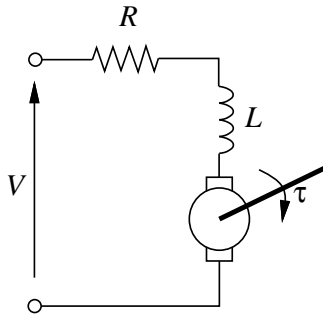


Figure 3.9 *Electrical model of the DC motor.*

The back emf (or “generator” effect mentioned earlier) is also, as it turns out, a linear function of the rotor velocity, $V_b = K_b \dot{\theta}$. The induced current flow induces a backwards voltage potential, V_b , proportional to the angular velocity $\dot{\theta}$ through the constant, K_b . By relating the the mechanical power out $\tau \dot{\theta}$ to the electrical power input VI and resistive losses, we can derive the fact that the torque constant, K_t , is exactly equivalent to the back emf constant, K_b . Consequently in the following, we will refer to both quantities simply as K .

Writing the sum of voltages around the circuit yields:

$$V = IR + L \frac{dI}{dt} + K \dot{\theta} \quad (3.1)$$

Often, the inductance introduced by the motor windings is negligible and can be omitted. Under these circumstances, the loop equation becomes:

$$V \approx IR + K \dot{\theta} \quad (3.2)$$

The dynamic equation of motion for the motor can be derived by summing all the torque applied to the rotor and employing Equation 3.2:

$$\begin{aligned}\sum \tau = J\ddot{\theta} &= KI \\ &= K \left[\frac{V}{R} - \frac{K\dot{\theta}}{R} \right]\end{aligned}$$

Rearranging terms, we get:

$$\ddot{\theta} + \frac{K^2}{JR}\dot{\theta} - \frac{KV}{JR} = 0 \quad (3.3)$$

Equation 3.3 is a *second-order differential equation of motion* that approximates the motor's dynamics. We will see many more examples of second-order dynamics later in Chapter ???. An input voltage applied when $\dot{\theta} = 0$ will produce the maximum freebody acceleration, KV/JR . This acceleration will be diminished as $\dot{\theta}$ increases by the term $(K^2/JR)\dot{\theta}$.

The ability to accelerate is inversely proportional to the rotational moment of inertia, J (Section D.3). Our model lumps the effects of the rotor inertia and the external load. Moreover, motors are most efficient at high speeds, and therefore, gearboxes are often used to reduce the rotational velocity of the load. As we will see, the reduction in the gearbox will also effect the net rotational moment, J , as well.

Gearheads

Consider the compound load depicted in Figure 3.10. The motor produces a torque, KI , that accelerates the entire load consisting of a mass moment of inertia for both the motor, J_M , and the load, J_L , as well as the viscous damping in the motor, B_M , and in the load, B_L . Figure 3.10 shows a pair of gears between the motor and the load that reduces the angular velocity of the load by a factor $\eta < 1$ relative to the motor.

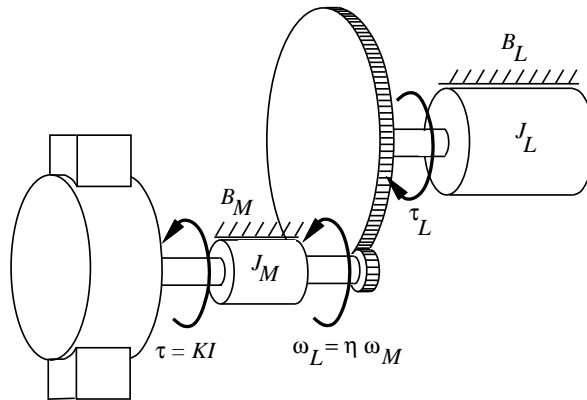


Figure 3.10 *The compound load of the motor-gearhead combination*

If we consider the transmission to be perfectly efficient and linear, then

$$\begin{aligned}\theta_L &= \eta\theta_M, \\ \dot{\theta}_L &= \eta\dot{\theta}_M, \text{ and} \\ \ddot{\theta}_L &= \eta\ddot{\theta}_M\end{aligned}$$

Moreover, if the transmission is perfectly efficient, then the power input is equal to the power output, or

$$\begin{aligned}\tau_{out}\omega_{out} &= \tau_{in}\omega_{in} \\ \tau_{out}(\eta\omega_{in}) &= \tau_{in}\omega_{in} \\ \tau_{out} &= \tau_{in}\frac{1}{\eta}\end{aligned}\tag{3.4}$$

Therefore, the transmission amplifies the output torque; if the reduction $\eta = 0.01$, then the output shaft carries one hundred times the torque at one hundredth the velocity of the input shaft.

