Chapter 1

Background and Related Work

Robots have been very successful at performing tasks that allow it to move in free space under position control. Tasks such as spray painting vehicle exteriors, pick and place of IC chips, arc welding and spot welding fit very well into this paradigm. There are other tasks that require much more sophisticated trajectory control methods. Nevertheless, assuming that the robot will be working in free space, there are many techniques, both linear [12] and non-linear [48], that allow this type of high performance control. However, very few robots are capable of interacting freely with the world and an unknown environment. In fact, very simple tasks such as driving a screw, turning a crank, assembling legos, and writing on a chalk board are extremely difficult for most robotic manipulators [5]. While many robotic applications which use position control have found their way into the commercial sector, robots which contact the surrounding environment and work within kinematic constraints has for the most part been limited to laboratory research. Instead of position control, these robots require force control. In order to do this well, the robots themselves must be capable of modulating and controlling its actuator torques and forces.

1.1 Force Control

In order for robots to work properly within an uncertain environment like humans and other animals do, the robot must have the capability of sensing and controlling forces in addition to knowing where it is in its work space.[1] *Force Control* or *Compliance Control*, terms often used interchangeably, is the title given to this research area. This is not a new subject of research and a great deal of progress has been made over the past several decades.

Let me adapt an explanation for why force control is necessary when a robot is interacts with an unknown environment [34]. When any two physical systems energetically interact, the interaction is defined at the interface by a set of orthogonal variables: flow and effort. In a mechanical system, flow is the velocity or motion and effort is the force. In any power domain such as mechanical, hydraulic, electric, thermal etc., there are equivalent flow and effort variables (Table 1.1). The product of these two variables is the power transfered across the system interface. Interestingly, one physical system cannot independently control both the flow and the effort at the point of interface. In other words, the interaction power cannot be controlled. A system may define and control one of these variables but not the other. For example, most workpieces and environments with which a robot will interact are kinematically constrained. A door swings on a hinge. A wall and floor are vertical and horizontal barriers respectively. Therefore, the environment often defines the flow interaction. This leaves the robot with only the option to modulate the effort. If the robot tries to control the position, there exists a basic incompatibility between the two physical systems. Therefore, whenever a robot is not simply moving around in free space and interacts with an environment or workpiece, it must use force control. At a minimum the robot must have some capability of being compliant in order to

[1] The term *force* denotes a generalized force/torque vector. The term *position* is the generalized position/orientation vector.

Table 1.1: Flow and effort for different power domains

Power Domain	Effort	Flow
Mechanical	Force (N)	Velocity (m/s)
Hydraulic	Pressure (Pa)	Flow rate (m^3/s)
Electric	Voltage (V)	Current (A)
Thermal	Temperature (K)	Entropy rate (J/Ks)

effectively match the given constraints. This allows the causality of the robot-environment interface to maintain proper order.

It is important to point out that all environments have some compliance. While most constraints are thought of as stiff like a wall, there are other things which are very compliant such as sod or carpet. In fact some systems, like water, can exhibit variable compliance depending on the conditions. In these cases it may be necessary to control some linear combination of flow and effort. Nevertheless the robot must be capable of being soft or compliant. It cannot be stiff only. Therefore, good force control is essential.

The following discussion covers different ways that robots can match compliance requirements with the environment. This will include passive as well as active methods. The discussion will also outline some of the robot applications where force control has become important and even necessary.

1.1.1 Passive Compliance

A simple method to achieve pseudo force control is to have a robot use conventional position control but incorporate inherently passive compliance. Passive compliance can be found in the robot structure, joints, and at the end effector. To distinguish between active force control, passive compliance does not use force information for feedback to modulate the control algorithm.

By introducing passive compliance into the joints, the loop gain for the position control loop is effectively *softened*. Similarly, robot structures (links) have compliance that can be increased. With a combination of low servo stiffness and low structural rigidity, the robot may be able to successfully interact with a work piece or environment simply by using position control schemes. For example, a bipedal walking robot build by Honda (*P2*), uses a compliant damping material as a coupling between the robot actuators and joints [19]. The coupling protects the robot's actuators from the shock loads in each step. However, while adding passive compliance into a robot may be beneficial in some implementations this method is successful in some robot implementations, robot can now interact with the environment, it may be very *sloppy* in its task execution and fail in its overall goal [14]. To compensate for this potential problem, *P2* also has active force sensors in the ankles which give feedback to the control system and are critical to its walking stability.

