

Novel Actuation Methods for High Force Haptics

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1. Introduction

Most haptic devices are intended primarily, if not exclusively, to exchange information with a human operator, and often replace or augment traditional computer displays with backdrivable, force-producing tactile interfaces. This includes popular commercial devices such as the PHANTOM (Massie & Salisbury, 1994) that are typically limited to at most several Newtons of endpoint force capacity, just enough to display simple virtual environments to the operator. Less conventional wearable haptic devices operate differently, but similarly have a low force capacity sufficient only to convey information (e.g. see devices described in (Biggs & Srinivasan, 2002)). By contrast, a class of applications that we refer to as *high force haptics* requires devices that exchange significant forces (and sometimes power) with an operator, often up to and exceeding the force to move limbs or even large fractions of body weight. While achieving high forces, these devices must also present low mechanical endpoint impedance to the operator (i.e. be backdrivable or feel “gentle”) in order to avoid injury and, frequently, to exchange information with the operator by representing virtual environments. We propose the following working definition:

High force haptic device: A mechanical device for physical interaction with humans in one or more degrees of freedom that can actively produce controlled force and motion comparable to the capability of the limbs it interacts with and can be back-driven over the same motion range by forces much less than the capacity of the same limbs.

This definition is not intended to be rigid or comprehensive but to provide a framework to elucidate the challenges of developing devices with high force capacity and low mechanical endpoint impedance capable of rendering virtual environments. “Force” and “motion” are considered here to be generalized quantities that include force and position as well as their derivatives or integrals, which are often important. For instance, velocity is important to accommodate typical limb motion, and the rate of change of force is important to display impact-like experiences. This applies to controlled outputs from the devices as well as to backdriving. “Comparable to” means exceeding $X\%$ of (force and motion capabilities of relevant limbs), where X is as close to 100 as practical – often tens to hundreds of Newtons or more. “Much less than” means less than $Y\%$, where $Y \ll X$; in fact the ratio X/Y is a key measure of high force haptic performance, and maximizing this ratio is the central challenge.

The application of robots to provide sensory-motor physiotherapy is a flagship application of high force haptics, and provides an instructive example of the engineering challenges unique to this emerging area. The ultimate goal is to promote, enhance and accelerate recovery after any injury that affects motor behavior. Common examples include stroke (cerebral vascular accident) (Volpe et al., 2009) and cerebral palsy (Krebs et al., 2009). Scientific and clinical evidence has shown that movement of the affected limbs is a key element of the recovery process. The compromised ability to move that immediately follows injury such as stroke may lead to permanent motor disability if left unaddressed, even though the peripheral neural, muscular and skeletal system is intact, a phenomenon that has been termed “learned non-use” (Taub and Uswatte, 2006; Wolf et al., 2006). In the case of cerebral palsy, unaddressed motor deficits also interfere with a child’s development, leading to severe, permanent motor disability. In contrast, studies (Nudo, 2007) have shown that activity-dependent neural plasticity can offset these degenerative trends and, in some cases, even reverse them.

The process of recovery resembles motor learning (Hogan et al., 2006) though there are notable differences, such as abnormal muscle tone or spasticity, that do not occur in motor learning. Providing a high “dosage” or “intensity” of movement experience (many repetitions) is one of the ways robotic tools may augment conventional physiotherapy. However, repetition alone is not enough: voluntary participation is essential (Volpe et al., 2004). To ensure voluntary participation, the machine must assist only as needed. Even more important, the machine must not suppress any productive movements a patient can make. It must “get out of the way” of appropriate movements while gently resisting inappropriate movements; *guidance* is more important than *assistance* (Krebs et al., 2003). The requirement to provide permissive guidance—encouraging “good” movements while discouraging “bad” movements—is perhaps the most important distinction between therapeutic robotics and assistive technologies such as amputation prostheses, powered orthoses, etc. The latter compensate for a motor deficit; the former attempt to ameliorate it.

This may account for the contrasting results to date with upper-extremity and lower-extremity robotic therapy. Robotic treatment of upper-extremity stroke-related motor disorders has consistently succeeded, typically providing more than twice the benefit of conventional therapy alone (Kwakkel et al., 2007; Prange et al., 2006). It has even proven beneficial for stroke survivors in the “chronic phase”, many years after injury, when all recovery had apparently ceased. In contrast, clinical studies to date have shown that robotic treatment of lower-extremity motor disorders is about half as effective as conventional approaches (Hidler et al., 2009; Hornby et al., 2008). This may be due, in part, to the relatively smaller number of clinical studies but it may also be due to the fact that early lower-extremity therapy robots were designed to impose motion rather than provide guidance (Neckel et al., 2008; Israel et al., 2006). More recent designs for locomotor therapy have begun to address the formidable challenge of providing highly “back-drivable” (low impedance) interaction (Roy et al., 2009; Veneman et al., 2007) while supporting substantial fractions of body weight (Roberts, 2004).

Additional examples of high force haptic applications include human-assistive and exoskeletal devices (Guizzo & Goldstein, 2005; Kazerooni & Guo, 1993), physically cooperative man-machine systems (Peshkin et al., 2001) and similar applications. Like these

other high force haptic devices, successful therapy robots must simultaneously embody a formidable set of capabilities, usually including all of the following:

- 1) The capacity to deliver large forces, sufficient to move human limbs actively against strong muscular effort by the subject (e.g. due to abnormal tone), and in some cases (e.g. balance & locomotion) to support substantial fractions of body weight
- 2) The ability to represent controlled, virtual environments (e.g. virtual walls or springs), in order to provide physical guidance, assistance (but only as needed), protection from force spikes, resistance (e.g. for strength training), and to communicate information
- 3) The ability to be backdriven, to avoid inhibiting a patient or operator's attempts to move or observe the outcomes of these efforts
- 4) Large workspaces, up to a cubic meter or more, to accommodate the range of motion of human limbs
- 5) A number and arrangement of degrees of freedom compatible with large and small scale human movement
- 6) Guaranteed stability and safety while exchanging significant force and power with non-expert, impaired and unpredictable human subjects

In contrast, most existing haptic and robotic systems embody some subset of this list of features, but not all. More specifically, most existing robotic devices have either low force capacity with low mechanical impedance or high force capacity with high intrinsic impedance. Achieving this full set of features is a formidable engineering challenge that is limited by existing actuator and control technologies.