We may write the dynamic equation of motion for this compound load by equating the torque derived from Lorentz forces on the rotor with the torques consumed to accelerate the load and dissipated in the viscous friction.

$$\tau = [J_M\ddot{\theta}_M + B_M\dot{\theta}_M] + \eta [J_L\ddot{\theta}_L + B_L\dot{\theta}_L]\tag{3.5}$$

Where the second term is the external load. By using the velocity relationship across the transmission ($\theta_L = \eta\theta_M$), and rearranging terms:

$$\begin{aligned}\tau &= [J_M\ddot{\theta}_M + B_M\dot{\theta}_M] + \eta^2 [J_L\ddot{\theta}_M + B_L\dot{\theta}_M] \\ &= [J_M + \eta^2 J_L] \ddot{\theta}_M + [B_M + \eta^2 B_L] \dot{\theta}_M\end{aligned}$$

The effective inertial load, including the rotor and the external load, is then $J_{eff} = J_M + \eta^2 J_L$ and the corresponding effective viscous load is $B_{eff} = B_M + \eta^2 B_L$. For large reductions (η small) the inertia of the compound load is dominated by the rotor. This is very significant, since the rotor inertia is not dependent on the robot configuration, unlike the load inertia.

We may also wish to determine how much torque is required to *backdrive* the system. That is, how much torque is required *on the load shaft* to accelerate the compound load. This is precisely the same analysis, except that we will reference torque and velocity to the load shaft rather than the motor shaft.

$$\begin{aligned}\tau_{in} &= [J_L\ddot{\theta}_L + B_L\dot{\theta}_L] + \frac{1}{\eta} [J_M\ddot{\theta}_M + B_M\dot{\theta}_M] \\ &= [J_L\ddot{\theta}_L + B_L\dot{\theta}_L] + \frac{1}{\eta^2} [J_M\ddot{\theta}_L + B_M\dot{\theta}_L] \\ &= \left[J_L + \frac{1}{\eta^2} J_M \right] \ddot{\theta}_L + \left[B_L + \frac{1}{\eta^2} B_M \right] \dot{\theta}_L\end{aligned}$$

Therefore, from the perspective of the output shaft, a 100:1 reduction ($\eta = 0.01$) effectively amplifies the rotor inertia 10,000 times! Therefore, actuators with large reductions are passively stiff since the rotor behaves like a massive flywheel. Manipulators that employ gearboxes with large reductions will, therefore,

be insensitive to unexpected contact forces. Even large contact forces on the manipulator can be lost in noise above the background of the dominant inertial forces stored in the motor. As a result, manipulator dynamics are insensitive to external loads - those of the arm itself and unexpected “bumps.” In these situations, compliance to external perturbations can only be accomplished through feedback compensators. This is not how biological limbs behave and we will see that most design for “interaction” achieves passive backdrivability by attempting to eliminate large reductions in the transmission.

3.1.3 Artificial Muscle

So-called “muscle-actuators” introduce a passive impedance that influences limb control. These actuators are usually conceived of in redundant configurations to address robustness and flexibility. Many important applications have become feasible by virtue of the research into non-traditional motors. Shape memory alloys have been used to steer endoscopes during minimally invasive surgery [REF]. They are implanted to assist weakened scleral muscles and to help focus images in the eye (Section 2.3.4) [REF]. In another application, time released medications are delivered from an implantable capsule that dispenses drugs through microscopic holes that are controlled using a soft, gel-like plastic [REF]. One of the most futuristic visions for the application of artificial muscle involves assistive devices for weakened or diseased heart muscles. Some think it is possible that a blanket of contracting artificial muscle could be wrapped around the heart to increase the effectiveness of contractions while a heart patient heals.

There has also been renewed interest in these materials as robot designers search for actuators with the right passive character to address applications that require packing many actuators into smaller and smaller volumes. Integrated hand-arm systems are such an application, and there are many examples of interesting approaches available today. The field is still relatively young. For some artificial muscles under consideration the range of mechanical properties such as the elastic modulus, tensile strength, stress-strain relations, fatigue life, and thermal and electrical conductivity is not yet understood. There are thermodynamic issues such as efficiency, power and force densities, and power limits. Moreover, there are basic engineering concerns such as power supply and delivery, device construction, manufacturing, power transmission, dynamic modelling, control, integration and packaging.