Since many robots interact with the environment only at the manipulator endpoint, another successful strategy is to create a passive end-effector. The robot uses position control to roughly locate the endpoint properly in its workspace. The endpoint then performs its workpiece interaction task. For example, many end effectors simply have a soft rubber covering. This effectively decouples the robot from the workpiece through the compliance. This has also been shown to be an effective tool for active force control as well [14]. Biology does it too. Human hands and feet have a soft compliant covering which aids in manipulations and locomotion [3].

It is also common to see pneumatic end effectors that effectively convert the end of the robot into a force control device. This is because pneumatics are inherently compliant. By controlling the pressure in a pneumatic piston, it converts gas pressure into a mechanical force.

Another clever passive end-effector is the remote center compliance (RCC) that is set up to automatically perform a peg-in-hole assembly [13]. The configuration of the RCC creates a compliance center at a certain point within its structure. Forces acting on the compliance center of the RCC result in pure translation and torques at that point cause pure rotation. By placing a peg tip right at the compliance center, it can be assembled into it hole without jamming.

1.1.2 Active Control

In order for a robot to be more successful at force control, it must be very capable of generating and responding to a wide range of forces from very small to very large[2]. Clearly, passive methods have limits when trying to increase the capability of force control robots. This leads to the need for active feedback of measurements and control of forces on the either the manipulator endpoint, joint actuators or both.

Even though this thesis deals only with single degree of freedom force controlled actuators, I present an overview of several force control methods and algorithms for multi-degree of freedom robots. Also included are a few general applications which require force control. More will be discussed about the physical capabilities of robots and actuators in the next section.

The vast majority of active force control techniques and algorithms have been developed to control and monitor the end point forces and torques via a force sensor at the robot tip. Mason [29] and Whitney [56] give good summaries of formalized compliance control and other active force control methods. These methods include stiffness control, damping control, impedance control and hybrid position/force control. Other methods include explicit force control and virtual model control.

- **Explicit Force Control** creates a virtual endpoint force *servo*. The controller input is the error between the desired force and actual measured endpoint force. The controller can typically be any form of PID control. The difficulty in this type of controller is that there is no positional feedback on the robot which means that there is no control on the absolute endpoint position. Therefore, this approach is somewhat difficult to apply to a multi-degree of freedom robot without a higher level control system modulating the forces.

  It should be noted that this thesis deals with the explicit force control of a single degree of freedom robot actuator. An assumption is made that a high level force control algorithm, many possibilities of which are discussed below, will be used in the coordination and control of the entire robot system.

- **Stiffness Control** [45] creates a virtual six degree of freedom *spring* in robot end point coordinates. It measures the endpoint forces as well as the joint positions in order to generate a desired force set point. The joint velocities are also measured and used in feedback to make the system lightly damped. No inverse kinematic calculations are needed but the Jacobian transpose is required.

- **Damping Control** [56] creates a virtual six degree of freedom *damper* in robot end point coordinates. This method requires the endpoint forces and joint velocities to generate desired actuator torques which implement velocity changes to the endpoint.

- **Impedance Control** [21] generalizes the ideas of stiffness control and damping control. The position and velocity of the robot endpoint is commanded. In addition, the control system modulates a manipulator *disturbance response* which will allow the control of dynamic interactions. The robot disturbance response is modeled after a second order mass-spring-damper behavior. In other words, the robot endpoint will behave as if it is a second order system. Therefore the endpoint forces, joint positions and velocities are used to generate actuator torques. The gain matrices which set the effective stiffness, damping and inertia of the manipulator endpoint correlate directly with stability and bandwidth criteria for the robot.

