Programmable Springs: Developing Compliant Actuators for Autonomous Robots

Bill Bigge **Inman R. Harvey**
Centre for Computational Neuroscience and Robotics
University of Sussex
Brighton BN1 9QH, U.K.
{wb23, inmanh}@sussex.ac.uk

Abstract

Conventional approaches to actuation and motion control are designed to eliminate any perturbations from the system and provide smooth precise control of speed or position and a high level of stiffness. By contrast, emerging approaches to autonomous robotics rely on exploiting the environment to aid motion. In passive dynamic systems motion is modulated by interactions between the mechanism and the environment; instead of forcing the actuators to follow pre-planned trajectories the environment is used to guide motion.

Developing real robots that can exploit these dynamics requires the use of actuators that can react to the environment, exhibiting behaviour that varies from high stiffness to complete compliance or zero impedance. We will outline our design for an electric actuator, called a programmable spring, which can be configured to emulate many complex sprung and zero impedance systems within its range of movement and mechanical limits. This design forms the basis for a prototype actuator intended as a cost effective 'off the shelf' component for robotics development. Our design includes a sophisticated control architecture that allows the actuator to exhibit complex autonomous behaviour whilst offering the user a high degree of control. The addition of programmable damping behaviour and possible applications for this type of system beyond the field of robotics are also discussed.

1 Introduction

Motion control in robotics is a long established and well understood field. It forms the basis of most modern manufacturing technology where robots are employed to perform tasks that include cutting, welding and assembly within a factory. The demand for high accuracy and repeatability is achieved by employing high stiffness mechanisms with high fidelity sensors and control systems. This ensures that any perturbations introduced from the environment are cancelled out.

The wide and diverse use of industrial robots and the depth of current knowledge relating to their design and control make it unsurprising that these techniques form the basis of attempts to develop autonomous robots. These design and control principles can be seen in the advanced humanoid robots being developed in Japan as well as robots used in research and the emerging hobby and consumer markets.

Recent developments in autonomous robotics have shown that conventional approaches to actuator control may be unsuitable for many tasks and that perturbations introduced from the environment can be beneficial to the behaviour of the system. McGeer (1990) has demonstrated mechanisms that rely solely on the dynamics of the body interacting with the environment to produce stable bipedal walking, referred to as passive dynamics.

Similar work is being pursued here at Sussex (Vaughan., et al, 2004) in an attempt to develop a fully articulated, powered bipedal robot that exploits passive dynamics. Studies of biological systems have also shown the importance of variable stiffness and compliant mechanisms in generating effective walking and running systems (Alexander, 1988).

We believe that actuators capable of compliant behaviours could significantly benefit research into autonomous robotics but to date there are few, if any, viable actuators available as off the shelf components.

In the following sections we will briefly outline the concept of the Series Elastic Actuator, developed at MIT (Pratt and Williamson., 1995) as a force controlled actuator, and then our patented prototype design for a 'Programmable Spring' intended as a versatile low cost solution for developing robots that exhibit dynamic compliant behaviour. A high level programming and control method for this type of actuator is explored along with the design for our second generation prototype.

2 Series Elastic Actuators

In order to address some of the issues of compliance in autonomous robots the Series Elastic Actuator was proposed (Pratt and Williamson,., 1995). This consists of an actuator coupled to a load via an elastic element, typically a set of springs, and containing a sensor to measure the degree of force being transferred through the elastic element. A feedback loop is then employed to produce a system that will apply a specified force to the load as shown in figure 1.

The resulting actuator can behave as a very low impedance system; if the user specifies zero force then the actuator will offer little resistance to perturbations. By varying a control signal the user can cause the actuator to apply a varying force in either direction.

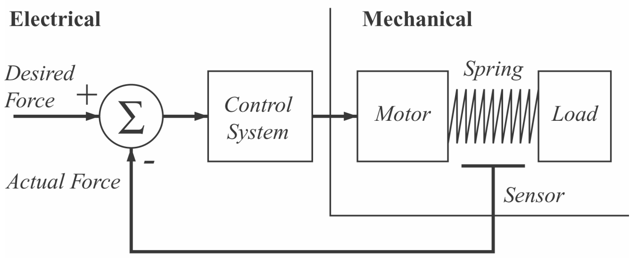

Figure 1: Schematic diagram of a Series Elastic Actuator.