Pneumatic Actuators

One of the oldest theories of muscular movement, dating back to the third century B.C., held that animal spirits, *pneuma*, flowed down nerves to fill muscles and cause contraction [136]. However naive this may seem today, it is interesting to note that one of the most competitive examples of a nontraditional actuator for manual dexterity is driven by air pressure.

Pneumatic actuators use compressed air as the working fluid. Air is inherently elastic at low velocities and as a consequence, these actuators are passively backdrivable and naturally compliant. A 60 – 100 psi reservoir provides a relatively large energy density that can be routed via flexible tubing to the place where mechanical

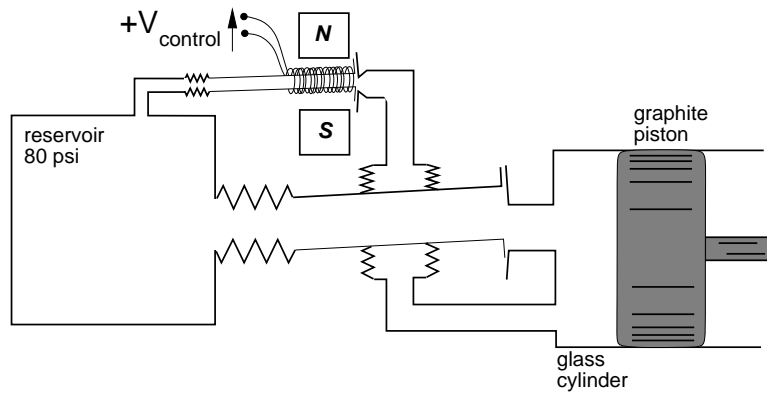


Figure 3.11 *The jet-pipe servo valve for controlling pneumatic actuators.*

work is required. These actuators are often used in antagonistic pairs[85].

Pneumatic Cylinders One way to produce mechanical work from compressed air is to use it to drive a piston. The means of controlling such a device can range from a “bang-bang” form of pneumatic solenoid to a continuously controllable force source (Figure 3.11). This servo valve combines power and speed by controlling a large air flow using a small, light jet-pipe. An input voltage deflects the jet-pipe within a magnetic field to adjust the differential pressure in a bellows that deflects to regulate the pressure in the piston. The result is a high performance, continuous force source. These actuators are relatively light and cheap, with a power to weight ratio in the range of 16:1 and relatively high bandwidth (40 Hz). They can, however, be subject to stiction, they may need additional passive damping for stability, and can be relatively delicate and sensitive to shock. The Utah/MIT dexterous hand (Section 3.2) uses these actuators and servo valves in antagonistic pairs for each of its 16 degrees of freedom.

McKibben Air Muscles Another form of pneumatic actuator is popular for its strength at the expense of the speed of pneumatic cylinders. These actuators use the energy stored in compressed air (in this case, usually 0 – 60 psi) just as the cylinder/piston arrangement does. Air muscles consist of a cylindrical rubber bladder surrounded by a tough plastic netting as illustrated in Figure 3.12. When the bladder expands radially the plastic mesh “scissors” and shortens in length. As a result, the transformation from pressure to force is non-linear. The greatest

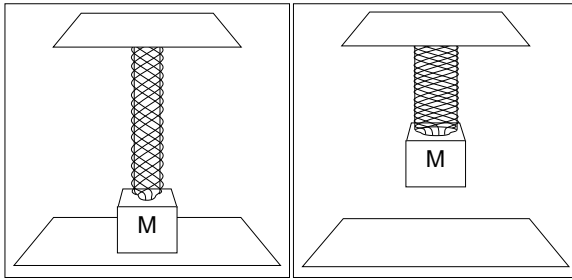


Figure 3.12 *The construction of an Air Muscle*

forces are possible when the muscle is fully elongated and force capacity decreases as the muscle contracts. The simple construction leads to very lightweight actuators that are robust with respect to misalignment, passively compliant and backdrivable, with maximum power-to-weight ratio on the order of 100:1. The range of motion in the actuator is proportional to the length of the bladder - they can contract by up to 40% of their original length - and the overall strength is proportional to the bladder diameter.