- **Hybrid Position/Force Control** [39] is a method which combines conventional position control and force control. The environment dictates natural constraints such as being in contact with a surface where only force control can be used. Similarly, position control is used in the directions where there are no constrains and the robot can move freely. The trajectory and path that the robot follows are called artificial constraints. A systematic method for

[2]A term often used to describe the efficacy of robots and robot actuators is *dynamic range*. This is the maximum output force divided by minimum resolvable force. It gives a sense for how well a robot can output small forces with respect to its full force output capability.

understanding and defining natural and artificial constraints has been outlined in several places [5, 30, 49]. Actuator torques are then commanded to make the robot operate within the given constraints.

- **Virtual Model Control** [37, 38], unlike the previous five control techniques, does not simply rely on nor control manipulator endpoint forces. It is a motion control language which allows the control designer to use simulations of virtual mechanical and/or other components, linear or non-linear, to create reaction forces which are transmitted through the robot via joint torques. The robot behaves as if the virtual components are actually attached to the robot. This algorithm method can be formulated into a state machine so that different virtual simulations control the robot with each change of state. Virtual model control also does not require that a robot be fixed to the ground. While this control language in its different variations has been applied to legged robots which successfully accomplish their task of graceful locomotion [26], there currently are no formal methods for quantifying stability.

There are many applications which require real time force control. While each application does not have a specific technique associated with it, I list some of the applications here to give emphasis to the importance of force control. These applications are: teaching and skill acquisition both for people teaching robots and robots training people, Telerobotics, haptics and biomimetic robots.

- **Teaching and Skill Acquisition** [7] – Off-line programming has had only partial success in applications in manufacturing such as grinding and deburring. In these cases, interaction forces for the task must be acquired or learned. These skills are often difficult to teach to people let alone robots. Often it is easiest to train force interaction skill in a teach-by-showing method. It is then possible to embed that information to one of the active control methods listed above such as hybrid force/position control or impedance control. In order for the robot to learn these skills, must be compliant in the instructors hands. This requires good force control.

  Conversely, to humans teaching robots, it can work the other way around. For example, experiments are being done with robots helping in the rehabilitation process of upper limb control for people recovering from strokes [2]. These robots must be very force sensitive and inherently safe.

- **Telerobotics** [46, 47] typically, places a human in the control loop of a robot. One standard form places a human on a master manipulator and the robot slave mimics the motion of the master. To add the capability of the system, a controller will reflect the forces felt by the slave to the master. While, it is not recommended that the slave manipulator have endpoint force control from the standpoint of stability, force control locally on each individual joint is highly recommended if not required for proper teleoperation [33]. Advances in manipulator design and control algorithms have allowed for the development of a teleoperated micro-surgery robot [42].

- **Haptics** [43, 41] is a close cousin to teleoperation where the only difference may be that there is no slave manipulator. A haptic interface will generate forces at its end point as it follows the users motion. The desired forces are created in a virtual environment rather than reflecting a remote real environment. However, the haptic interface gives the illusion that an environment actually exists. Good force control is critical in haptically representing a virtual environment.

- **Biomimetic Robots** are those which try to imitate motions and actions like those of humans and animals. Robots that walk[26], run[40], catch[23], grasp[43], swim[53], etc. are all currently far inferior to their biological counterparts. Since muscle is essentially a force causal actuator, several researchers have found that using actuator level force control for these types of robots is very beneficial.

1.2 Robot Actuators and Active Force Control

Regardless of the application, algorithm or technique, there is often an assumption made in the control system that desired force equals actual force. The above algorithms and applications, while using a different method of calculation, generate desired output forces for each of the joints in response to joint positions, endpoint forces, desired behavior, and/or the environment. Often this assumption about desired force equaling actual force is poor, particularly at very low forces when desired force is zero. There are many reasons why this is the case. Friction, stick-slip, intermittent environment contact (impacts), transmission dynamics, actuator dynamics, actuator saturation, reflected inertia and noncolocated control are all limiting factors. Despite the fact that actuators are often assumed to be *black box* force devices, it is simply not the case.