The devices developed so far have suffered from some limitations, principally the size and complexity of the elastic force sensing element. The devices have been implemented as linear actuators resulting in bulky and expensive mechanisms due to the use of a ball screw to drive the load and the complexity of the resulting mechanism.

Rotary versions of the actuator have also been developed and been employed at MIT to control robotic arms (Williamson, 1998) however these required the use of expensive custom-made torsion springs. To address this issue a simpler rotary sensor has been proposed that relies on standard compression springs (Torres-Jara and Banks., 2004).

The use of a force sensing elastic element to couple a drive system to the driven load brings a number of advantages to a system in addition to the ability to regulate force. The elastic element can act as a shock absorber preventing damage to gear teeth during unexpected collisions and it can function as a short term energy storage system to aid efficient motion, particularly in cyclic or harmonic tasks. The elastic element also serves to improve overall performance without requiring high quality motors or gearboxes by making the dynamic effects of motor inertia and gear train friction that affect force fidelity almost invisible at the output (Pratt and Williamson., 1995).

Their robustness to shock and their controllable compliant behaviour make Series Elastic Actuators well suited to the task of actuating articulated robotic mechanisms in unstructured environments. This has led us to explore the design of these types of actuator in more detail and develop a more comprehensive solution for robot builders.

3 Programmable Spring Actuators

The series elastic actuator provides a means of regulating an actuators' motion by force but it does not directly introduce any position based control. To date, applications for series elastic actuators have employed position sensing as a separate sensor modality within the construction of the robot (Williamson, 1998).

Our approach at Sussex has been to concentrate on the development of an integrated actuator containing force and position control within a single unit along with an integrated control system and programming interface. Such an actuator can then be manufactured and employed as an 'off the shelf' module for fast construction of robotic systems. A block diagram of the proposed actuator is shown in figure 2.

We constructed a test rig shown in figure 3 that contains an electric motor and gearbox driving a mechanical arm and angle sensor via an elastic force sensing element. Both the sensors were connected to a microcontroller which could generate signals to drive a DC motor.

A PID control loop was implemented in software running on the microcontroller that provided a control loop between the force sensor and the motor, replicating the behaviour of a Series Elastic Actuator.

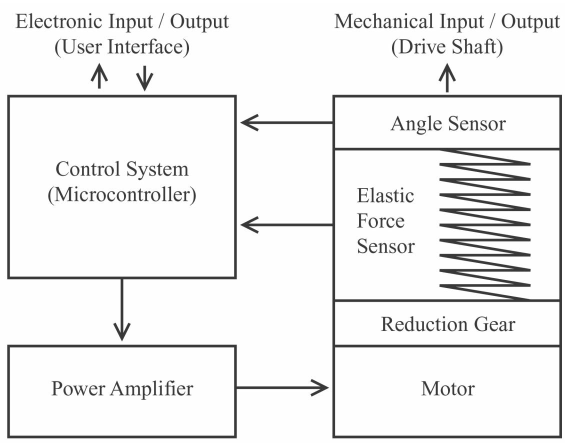

Figure 2: Schematic diagram of a Programmable Spring.

We then introduced a second control loop that generated the force values based on the angle of the mechanical arm. This control loop contained three variables designed to make the actuator behave like a system consisting of a mechanical load constrained by two variable springs. Figure 4 indicates the behaviour visualised as a linear system with a load mounted on a rail along which it is free to slide. A graph below illustrates the force at each position.

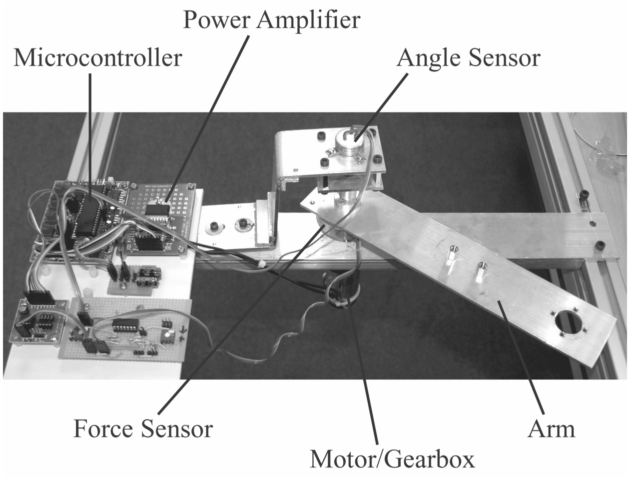

Figure 3: The test rig for a programmable spring controlling a mechanical arm.