Shape Memory Alloys - Muscle Wire

Nickel Titanium (also known as Nitinol) is in the unique class of materials known as shape memory alloys. A crystallographic phase transformation in the material is responsible for its shape memory effect. When heated by an electric current, the alloy undergoes a transition from Martensite to Austenite and the resulting strain in the new crystal structure can be used to cause the filament to deform into a preset shape. Thus Nitinol is a candidate for transformations from thermal energy to mechanical work.

Flexinol[®] is a trade name for small diameter shape memory alloy actuator wires. Individual wires contract like muscles when electrically heated. These alloys contract by 5-7% of their length when heated and can then be easily stretched out again as they cool back to room temperature. The contraction of actuator wires when heated is opposite to the ordinary thermal expansion and is one hundred times larger. Even though the wires are small diameter, they can exert comparatively high forces and are well suited to applications like smart endoscopes that can be steered by the surgeon and stents for use in structural support for veins and arteries that are inserted and positioned in one shape and then left behind in another. Nitinol wire can take a lot of current to heat electrically and responds rather quickly although its cycle (heating-cooling-heating) time is quite slow (on the order of 1 Hz).

Polymers

The mechanical properties of various polymers are sensitive to thermal, electrical, and chemical properties of the environment, which makes these materials candidates for new kinds of actuators. For example, polymer gels can exhibit abrupt volume changes (up to 1000 fold) in response to temperature, pH, and electric fields. These changes are relatively large and reversible. A number of devices have already been constructed that demonstrate the conversion of chemical or electrical energy into mechanical work in this manner with forces up to 100 N/cm^2 and contraction rates on the order of a second [192].

Chemical Gels Chemical gels are intermediate between liquid and solid, consisting of a polymer lattice with an interstitial fluid. There are many examples of natural gels (i.e., Jello and the vitreous humor of the eye (Section 2.3.4) and artificial gells (like polystyrene). The shape and dynamics of a gel are defined by the interaction between the polymer and the fluid. Chemically activated gels are compliant elements that undergo reversible length changes in response to chemical stimuli. Gel dynamics are limited by the diffusion of molecules in the fluid through the polymer lattice. Consequently, the larger the distance that a molecule must migrate, the longer it will take for the material to cycle through full range. Therefore, polyacrylamide gels with a diameter of 1 cm take about 2.5 days to contract, while an artificial muscle formed by 25 μm fibers is reported to contract on the order of a second [30]. In addition, some gels support substantial loads. Polyacrylonitrile-polypyrrole (PAN-PPY) and polyvinylalcohol (PVA) gel fibers generate up to 100 N/cm^2 [30], approximately equal to that of a human muscle.

In one published study, researchers explored using an antagonistic arrangement of polyvinylalcohol muscles to actuate a parallel jaw gripper[23]. The author describes an apparatus in which the artificial muscle is innervated by changes in acetone concentration [23]. However, in general, these devices are still very slow and weak compared to other actuators. Recent research focuses on thin films and groups of small fibers that lead to faster contraction rates and larger forces. A number of fundamental issues remain to be addressed. Foremost among these is the design of an actuator package that can bathe the gel in succession of chemical solutions (acid and base, for example) in a manner that is feasible given the robot mechanism.

Electroactive Polymers Electroactive polymers are plastics that expand or contract in the presence of an electric field. These materials store electrons inside the large molecules that constitute the polymer and allow charge to migrate between molecules. As a result, these polymers can be used as batteries/capacitors. Moreover, as charge is stored, the length of chemical bonds in the polymer is changed which leads to its potential as an artificial muscle. However, electroactive polymers require a considerable amount of voltage to push electrons into the polymer and thus change shape. Most electroactive polymers capable of large shape changes deform to a degree that is proportional the square of voltage. Movements on the order of 10 percent of the original length are attainable.

The dielectric constant is a relative measure of a materials ability to store electric charge - the greater the dielectric constant, the better the material will store an electric charge. Practical electroactive polymers like those used in batteries have dielectric constants of around 5. However, new composite electroactive polymers exhibit dielectric constants as high as 1,000[213] without sacrificing the elasticity of the polymer substrate. These new hybrids may reduce the voltage necessary to induce a movement, which would make these actuators more friendly to other electronic devices.