An actuator is defined as a device that converts some form of energy into the mechanical domain. There are many types of actuators both biological and technological. Studies have been made which compare and contrast different actuation domains including internal combustion engines, electro-magnetics, hydraulics and pneumatics as well as other developing technologies such as shape memory alloys (NiTi), electro-active polymers, braided pneumatics (McKibbon muscles) with biological muscle properties as a benchmark. These studies focused on characterizing and generalizing different actuators into the shape of their flow-effort relationship [17] and on looking at the power density and force density of each actuation method [22]. This thesis only looks at traditional actuation methods and the following discussion focuses on how each one performs with respect to force control. Emphasis is given to electro-mechanical and hydraulic actuators and pneumatics are mentioned for completion.

1.2.1 Electro-Mechanical

The vast majority of robotic actuators in use today are some form of electro-magnetic motor with a transmission. The purpose for having a transmission is that EM motor's most efficient operating conditions are at high speed and low torque. Robots, however, typically operate at low speed and high torques. This is especially true for robots that are trying to mimic natural tasks of humans or animals. A physical as well as a mathematical power transformation can occur with a gear train or transmission. While mathematically this works wonderfully, physically it presents problems for both position as well as force control.

Electro-magnetic motors by themselves are well understood. They are fairly easy to model and control because they are for the most part linear. In the simplest model, motor torque is proportional to current. Transmissions, on the other hand, are not linear and introduce several problems including flexibility, friction, backlash and reflected inertia. Each of these problems lead to torque noise. If we try to eliminate one of these problems, another one will increase in magnitude. For example, non-backlash gears create a stiffer transmission but will correspondingly increase drive friction [15].

Power transmissions also increases the dynamic mass of the motor by N^2 where N is the reduction. For geared motors, the large reflected inertia leads to broken gear teeth, damaged ball screws and ruined actuators when large unexpected loads appear as the robot interacts with an environment. Also, the motor inertia as seen through the transmission will typically be in the same order of magnitude as the robot link inertia if not greater. Therefore, the dynamic behavior of the robot link can be significantly greater than just its own inertia since the two are coupled together.

Electro-magnetic motors by themselves are typically very easy to back drive. This means that a small external torque on the motor shaft will cause it rotate. In other words, the impedance of the motor is very low. However, with a large transmission, due to the increased real and apparent friction and increased reflected inertia, an electro-magnetic motor becomes significantly more difficult to back drive. With this increased impedance, the actuator becomes much more of a position causal system rather than a force causal one.

In an effort to make a clean, low-friction, low-impedance actuator, Asada et. al. created direct-drive actuators and robots [6]. Direct-drive eliminates the transmission and connects a DC brushless motor directly to a robot link. This construction eliminates friction and backlash and creates a very force sensitive actuator. Advanced torque sensors in the actuators have added to the capabilities of direct-drive robots [1].

From a modeling and control standpoint, direct-drive robots are simple systems. The motor (magnet) mass is included with the link inertia. Unfortunately, to compensate for the loss of transmission, direct-drive motors must be large in order to achieve high enough torques. High torque requires high current. This in turn comes at the expense of increased motor mass and decreased efficiency. In weight sensitive and power sensitive robot applications such as mobile robots, direct-drive actuators are often unacceptable. Nevertheless, for ground based robots with few degrees of freedom, direct-drive actuators have been very successful in both force control applications and position control, particularly in semiconductor manufacturing automation.

In order to improve the force and power density of EM motors without sacrificing force sensitivity, work has also been done to create stiff, low-friction, *clean*, light-weight cable transmissions for EM motors [52]. Because of the size constraints of pullies, cable transmission can only achieve moderate transmission ratios. Nevertheless, cable transmissions have been used on novel robots such as the *Whole Arm Manipulator* [44] used in robot catching [23] and digging, the *PHANToM* [31] used as a three degree of freedom haptic point interface, *Robotuna* used to study undersea oscillating foil propulsion [8, 53] and robots for minimally invasive telerobotic surgery [28, 42].

Force control with slightly higher ratio gearing has been achieved with very careful actuator design and development in the construction of *Artisan*, a ten degree-of-freedom manipulator [54]. Instead of using single stage helical gears, Vischer and Khatib used *evoloid* [9] gear sets for each joint. These gears have higher load capabilities than helical gears but are still backdrivable. This transmission used in conjunction with a novel torque sensor, has helped *Artisan* to demonstrate compliant behavior.