3.1 Dynamically controllable springs

The three variables employed in our system are used to describe the relationship between force and position. These consist of the two positions or angles at which the two springs were placed and a gain value for both springs.

If the position of the load went beyond either of the spring starting positions then the value applied to the force control loop was taken as the position of the arm relative to the spring start point multiplied by the gain value. With this control system it was therefore possible to dynamically alter the position and strength of each spring whilst the system was running.

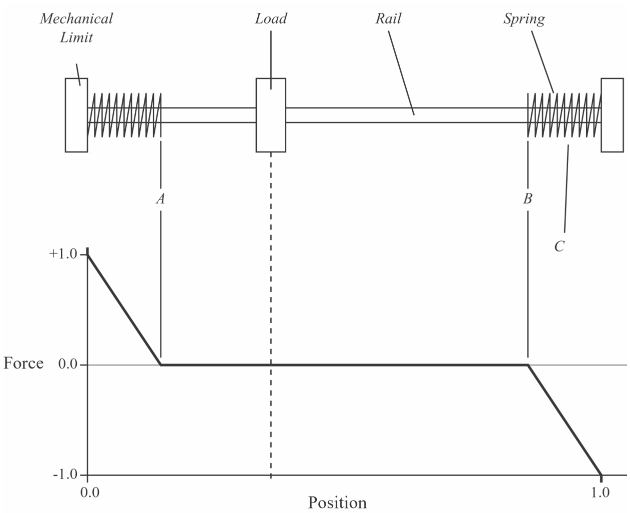

Figure 4: A linear model of our prototype is represented at the top with a graph indicating the relationship between force and position at the bottom. The three control variables used to define the system are the spring start positions (A and B) and the gain value or virtual spring constant (C).

It should be noted when the position output reaches either end of its range of movement and encounters the mechanical limits of the system the force will tend towards infinity until a mechanical breakage occurs. The maximum force deliverable by the system within these limits will be the maximum torque of the motor or actuator used.

3.2 Force profiles for defining complex spring systems

The system outlined above is capable of producing some useful behaviour for controlling a robotic system. We can configure it to emulate passive dynamic behaviour by placing the springs at the ends of its range of motion, leaving the load free to move under its own momentum. If we want to impart movement to the load we can move the springs together and shift their combined positions along the rail causing the load to move, and we can increase the stiffness by increasing the gain values for each spring. This produces compliant actuation that has been shown to be beneficial in exploiting natural dynamics in certain tasks (Williamson, 2003).

This method of control does not allow for the full potential of the system and a more complex control method was devised that will be integrated into a new actuator currently under development. We introduced the idea of force profiles where the behaviour of the actuator is programmed into the controller as a look up table of values representing the force to be applied at any given position. With this system we can specify any complex spring system including non linear springs, constant force zones and zero impedance zones. An example of a complex profile is shown in figure 5.

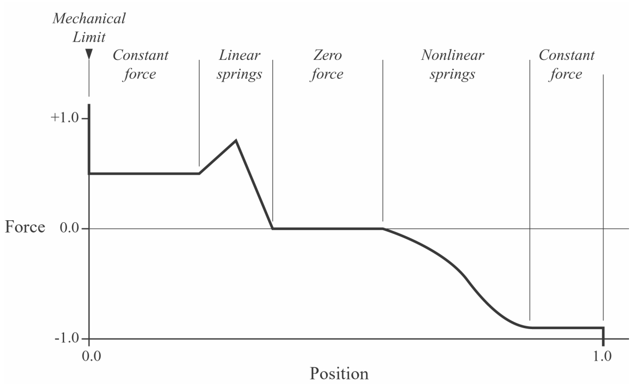

Figure 5: An example of an arbitrary complex spring profile that includes regions of zero force, constant force, linear and non-linear springs.

Whilst the use of this profile system makes it possible to programme complex spring behaviours into the actuator it also introduces some potential control issues. If we want to impart motion into the actuator rather than letting it behave autonomously as defined by the profile it is necessary to re-load a new profile. This could involve delivering large quantities of data to the actuator just to produce simple movements.

We have addressed this issue in two ways; by introducing multiple profiles in a single device and by employing profile scaling and biasing values to modify the currently selected profile.