In this chapter we provide an overview of the tools available to address the high force haptic challenge by summarizing and critiquing available techniques, discussing several advanced approaches that show promise, and presenting a novel actuator architecture that may provide a superior solution for certain high force haptic applications. In the next section performance and stability considerations for high force haptic systems are summarized. Section 3 discusses the utility of available actuator and interaction control technologies for high force haptics. Section 4 introduces a novel hybrid actuator architecture that circumvents the fundamental limitations plaguing actuators for high force haptics. Analysis and experimental validation of a simple example are included. Concluding remarks are provided in Section 5. The prior and novel work presented here provides the foundation of a nascent toolkit of methods to design and build effective high force haptic machines.

2. Performance and Stability of High Force Haptic Systems

Haptic systems consist of a union between an engineered mechanical system (a haptic device) and a human operator. While haptic devices and robots both include actuators, sensors, control software, and mechanisms designed to achieve particular kinematics, haptics differ from most common robots because the physical coupling to an unknown and unpredictable human subject has a strong influence, by design, on the system's behavior. From a control standpoint, this significantly influences how both performance and stability are understood. For a traditional motion-controlled robotic system, performance is measured by the system's ability to track trajectories or move to locations in space. Stability is determined by the robot and its controller, possibly with consideration of static payloads.

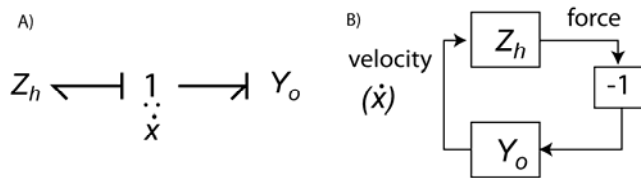


Fig. 1. Physical interaction between a haptic device and human operator, represented by port functions. A) Bond graph representation. B) Block diagram representation.

For haptic devices, the considerations are quite different. Rather than control motion, haptic devices are intended to represent virtual objects, meaning that they must convincingly transition between apparent free motion and apparent contact with objects with specified physical properties. Performance is best understood as the quality of the virtual environment, or the “feel” presented to the operator by the haptic device. Furthermore, the operator is a dynamic system that is physically coupled to the haptic device. A critical distinction between typical robots and haptic devices is as follows: In robotic systems, performance and stability are both properties of the robot. In haptic systems, including high force haptic systems, performance is solely a property of the haptic device, while stability depends on *both* the human operator and the haptic device. This indicates that traditional methods of analyzing the performance and stability of robotic systems are not ideally suited to analyzing high force haptic systems.

A proven method for analyzing physically coupled systems uses *port functions* to model energy flow between systems at physical points of interaction, or *power ports* (Hogan & Buerger, 2005). Port functions define the behavior of each system in terms of the relationship between conjugate “effort” and “flow” power variables, depending on causality. Impedance (Z) provides the effort output in response to a flow input, while admittance (Y) is the inverse. In the mechanical domain, force (or torque) is the effort variable while velocity (or angular velocity) is the flow variable. Figure 1 shows two interacting systems: a haptic system represented by its impedance (Z_h) and a human operator represented by its admittance (Y_o). In this representation, the direction of power flow is purely a matter of convention; it is depicted as positive into each system. No assumption is required regarding the magnitude of either the impedance or admittance port functions.

The performance of the haptic device can be derived from its port impedance, which can be loosely thought of as dynamic stiffness, can be linear or nonlinear, and includes stiffness, inertia, friction and other dynamic behaviors, e.g. modes of vibration. Specifically, the intended feel at the interface can be represented by some virtual environment, which can be quantified by some impedance function, which may be linear or nonlinear and may vary in space and time. Performance can then be quantified by measuring the difference between the target impedance (or the target virtual environment) and that achieved in hardware. Phenomena that may detract from this performance can include unwanted inertia, compliance, or friction as well as unhelpful or distracting vibrations. This is consistent with the definitions of “fidelity” found in the haptics literature. A related performance metric, “transparency,” generally refers to only the quality of the haptic hardware and its ability to minimize or disguise parasitic dynamics that are not part of the software-generated virtual environment (Carignan & Cleary, 2000). Specific high force haptic applications may benefit

from differing performance metrics based on the port impedance. For instance, when port impedance is linear or can be approximated as such, performance can be defined as a cost function C that consists of a frequency-weighted integral of the difference between the magnitudes of the actual (Z) and target (Z_{target}) impedance functions (normalized to 1 Ns/m to make the argument of the log dimensionless), yielding a single number to minimize:

$$C = \int_{\omega_0}^{\omega_1} W(\omega) \left| \log|Z(j\omega)| - \log|Z_{target}(j\omega)| \right| d\omega \quad (1)$$

The weighting function W can be used to emphasize general frequency regions of interest or particular features such as precise resonances, and ω can be replaced with its log to achieve logarithmic frequency weighting. In other cases more insight may be gained by quantifying performance in terms of intuitively familiar physical quantities such as the apparent inertia, Coulomb friction, etc. Metrics may be more complex when the port impedance is nonlinear, and performance can also be measured in the time domain, based on the desired and actual response to particular excitation at the port. Regardless of the specific metric used, we contend that performance of a high force haptic system derives from the port behavior as quantified by the mechanical impedance.