1.2.2 Hydraulic

Just opposite of electro-magnetic motors, hydraulic systems operate best at high force (pressure) and low speed (flow rate) which is perfect for robotics. In fact, hydraulic systems have one of the highest power density of modern controllable actuation methods [22]. The system can operate at 3000 psi and higher. Hydraulics can hold large loads indefinitely without consuming power. This is something that would cause electro-magnetic systems to overheat. Hydraulics are particularly used in high force and high power density situations such as construction machinery, airplanes and automobile steering systems. However, there are several downsides to hydraulics which have caused them to be replaced by electro-magnetic servos in the robotics industry. There is an inherent messiness with hydraulics. Modern system design has alleviated some concerns regarding leakage of hydraulic fluid. Nevertheless, the threat is always there. Since pressure and return lines must be run to hydraulic actuators, there is increased system complexity. The final downside to hydraulic systems is that they are very non-linear from a control perspective. Null bias, null shift, hysteresis, threshold, internal leakage and square root flow-load characteristics are all real non-linear effects in hydraulics.

Hydraulic actuators typically consist of a pressure source and a flow control valve (i.e. spool valve). In the simplest dynamic model, fluid flow rate is proportional to current. The valve directs high pressure fluid into one of two chambers which drives a piston thus converting fluid flow into a mechanical motion. Thus, in this configuration hydraulics are very good at position control. It may seem natural that it would be possible to modulate the chamber pressure in order to get good force control. In actuality, because of friction and stiction in the piston, supply pressure variations and seal friction, actuator force control can prove very difficult. The pressure in the chamber is not a good representation of the force at the actuator output. Another reason the force control is difficult is that since the fluid goes through a servo valve, hydraulics are not backdriveable. They have very high impedance. It essentially has *infinite* mass. In general, force control of hydraulic actuators is a difficult problem [11].

In order to reduce the sliding friction, the seal tolerance can be lifted. But, that has a direct effect on system efficiency not to mention the problems of keeping the work environment clean. In Raibert's hopping robots, the legs had two sets of loose seals [40]. The first set allowed leakage flow from the pressure chambers. The second seals simply scavenged the leakage. This configuration helped the piston to slide very smoothly. Even so, using pressure as an estimate of actuator output force proved inaccurate.

Given the natural non-linearity of hydraulic systems, a Lyapunov based controller has been proposed for hydraulic force control [4]. This controller also includes adaptive behavior for parametric uncertainty compensation since many parameters in the hydraulic system are either difficult to measure off-line or are time varying with temperature.

Recognizing, that most robot systems are essentially position control systems, position-based end-point impedance control has been previously applied to EM position controlled robots [35]. This has also been implemented on an industrial hydraulic robot [18]. While somewhat successful, due to limitations in the positioning accuracy and the bandwidth of actuators, the robot would exhibit a hunting behavior when in contact with a semi-stiff environment.

1.2.3 Pneumatic

While pneumatics are not dealt with explicitly in this thesis, they are included here for completion of standard actuation methods. Pneumatic actuators have many features which are close to hydraulics but with significant differences resulting from the operating fluid. Pneumatics typically consist of a piston and a valve connected to a pressure source. The biggest difference between hydraulics and pneumatics is the compressibility of gas. As mentioned previously, pneumatics are often used as end effectors because of its inherent compliance. Pressure in a piston chamber converts the piston into a force compliant actuator.

Another configuration for pneumatics other than a piston is an inflatable elastic tube covered by a braided mesh typically called McKibben muscles [22]. When pressurized, the tube shortens or contracts like a muscle. It has been found that McKibben muscles can exhibit behavior very similar to biological muscle [27]. These actuators have been shown to also have force and power density similar to electro-magnetic systems.

There are several problems with pneumatics that limit it's applicability to robotics. First, unlike hydraulics, pneumatic systems run at relatively low pressures (100 psi) for safety reasons. It can operate at higher levels but compressed air stores vast energy. If there is a rupture in the line, pneumatics become very dangerous. Other reasons include thermodynamic effects of compressing and expanding air which heat and cool the system dramatically. The natural compliance of pneumatics can also vibrate with robot link inertias and clever damping schemes are required for stability.