In one example, researchers made an actuator by using two polypyrrole films to sandwiche an insulating plastic tape[149]. When the sandwiche is polarized by applying a positive voltage to one side of the sandwiche and a negative voltage to the other, the composite bends. Polypyrrole is interesting as an actuator for dextereous robots since its electrical conductivity changes proportionately with pressure. Since actuator sandwiches draw a small amount of current, it is possible that such devices may serve as tactile sensors as

well.

Electro-Rheostatic Gels The main problem with the polymer technologies is their relatively slow response (on the order of seconds). Electrorheological (ER) fluids are materials that change from a liquid to a solid upon application of an electric field. These fluids have a response on the order of a millisecond. A novel approach to artificial muscle utilizes the fast time response of ER fluids and the elasticity of polymeric gels to create a faster artificial muscle [17].

A polymer gel with electrorheological fluid (ERF) stiffens to a solid within 100 msec after the application of an electric field. This approaches the time in which human muscles react to signals from the brain. When subjected to a strong electric field (3000 V/cm), the material “flexes.” Although the system responds at roughly the speed of human muscle, its strength is limited (0.001 N) and the voltages required are very high.

Biological Muscle Proteins

Instead of synthetic polymers, artificial muscle has been fabricated from naturally occurring long chain proteins. Two proteins (actin and myosin), found in biological muscle tissue have been extracted from shellfish and used to produce gels. In muscle tissue, actin and myosin fibers interlock to form a kind of biochemical ratchet (Section 2.3.1). Energy-rich ATP molecules power the attachment, bending, and straightening of the myosin strands.

Researchers have extracted actin and myosin proteins from scallops, and used chemical reactions to link the molecules together into polymeric gels. When a microscopic piece of actin gel was placed against the myosin gel and immersed in an ATP solution the actin gel sprang into motion at about one thousandth of a millimeter per second [101]. Obviously, this approach has a long way to go before it leads to practical actuators if it ever does at all, but the technology may hold promise for implantable assistive technology for human muscle since the body’s immune system might accept implants made from human muscle proteins.

Bucky Tubes

Fullerenes (“Bucky Balls”) and nanotubes (“Bucky Tubes”) are new configurations of graphitic carbon. Carbon nanotubes are very thin and long tubes. Their diameter is only a few nanometers, about the diameter of typical molecules, and they can be up to millimeters in length. Carbon nanotubes increase their length when electrons are pushed into the carbon structure. This effect can be used for electromechanical actuators. The relatively large length change and the high elastic modulus lead to very large forces for carbon nanotube actuators.

Another sandwich configuration has been fabricated to demonstrate the use of carbon nanotubes as actuators [9]. The polarization of the sandwich in this actuator can be accomplished using relatively small voltages,

on the order of ± 1 V. A film of bucky tubes on a tape substrate that is rigid in tension but can bend, will elongate when electrons are introduced and contract when electrons are removed. The laminar composite will bend as a consequence. Carbon nanotubes can, in principle, be used to create macro-, micro-, and nano-scale actuators that are extremely robust to harsh thermal and chemical conditions. Moreover, these new actuators can potentially achieve a greater mechanical stress than any other technology - much more than muscle tissue.

3.1.4 Hybrid Actuators

Poly-Articular Actuators

actuator “tendon” can cross multiple joints, torque is then also coupled to produce couple co-articulated motions and forces - Salisbury hand, WAM

Series Elastic Actuators

Elastic members are placed in series with force sources (can be low-reduction, i.e., near 1:1 actuators - but this is not necessary) capable of energy recovery, tonic, and phasic output.

motivated by low-level muscle dynamics as in Figure 2.7 (Section 2.3.1).

Smart Actuators

high performance DC motors with local computation and load sensing, simulate reference dynamics, coupled-oscillators, Matsuoka oscillators.

Dutch mathematician Christian Huygens (1629-1695) observed that two asynchronous pendulum clocks with slightly different periods hung on the same wall will eventually *entrain* - their beats become synchronous. The weak mechanical coupling expressed through the wall that they each hang on is sufficient to lock their period and phase together.

The phenomenon where a small external forcing function imposes its frequency on a nonlinear oscillator (clock) is called the *entrainment of frequency*. The strength of the coupling must be sufficient, the two must have periods that are close enough, and the zone of entrainment can be influenced by the relative strength of the pendulum (its damping and impulsive “ticker”) relative to the coupling force. The clock can be entrained by harmonics of the endogenous pendulum frequency, i.e., if the coupling force is $1/2$ the pendulum frequency, this may lead to entrainment where the pendulum beats twice for every one beat of the shaker.