In contrast, the stability of an interactive system like that shown in figure 1 depends on the dynamic properties of both coupled ports. If both port functions are linear, the characteristic polynomial of the system in Fig. 1B is

$$1 + Z_h Y_o. \quad (2)$$

The stability of the coupled system, termed *coupled stability* (Colgate & Hogan, 1988), is determined by the real part of the roots of this quantity. Clearly, the dynamics of the human operator contribute fundamentally to total system stability. This fact, taken with the previous paragraph, highlights an important distinction between physically interactive systems and servo controlled systems. In linear servo controlled systems, the same characteristic equation determines closed-loop stability and influences performance (in terms of frequency response, time response, etc.) In linear interactive systems, performance is dictated by the port function of the haptic system alone (Z_h) while stability is determined by equation 2, which includes properties of the operator as well (Buerger & Hogan, 2007).

Because the dynamic properties of the operator cannot be controlled by the haptic system designer, guaranteeing coupled stability poses a challenge. One valuable concept for understanding coupled system stability is *passivity*. A power port with a passive port function cannot release more energy than has been put into it. For the linear time-invariant case, a system defined by the linear 1-port impedance function $Z_p(s)$ is passive iff:

1. $Z_p(s)$ has no poles in the right half plane
2. Any imaginary poles of $Z_p(s)$ are simple, and have positive real residues
3. $\text{Re}(Z_p(j\omega)) \geq 0$ (3)

Such a port function has phase between -90° and $+90^\circ$ for all frequencies. Colgate showed that when two passive port functions are coupled together as in Fig. 1, the total open-loop phase must be between -180° and $+180^\circ$ at all frequencies, and the Nyquist stability criterion cannot be violated, so the coupled pair is guaranteed to be stable (Colgate & Hogan, 1988).

This is consistent with the energy properties of passive ports. If two passive ports are coupled, neither can generate energy indefinitely, and therefore stability is guaranteed. Because it is energy based, this extraordinarily powerful result works for linear and nonlinear systems (for nonlinear extensions, see e.g. (Wyatt et al., 1981)), and applies (perhaps with fine tuning) to all physical domains. To the extent that humans can be assumed to act as passive mechanical systems at their ports of interaction, passivity provides a powerful stability metric for high force haptics. While this has not been conclusively proven, given the complexities of the neuromuscular system, available empirical results and theory strongly suggest that this is indeed the case (Hogan, 1989). Unfortunately, making high force haptic systems passive can often limit performance. Certain simple control laws can preserve passivity, but given the limitations of available actuator hardware, these simple controllers often can not achieve adequate performance at the haptic system port. These challenges are reviewed in the next section.

3. Actuator and Control Technology for High Force Haptic Systems

Ideal high force haptic systems would achieve high forces while representing port impedance ranging from near zero to near infinite stiffness, friction and inertia, while guaranteeing passivity and coupled stability. Actuators for these idealized systems would require similar properties, plus some additional properties (e.g. low mass), depending on the system configuration. In this section we assess the value of various technologies in approaching this ideal, first by seeking a purely physical solution in the form of actuators effective at human scales (tens to hundreds of N, cm to m motions, frequencies less than 10 Hz), then by exploring the benefits of available advanced control methods.

3.1 Classical Actuator Technologies for High Force Haptics

Electromagnetic actuators can represent desired forces with extremely high fidelity when used in direct drive configurations. Friction can be extraordinarily low, especially at the low frequencies typical of interaction with humans (at higher frequencies eddy current or IR losses create drag). With the low intrinsic impedance of these actuators, simple and robust control algorithms, discussed below, may be used to provide a stiff interface and to preserve passivity. The main drawback is limited force density (Hollerbach et al., 1992), meaning that high forces lead to large, heavy actuators. Electromagnetic actuators are easy to use, and in many cases systems can be successfully designed to meet certain limited requirements in spite of force density limitations. An example is the MIT-MANUS robot for upper-limb physical therapy, which uses direct-drive rotary motors with a two-DOF (degree of freedom) planar closed-chain configuration that allows both actuators to remain stationary (Krebs et al., 2004). Other devices are effective due to very small translational workspaces (Berkelman et al., 1996). The force density limitation is far more difficult to overcome for open-chain serial systems. If the actuator for DOF #1 is carried by DOF #2, as is common for serial robot arms, then the mass of the actuator not only increases the force required for the DOF #2 actuator, but also adds to the endpoint inertia of that DOF. This problem emerges for most non-planar mechanisms, and is therefore very common. As forces increase, carrying the full weight of direct drive actuators rapidly becomes prohibitive. When rotary motors cannot be used, large motions pose an additional problem, as the high mass per unit force increases nearly linearly with range of motion.

An obvious way to improve the force density of electromagnetic or other actuators is to add gearing. This approach makes carrying actuators in a serial mechanism feasible and is used extensively in robots. Unfortunately a gear train compromises endpoint impedance, increasing the actuator's apparent inertia and friction due to eddy current or IR losses, as observed at the endpoint, by the square of the gear ratio. Coulomb friction and stiction in the actuator are amplified linearly by the gear ratio. Furthermore, the gear train adds its own friction, inertia and backlash. As a result, even when transmissions are designed explicitly to minimize friction, high impedance is difficult to escape (Buerger et al., 2001). While some applications are amenable to modest gear ratios (typically less than about 5:1), larger gear ratios rapidly lead to unacceptable levels of reflected inertia and friction. The failure of gearing to solve the underlying force density problem in high force haptics distinguishes this problem from most robotics, where gearing is generally very successful.