1.3 Series Elastic Actuators

There are many different methods of robot actuation, as just discussed, each with there own set of strengths and weaknesses with respect to force controllability. Some robot applications which require good actuator force control are also very weight sensitive such as legged locomotion and space robotics. If these robots use electro-mechanical actuation, direct-drive and even cable transmissions often do not provide the force or power density needed for certain tasks. In order to get high power density out of electric motors, they must run very fast. Consequently, they need a high ratio transmission with all of its inherent problems with respect to force control.

1.3.1 Electro-Magnetic

Accepting this as a constraint, Howard [24] build and analyzed an actuator with a spring in series with the motor and transmission. He then measured the relative spring deflection by taking the difference between the motor rotation and output shaft rotation. By controlling this deflection he essentially was controlling the actuator output torque by Hooke's Law where

$$F = kx. \tag{1.1}$$

By using a smaller motor and larger transmission ratio, the output force and power density increased while maintaining good control over force. The down side to this is that the control system and

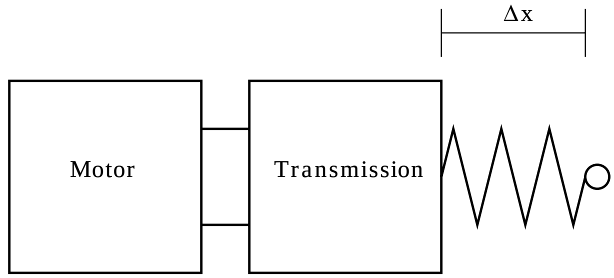

Figure 1-1: A spring is intentionally placed in series with the output and the spring deflection is controlled thus inferring force control.

motor must expend extra control effort at times to overcome the effects of the spring.

Introducing compliance into the drive system is contrary to conventional machine design wisdom. However, it is interesting to note that biological actuators, force generating muscles, are connected in series to a link output through elastic tendons [3]. There are many reasons why this is thought to be the case. Ideas include energy storage and increased efficiency, stability when contacting environments and filtering shock loads to the body. Even though it is not completely fair to compare muscles to motors, elastic elements can perform the same function regardless of being biological or technological.

Building further on the ideas that elasticity in an actuator could be beneficial, Pratt[36] and Williamson [57] created a similar actuator to that of Howards. In addition, they pointed out using passivity arguments that the actuator was stable under PID force feedback control. They also showed that to get a better force measurement, the strain/deflection of the spring must be measured directly and not as the difference of the motor and output shaft. These actuators, called *Series Elastic Actuators*, (figure 1-1, mechanically filter friction and backlash and other non idealities in high ratio transmissions drives. They also filter shock loading from the environment.

The reason that these actuators are able to perform so well, is that by introducing compliance into the actuators, the loop gain of the actuator system is significantly reduced. Consequently, the control gains can be increased proportionally. With high gains even in a simple controller, noise, impacts, friction, etc. can be greatly reduced. The proper choice of spring, sensor and control system.

Unfortunately neither Howard, Pratt nor Williamson gave design guidelines for choosing an appropriate spring constant in the actuator. However, through trial and error iterations, versions of series elastic actuators have been demonstrated in a few biomimetic robots.

- *COG* (figure 1-2) [10] is a humanoid robot with with upper torso and head. Series elastic actuators are used in its arms which have 6 degrees of freedom. Using the natural dynamics of the arms, low noise force controllable actuators and dynamic oscillators for control, *COG* was able to do many tasks previously thought to be very difficult for robots such as hammering and turning a crank [58].

- *Spring Flamingo* (figure 1-3 is a planar bipedal walking robot with series elastic actuators driving its 6 degrees of freedom (three in each leg for hip, knee and ankle) [26]. It can walk at $1m/s$ on flat terrain. It has also walked blindly over terrain of alternating 15 degree slopes.

There are other examples where springs have been used in series with transmissions. Elastic transmissions are an integral part of Morrell's parallel coupled micro-macro actuators [32]. In this scheme, a small direct drive actuator is coupled in parallel with a larger geared motor through an elastic transmission. The large motor creates a force with gross sensitivity and the small direct drive motor accounts for the error. While increasing the complexity of the actuator, a substantial increase in dynamic range is achieved.

Figure 1-2: COG is a humanoid robot with upper torso, arms and head. The arms use series elastic actuators for each of its six degrees of freedom. Here COG is turning a crank using a dynamic oscillating controller.

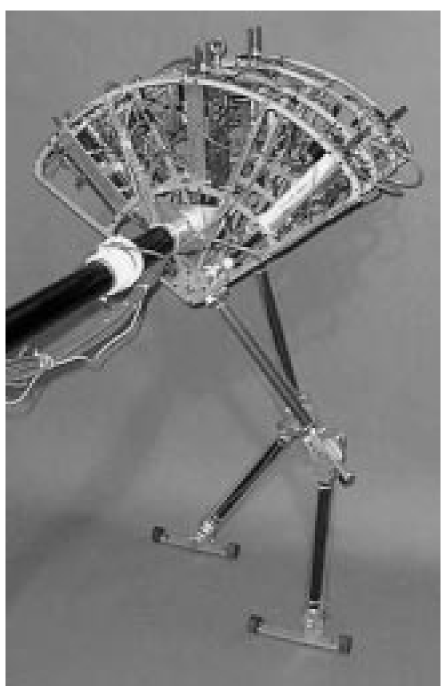

Figure 1-3: Spring Flamingo is a planar bipedal walking robot. It uses series elastic actuators to actuate its six joints. Its top walking speed is 1 m/s.

In the control and handling of arbitrary two dimensional objects, Hanafusa created a three finger gripper with springs at the end of each finger [16]. The fingers were driven by a single motor and by measuring the deflection of each spring, stable grasping forces were achieved.

In the manipulator design for mobile robots to do cooperative object handling, Sugar built a three degree-of-freedom parallel manipulator which can generate forces in the x and y directions and a moment in the z direction [51]. The actuators for the manipulator have springs after the motor and transmission and the force is controlled by measuring the deflection of the spring. This design is very similar to series elastic actuators described above.

Sugano designed and build a compliant one degree-of-freedom finger [50]. The finger's compliance could be set by changing the effective length of a leaf spring which was in series with the motor and transmission. The actuator required three motors. One would drive the position and one would set the spring stiffness. An additional motor was required as a brake and used to damp out the residual vibration from the spring.

1.3.2 Hydraulic

Springs and other compliant mechanisms have also been used in a similar manner for hydraulic actuators. Following the example from biologic understanding of running [3], Raibert's hydraulic legged robots use springs to recover impact energy from each step during locomotion [40]. These same robots were able to perform simple gymnastics such as a flip [20]. These robots were not under force control. However, the springs in the legs are necessary to maintain stability under such high shock loading to the robot.

The first force reflective teleoperated hydraulic manipulator was built by Sarcos, Inc. (Salt Lake City, UT) [25]. Using one of the actuators for this robot, Wells characterized a hydraulic piston with accumulators which gives the actuator intrinsic compliance [55]. Due to the compliance in the piston chambers, the actuator was much better able to tolerate external disturbances.

Placing a mechanical spring at the end of a hydraulic actuator and measuring the spring's displacement for force control is noticeably absent from the literature. I describe and analyze just such an actuator in this thesis.

1.4 Summary

Force control is important to robots which interact with an external unknown environment. There are many applications for this type of robotic work. There are several types of algorithms and methods for implementing force control but there is a lack of actual robots than can achieve predicted performance particularly because of the actuators.

Robot actuators are especially poor at force control when high force and power density are required. In order to do this, electro-magnetic motors that require power transmission which introduces many sources of force noise. Hydraulic actuators fit the high force and power density requirements, but along with electro-mechanical actuators are much better suited for position control. Actuator force control has been shown to be improved with the introduction of compliance and controlling the deflection of the compliant member. The rest of the thesis describes and quantifies this finding and gives ideas for implementing series elastic actuator design.

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