The most significant problem with using direct-drive electromagnetic actuators for high force haptics is the need to carry their substantial mass when complex or serial mechanisms are used. Mechanical transmissions such as cables, belts, tapes and rods offer a potential opportunity to keep the actuators stationary or nearly stationary, in some robot configurations, while transmitting their force, motion and impedance properties to the interaction port. Cable transmissions, in particular, have been elegantly and cleverly designed to achieve reasonable force and impedance capabilities in high-DOF serial arms, e.g. the WAM arm (Townsend & Guertin, 1999). The complexity of the mechanisms that enable the WAM underscore the fact that routing of mechanical transmission members can be extremely challenging. When actuators for multiple DOFs of a serial mechanism are mounted at the base, the transmission elements for one or more DOFs must pass through or around other joint(s). This presents an extreme packaging challenge as the number of DOFs grows, and this challenge is compounded by the fact that fixed separation must generally be maintained between transmission nodes (e.g. between pulleys in a cable system). Cables, belts and transmission tapes must be held in tension, requiring tight, deterministic coupling between the actuators and the intermediate and terminal joints that they actuate, even as the intermediate joints are independently actuated. These flexible members also tend to introduce problematic dynamic resonances (a "guitar-string" effect) and can severely limit bandwidth. Transmission rods can be made more rigid, but present an even more difficult plumbing challenge, as the gears that mate adjacent rods must be kept in tightly controlled contact. In certain configurations, mechanical transmissions can offer an acceptable high force haptic solution, and thus represent an important tool. However, for other applications their limitations are insurmountable, and other options must be sought.

Appealingly, hydraulic actuators can achieve force densities at least an order of magnitude better than ungeared electromagnetic motors (Hollerbach et al., 1992). Because the working fluid is nominally incompressible, hydraulics can achieve very high stiffness relative to humans. Pressure sources and valves can be located remotely, with force and motion coupled to the interaction port through flexible tubing, which can be routed with greater flexibility than mechanical transmission elements. In spite of these apparent advantages hydraulics have been little-used for haptic interfaces (with some exceptions, e.g. see (Kazerooni & Guo, 1993, Lee & Ryu, 2008)). This is because the operation of conventional servovalves causes hydraulic actuators to have high intrinsic impedance, and in fact generally to be non-backdrivable. Hydraulic actuators rely on nonzero valve impedance to

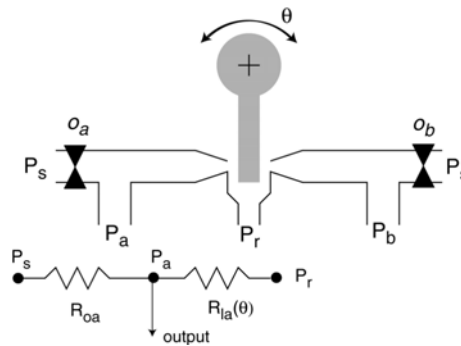


Fig. 2. Schematic of flapper servovalve, with resistor model of left half.

regulate output, placing a lower limit on the output impedance. The fundamental nature of this limit can be demonstrated by considering a typical pressure control valve design.

A servohydraulic system includes a high-pressure energy source, usually controlled to produce nominally constant pressure P_s , and a servovalve connected to a control system that meters the flow (or pressure, depending on the valve design and control structure) to the actuator, where energy is converted to mechanical energy. The servovalve determines the mechanical characteristics of the output, including force or motion as well as the mechanical impedance. A common valve architecture for pressure regulation is the flapper valve, shown schematically in Fig. 2 (jet-pipes offer a different configuration subject to largely similar tradeoffs). The flapper configuration is used, for example, as the first stage of the Moog Series 15 pressure control valves (www.moog.com). The output of this valve is the differential pressure ($P_a - P_b$). Two streams of fluid from the high-pressure source P_s push in opposite directions against the flapper, which is attached to the rotor. Both fluid streams then drip to the return at pressure P_r . The flapper rotates to partially restrict one side and raise the fluid pressure in that branch. For the change in fluid resistance at the flapper to have an impact on P_a and P_b , each side of the valve must be separated from P_s by an orifice (o_a and o_b). Unfortunately, any fluid supplied to the load must pass through one of these orifices, increasing the impedance and degrading the valve's quality as a pressure source.

This can be seen if the left half of the valve is modeled as a pair of fluid resistors, as shown below the schematic. The input orifice is modeled as the resistor R_{0a} , and the flapper opening is modeled as the resistor $R_{la}(\theta)$, which creates a pressure drop between P_a and the return pressure P_r and depends on the rotor angular position θ . If $R_{0a}=0$, then the output pressure $P_a = P_s$, and the actuated flapper has no effect on output. If a single fixed rotor position $\theta = \theta_0$ is considered, $R_{la} = R_{la}(\theta_0)$. Deriving the output impedance $Z_a = P_a / Q_a$, where Q_a is the volumetric output flow rate, produces:

$$Z_a = \frac{R_{0a} R_{la}}{R_{0a} + R_{la}} \quad (4)$$

A pure pressure source would have $Z_a = 0$. If R_{0a} is too small, then changes in $R_{la}(\theta)$ have little effect on the output pressure P_a , and the valve will not function. Z_a can be made small by minimizing R_{la} . However, the total valve output impedance is:

$$Z = Z_a + Z_b \quad (5)$$

where Z_b is the port impedance for the other side of the valve, and has the same form as Eq. (4). But $R_{lb}(\theta)$ increases when $R_{la}(\theta)$ decreases, so the only way for the total output impedance to be low is for both flapper resistances to be low. This would allow substantial leakage through the flapper and would significantly reduce the output pressure. To achieve high output pressure requires amplification in a second stage (as in the Moog series 15 valve). The problems with this amplifier are twofold: first, even if it operates perfectly, it amplifies the impedance of the first stage at the endpoint by acting as a gear mechanism (hydraulic gearing is analogous to mechanical gearing); and second, it introduces more small orifices through which the fluid must flow. Enlarging the orifices in both valve stages simply produces a leaky valve, increasing power consumption and reducing efficiency. Thus without pressure feedback, the only way to avoid high impedance is with substantial leakage flow, which increases compressor size. Given the stringent impedance requirements of high force haptics, the leaky valve approach is generally impractical. High impedance in the valve is directly related to the ability generate output pressure, and cannot be eliminated. Furthermore, sliding cylinder seals represent another source of unwanted friction that can be challenging to avoid, particularly if operating at high pressures. Narrow pressure lines also contribute viscous damping and inertia. Another disadvantage of hydraulics is that at high pressures, safety risks can arise if lines rupture; however, the modest forces (by hydraulic standards) required for human interaction mitigate this hazard. Finally, the compressors needed for servohydraulic systems are usually heavy and noisy and therefore problematic for close proximity to human subjects. In section 4 of this chapter, we argue that in spite of these limitations, the force density advantage of hydraulics warrants further consideration in different configurations for high force haptics, and we present an architecture that circumvents the high-impedance servovalve challenge.

Pneumatic actuators are also capable of high force densities (Hollerbach et al., 1992) and provide behaviors unique among actuator technologies. While regulators that control gas pressure rely on flow restriction, much like hydraulic servovalves, low impedance is readily achieved due to the compressibility of the working fluid. Indeed gas compressibility presents one avenue to modulate the endpoint impedance, by directly manipulating the properties of the enclosed volume of gas in the actuator. However, representing high stiffness requires high pressure, and transitioning from low to high stiffness (e.g. to represent a virtual wall) requires rapid pressure changes. This can be understood by considering the simple example of a closed cylinder in compression due to force from a piston with cross-sectional area A , shown in Fig. 3. For simplicity isothermal conditions are assumed. Adiabatic conditions yield similar conclusions. Behavior at the port of interaction with the operator is characterized by the applied force F and displacement x . The gas in the cylinder is at the absolute pressure P , and the specific gas constant R and temperature T are fixed, while the volume V varies with x . P_{amb} denotes ambient pressure. A mass m of an ideal gas with molar mass M , is contained in the cylinder. The ideal gas law for this volume is:

$$PV = \frac{m}{M} RT \quad (6)$$

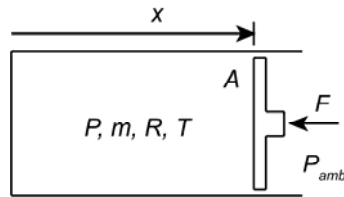


Fig. 3. Schematic of an ideal gas under isothermal compression in a piston-cylinder.

Pressure consists of ambient plus that due to the applied force:

$$P = \frac{F}{A} + P_{amb} \quad (7)$$

Substituting $V=Ax$ and eq. (7) into eq. (6) and rearranging produces:

$$F = \frac{RT}{M} \frac{m}{x} - P_{amb} A \quad (8)$$

Differentiating produces the stiffness:

$$\frac{dF}{dx} = -\frac{RT}{M} \frac{m}{x^2} \quad (9)$$

For fixed (or nearly fixed) x , for example when traversing a virtual wall, stiffness is proportional to the enclosed mass. To simulate a virtual wall with stiffness 100 times greater inside the wall than out purely by manipulating the properties of the enclosed fluid requires increasing the enclosed mass by a factor of 100 within the period of simulated contact with the wall. From eq. (6), this means that the pressure also must increase 100-fold. (For a real implementation, something must also offset the force due to increased pressure, usually a pressure against the other face of the piston). Thus discrete virtual environment features such as virtual walls are extremely difficult and inefficient to implement in this way. Another problem shown by eq. (9) is that stiffness is highly nonlinear in x , meaning the pressure must also be varied to maintain linear stiffness, if that is desired. An alternative approach would be to always operate at high pressures, keeping the transmission stiff, and modulating impedance at the valve source. Unfortunately this presents the same high intrinsic impedance challenge described in detail above for hydraulics. Pneumatic actuators are notoriously difficult to control, and the additional challenges of high force haptics exacerbate the problems. The fluid dynamics of pneumatic actuators are also forbidding for implementing closed-loop control using a regulator to respond to measured endpoint forces. Venting can be used to eliminate resistance from the gas, but this can be quite inefficient. Finally, compressed gas stores orders of magnitude more energy than liquids at the same pressures, and this can raise potential safety concerns. In spite of their challenges, pneumatic actuators have been proposed for certain haptic and high force haptic applications where their intrinsic compliance can be beneficial, including exoskeletal devices (Tressler et al., 2002) and other devices employing pneumatic muscles (Tondou & Lopez, 2000).

3.2 Interaction Control

Physical interaction requires control strategies that differ significantly from the more common position or velocity servo problems. Because of the unique characteristics of physical interaction described above, the prevailing approach is explicitly to regulate dynamic behavior at the port(s) of interaction, e.g. by using *impedance control* (Hogan, 1985). The most straightforward embodiment of this theory, termed simple impedance control, uses motion feedback with torque- or force-producing actuators to implement virtual dynamics on low-impedance hardware. Proportional position feedback produces virtual stiffness, and proportional velocity feedback (or derivative position feedback) produces virtual viscous damping. If implemented ideally with positive gains and co-located sensors and actuators, the result is passive port impedance (Hogan & Buerger, 2005). This approach is powerful, robust and easily implemented, and has been applied successfully (Krebs et al., 2004). Its major limitation is the need for low-impedance hardware. Simple impedance control can do nothing to counteract inertia and friction in the physical system. Thus while simple impedance control can effectively stabilize interaction by guaranteeing passivity, it can do little to address the limitations of actuator technology discussed in the previous section, providing significant motivation for the alternative techniques discussed here.

A class of control methods has been developed that uses measured forces (torques) at the port of interaction to close a feedback loop and expand the range of apparent dynamics that can be presented. This approach has the potential to mask the physical properties of the hardware, presenting a desired dynamic response at the port of interaction that closely tracks target dynamics derived independent of the physical hardware. For instance, the apparent inertia and friction can be reduced below the physical values by using the actuators to drive the device in the direction of applied force. When the target impedance is zero, this is termed force control. Unfortunately this approach seriously threatens coupled stability; in fact passivity is lost whenever the apparent inertia is reduced by more than a factor of two below the physical inertia (Colgate & Hogan, 1988, Newman, 1992). Natural admittance control exploits the fact that loss of passivity derives from reducing the apparent inertia, rather than the friction. This method provides a means of theoretically ensuring passivity while aggressively reducing the apparent friction well below the physical level by keeping the inertia at a level that ensures passivity (Newman, 1992). This approach can dramatically improve feel by virtually eliminating static friction, but cannot mitigate high levels of physical inertia, which are particularly common in geared actuator systems.

An alternative approach recognizes that passivity, though sufficient to stabilize interaction with human subjects, is not necessary. Passivity ensures stability when coupled to a wide range of environments including large inertial loads, kinematic constraints, highly nonlinear frictional contact, etc. On the other hand, the dynamic characteristics of human limbs are considerably more limited, even as they vary in time, configuration and across subjects. Port stability can be posited as a robust stability problem with conservative bounding values used for operator dynamic properties, and robust control methods can be used to shape the dynamics of the force feedback control loop to maximize performance (by minimizing impedance error) while guaranteeing coupled stability (Buerger & Hogan, 2007).

3.3 Advanced actuators

In spite of significant progress in advanced interaction control, achieving all six required characteristics of high force haptic devices listed in section 1 remains a persistent challenge, particularly for complex and high-DOF devices. Several recent advances in actuator development offer promising future alternatives for the high force haptic designer's toolbox.

Goldfarb has described monopropellant-powered actuators that chemically generate gas to produce pressure, and force output (Goldfarb et al., 2003). This approach dramatically improves energy density and eliminates the need for a compressor. However, force and impedance properties—and limitations—appear to be fundamentally similar to those of compressed-air systems. In particular, rapid changes of stiffness (to simulate contacting a surface) require high mass flow rates. Dramatic thermal changes would also impact endpoint impedance. In the authors' opinion, this approach seems quite promising, though as yet unproven for high force haptics.

Series elastic actuators, which include compliant members placed between high-impedance source actuators and the environment and use force feedback control, can achieve high force-density and low impedance (Pratt & Williamson, 1995). The elastic element provides several advantages for certain applications, but does not guarantee passivity, and a careful tuning process is generally required to achieve stability. This is problematic when interacting with variable, unpredictable humans. An alternative design method that includes carefully controlled physical damping in conjunction with natural admittance control can theoretically guarantee passivity (Dohring & Newman, 2002). Generally, the more aggressive the reduction of apparent impedance from the physical actuator level, the softer the compliant element must be. This limits the utility of this approach by limiting achievable stiffness. Still, carefully designed series dynamics are an important tool.

Research into electroactive and dielectric polymers has shown potential for high achievable stresses. These muscle-like materials could one day produce effective high force haptic actuators, but have not yet been shown to scale up to the forces needed (Bar-Cohen, 2004).

To the best of our knowledge, no existing actuator technology or control strategy provides a comprehensive solution for high force haptics. Additional tools are needed to improve the tradeoffs between force capacity, DOFs, workspace size, interface fidelity, and coupled stability. An alternative way of evaluating the potential of major human-scale actuator technologies is by available stress, which is strongly related to force density. The force output of electromagnetic actuators is limited by the shear stress in the air gap between moving and stationary components, which is typically tens of pounds per square inch (psi). Pneumatic actuators can achieve hundreds of psi but rapidly introduce hazards as pressure is elevated, due to high levels of stored energy. By contrast, hydraulic actuators routinely achieve thousands of psi (McBean & Breazeal, 2004). This fundamental promise warrants a second look at hydraulics to see if the underlying high impedance of servovalves can be avoided, and if the tradeoffs between the six criteria listed in section 1 can be improved.

4. Hybrid hydraulic actuators for high force haptics

Among actuator technologies available at the human scale, hydraulic actuators are alone in offering high force density, high stiffness, and flexible connectivity between power sources and the interaction port. Their main drawback is high impedance, which derives primarily from servovalves, and because of this they have been little-used for haptic interfaces. By contrast, electromagnetic actuators are widely used for haptics due to their favorable force and impedance behavior, but suffer from dramatically inferior force density. A hydraulic actuator capable of controlling pressure with low impedance rather than a high impedance servovalve would be a powerful development. We have investigated a hybrid architecture for actuators that exploits the benefits of both hydraulic and electromagnetic actuation while circumventing the weaknesses of each. In this design, sketched in Fig. 4, a hydraulic element is used purely as a transmission, while a remotely-located source actuator provides force and motion, and dictates the representation of the virtual environment. The hydraulic transmission is stiff in the direction of actuation but is embodied in flexible tubing, such that motion of the interaction port is decoupled from motion of the source actuator, and the source actuator may remain stationary. Critically, this architecture obviates the need for a hydraulic servovalve, eliminating the main cause of high impedance. The hydraulic transmission is analogous to a mechanical transmission but, unlike cables, tapes or rods, does not require a deterministic coupling between source and interaction port locations. This architecture also enables the use of effective source actuators, particularly direct-drive electromagnetic actuators, that can provide favorable force, motion and impedance properties. The source actuator can have large mass, because it need not move.

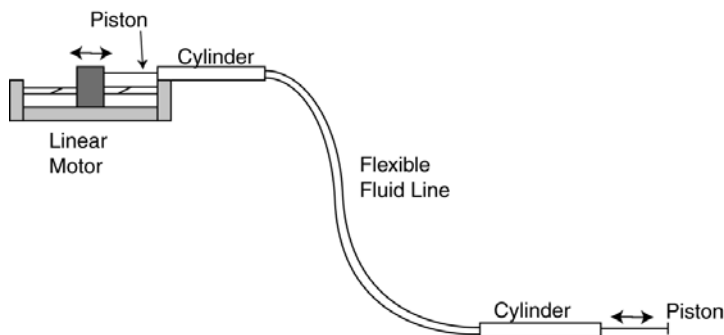


Fig. 4. Schematic of linear actuation scheme with fluid transmission.

While this proposed architecture can dramatically reduce endpoint mass, in its simplest form it actually increases the total system mass when compared to using only direct drive electromagnetic actuators. (The hydraulic transmission would be unnecessary if the actuator was connected directly to the endpoint.) Total mass is critically important for some applications (e.g. fully mobile exoskeletons), and this approach may not be suitable for those. However, in many cases the *placement* of mass is of equal or greater importance than total mass. Therapeutic robots, for instance, may tolerate being tethered to a stationary or independently mobile collection of heavy components, e.g. for power (Roberts, 2004). On the other hand, the absence of a compressor may lead to a lower system mass than a pure

hydraulic system. This passive hydraulic architecture decouples a portion of the drivetrain from the mobile interaction port and conducts energy to it in hydraulic, not electrical, form.

4.1 Design Model and Tradeoffs

Figure 4 shows a schematic of one embodiment of this architecture that uses a linear electromagnetic motor as a source actuator and a passive hydraulic system as a power transmission. The hydraulic system consists of a piston/cylinder on each end for conversion between mechanical and fluid power, and a flexible hose connecting the two. One piston connects to the source motor, and the other acts as an actuator. Unlike servovalve-controlled hydraulics, the mechanical piston-cylinders, each of which acts as both an energy and signal source for the hydraulics, and the tubing that joins them need not include small orifices to regulate pressure, and can be designed to have relatively low intrinsic impedance.

If the source actuator is capable of providing the desired force and impedance, then an ideal transmission is mechanically *transparent*. In this context, transparency (previously used to describe an objective for bilateral teleoperation systems (Lawrence, 1993)) means that the force, motion, and energy exchanged between a load and the transmission is equal to that exchanged between the transmission and the source actuator. The goal is to transport actuator behavior to a remote endpoint package that weighs less than the source. Figure 5 depicts a generic transmission architecture. If the transmission is perfectly transparent, the motion trajectories of ports 1 and 2 are identical for all time, the force exchanged at port 2 equals that exchanged at port 1, and the impedance at the interface to the environment exactly equals the actuator impedance. That is, a perfectly transparent transmission is lossless and has the following properties:

$$\begin{aligned}x_2(t) &= x_1(t) \\ F_2(t) &= F_1(t) \\ Z_p &= Z_r\end{aligned}\tag{10}$$

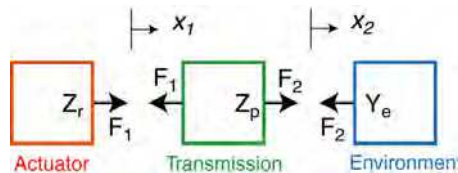


Fig. 5. Schematic depiction of a transmission between a source actuator and environment.

Any practical transmission will drain some energy and will therefore not be perfectly transparent. Furthermore any real physical system has nonzero inertial and compliant dynamics. To approach ideal behavior, the transmission should be designed to minimize inertia, compliance, and friction (although transmission dynamics may be used to advantageously shape the port impedance; see 4.3). While transparency is an important performance objective, an effective transmission must also be *flexible*. A perfectly flexible transmission would allow infinite separation (in all spatial degrees of freedom) of the endpoint package from the source actuator with zero reaction forces (torques). A practical transmission must provide sufficient freedom of motion from the source to cover the robot's

workspace. Forces and torques required to bend and twist the fluid line should be minimized. The requirements of flexibility and transparency are often in conflict, as detailed below. Whether a transmission is intended to be transparent or to shape impedance, its design specifications focus on how it impacts endpoint impedance. This distinguishes high-force haptic applications from conventional servo problems. Below we provide a model that enables the prediction of the transmission's transparency and its impact on endpoint impedance. First several issues must be addressed to ensure that useful actuators capable of bilateral power transmission can be configured and controlled to operate as intended.

From Figure 4 it is straightforward to envision the hydraulic components transmitting force, motion and power in compression. However most high force haptic systems must sometimes actuate bilaterally (pulling as well as pushing). If tensile forces are applied to a closed liquid volume, its pressure drops below ambient and the fluid evaporates locally (cavitates). If the seals are imperfect, air leaks in. Two simple options enable bilateral actuation: a bias pressure that exceeds the pressure needed to transmit tensile forces can be introduced, or actuator pairs can be used together. The latter is depicted in Figure 6, wherein the two actuation paths exist within the same two cylinders, joined by two separate fluid lines, one for "tension" and the other for "compression." This configuration introduces several difficulties, including additional weight and complexity as well as additional seals. Seals where the pistons exit the cylinders are particularly problematic, as any liquid that leaks there leaves the constant-volume system and must be replaced.

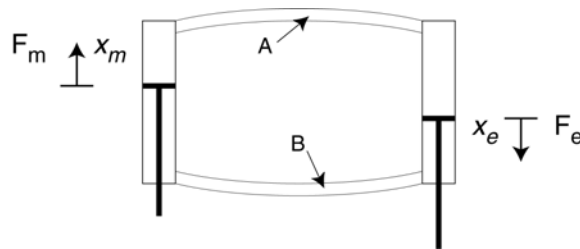


Fig. 6. Bilaterally actuated transmission with two fluid paths.

A simpler method of tensile force transmission that uses a single fluid path requires mechanically creating a bias pressure such that the fluid pressure is elevated above ambient without force applied by the actuator or environment. This can be accomplished by applying a constant compressive force to each piston. When the system is at rest, the forces on each side cancel, but the fluid in the chamber is at an elevated pressure. Tensile forces reduce the pressure, but if the force does not exceed the bias force level, the fluid pressure remains above ambient and cavitation and gas leakage into the system are avoided. This approach requires additional hardware to create the applied load, and increases the operating fluid pressure, but requires only two moving seals rather than four.

Using this mechanical bias force approach, the transmission can be modeled for design purposes as the simple straight-pipe system shown in Fig. 7. This model, used as the design basis for determining transmission impedance, includes each of the piston-cylinders (with diameters D_1 and D_2 and length L_1) and approximates the flexible line that connects them as

a straight, smooth and rigid cylindrical pipe (with diameter D and length L). The forces applied to the two pistons are F_1 and F_2 , and the piston velocities are v_1 and v_2 . The bulk fluid velocity in the line is v . The transition from piston diameter to hose diameter must also be considered. This simplified model can be used to predict losses due to friction, the weight of the fluid in the system, and the inertia due to fluid acceleration. Calculations based on this particular model are summarized below to illustrate the relationship between transmission geometry and system performance. From Fig. 7 it is evident that this hydraulic transmission can also provide an intrinsic gear reduction for force (or motion) amplification or reduction, without adding mechanical parts that might contribute backlash or friction. In this case, the gear ratio is equal to the ratio of the piston areas.

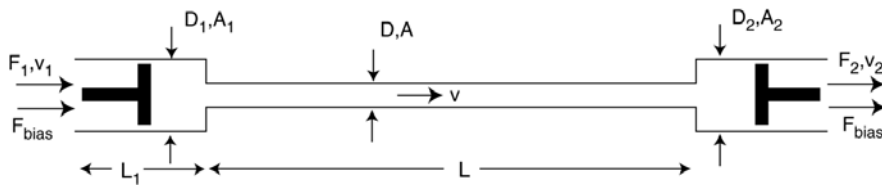


Fig. 7. Straight-pipe, dual piston model for a linear passive hydraulic transmission.

To be viable, the proposed actuator architecture must be amenable to control. By introducing a significant separation between the source actuator and the endpoint where behavior is controlled, with accompanying transmission dynamics, the structure of the system poses a potential challenge for effective and highly stable control. Because stability and passivity are paramount, one way to represent target impedance is to feed back motion only at the source actuator, closing a simple impedance control loop around only the well-characterized electromagnetic source actuator, yielding a robustly stable implementation. This arrangement depends on the transmission to reliably (and nearly transparently) transmit impedance between the source actuator and operator, but without using a sensor at the interaction port, it may be vulnerable to small and accumulating position errors. Fortunately, although humans excel at gathering information from physical contact, they are not generally sensitive to small changes in position. Provided that physical contact is represented as intended, small positioning errors can be tolerated with very little consequence, especially if the device is used in conjunction with a visual display. Compared to alternative transmission implementations (e.g. cable drives), a hydraulic transmission may provide superior damping of resonant transmission line modes via the intrinsic viscous behavior of the working fluid, and in fact the dynamics of the transmission may be intentionally sculpted to improve both interaction stability and performance via *impedance shaping*, as discussed briefly below.

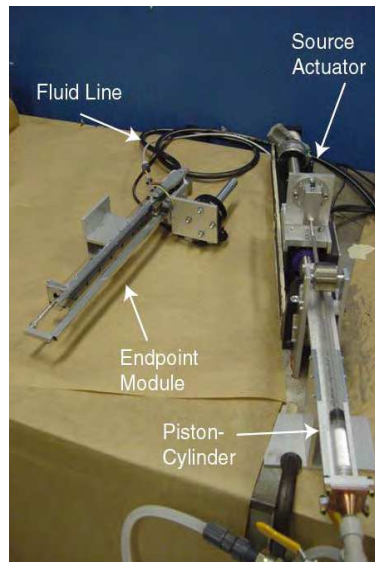


Fig. 8. Prototype passive hydraulic transmission system with linear source actuator.

To illustrate the key design issues for this architecture, a representative design problem is presented by applying the model in Fig. 7 to the specifications for an actuator for an upper-limb physical therapy robot device. This is intended as an out-of-plane “anti-gravity” addition to the planar MIT-MANUS robot, and has previously been addressed with two designs, one using a rotary electric motor and a low-friction roller screw and the other a direct-drive linear electromagnetic motor (Buerger et al., 2001, Krebs et al., 2004). The stringent and challenging target specifications for this application include a range of motion of 0.4 m, a force capacity of at least 65 N, a mass of less than 2 kg at the endpoint, a separation of at least 3 m between the stationary source actuator and the mobile endpoint, achievable stiffness of at least 2 kN/m, and minimal endpoint impedance including inertia less than 2 kg, Coulomb friction less than 2 N, and linear damping coefficient of no more than 10 Ns/m. Both previous designs violated the mass specification by nearly a factor of four. In this section the design model is developed to predict frictional and inertial dynamics of the transmission, and compliance is discussed. A prototype actuator (Fig. 8) was fabricated and its measured properties are discussed in the next section.

Damping: A major advantage of this configuration is its ability to avoid or minimize the viscous losses that arise in conventional hydraulics from forcing large volumes of fluid through small control orifices. Nevertheless, the long, narrow transmission line contributes some damping due to viscous drag. Assuming the fluid in Fig. 7 is incompressible, steady flow between any two points in the pipe is governed by the following expression, derived from the energy equation:

$$\left(\frac{P_1}{\rho} + \alpha_1 \frac{v_1^2}{2} + gz_1 \right) - \left(\frac{P_2}{\rho} + \alpha_2 \frac{v_2^2}{2} + gz_2 \right) = h_{li} \quad (11)$$

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