3.2.1 Profile resolution

The numbers of profiles that can be employed within a device are limited by two factors, the resolution of each profile and the amount of memory present in the microcontroller. Both of these restraints are considered non critical in the actuator design for two reasons; firstly we can use a low resolution profile and employ software interpolation and secondly we can rely on the low cost of memory and specify a microcontroller with a large memory capacity.

For our prototype system we intend to use a profile of 64 bytes where each byte represents a force value between a maximum of 128 and a minimum of -127. The output of the actuator will be able to move through approximately 200 degrees. Whist this produces a fairly low resolution system we believe it will prove sufficient for planned experimental work.

3.3 Multiple profiles, switching points and hysteresis

In order to increase the number of behaviours that the actuator is capable of producing we can employ a series of different profiles and include with each a position at which the system will switch to a different profile. This method allows us to produce a system that can exhibit hysteresis and produce oscillating behaviour.

To produce a system that exhibits hysteresis we can use a pair of profiles as shown in figure 6. In this system the actuator starts in profile 1 where the defined spring pushes the output to one end of its range of travel. When the system is perturbed to the point where the output has moved beyond the switching point, indicated by the grey area, a new profile is loaded that produces the opposite effect, forcing the output to the other end of the range of travel. This new profile also has a switching point that will return the system to the first profile.

3.3.1 Oscillating systems and damping profiles

Oscillating behaviour can be produced using the same system as hysteresis but where the switching points are placed at the opposite ends of the respective profiles. The system will then drive the output towards the relevant switching point rather than away.

In the absence of perturbations the resulting system should drive itself perpetually however the types of motion that may be generated are limited. More complex and possibly more useful oscillating behaviour can be produced with the addition of damping to the system.

Damping behaviour can be defined for the actuator in the same manner as force by providing a new pair of profiles. These would be used to define damping values for each direction of motion and rely on feedback from the angle sensor to modify the velocity of the output by adjusting the applied force.

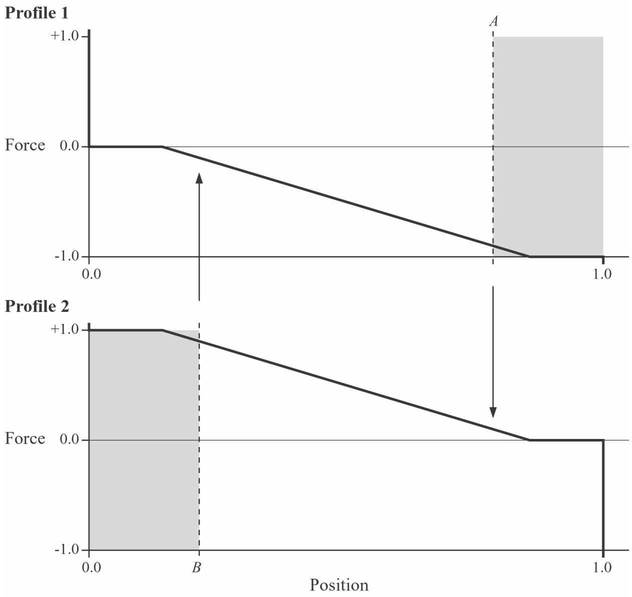

Figure 6: A system that exhibits hysteresis can be defined with two profiles each containing a switching point (A and B). When the position moves past the switching point the system will swap to the alternate profile.

3.3.2 Profile mirroring

Because the examples of hysteresis and oscillation use a pair of profiles that are essentially identical it should be possible to reduce that class of system to a single profile that becomes inverted. This would reduce the memory demand for such systems.

We can employ a method that inverts the behaviour of the system when a switching point is reached, this will produce the same behaviour as the dual profile system but with half the memory consumption. Whist this may be useful in some circumstances the ability to swap profiles enables dissimilar profiles to be combined in the same system to produce more complex profile switching systems.

3.4 Profile biasing and scaling for controlled actuation

The use of multiple profiles enables us to generate autonomous motion within the actuator. The degree of control we can exert is limited by the number of profiles already loaded into the system and the communications overhead required to load new profiles. A typical autonomous robot could employ many such actuators some of which may need to produce co-ordinated motion governed by some central control system

We can provide a method of more direct control over the actuator with minimum communications overhead by introducing two new variables to the profile being used. These consist of a bias value that shifts the profile up or down the range of travel and a scaling value that can compress or stretch the profile.

Figure 7 shows a profile defined as two linear springs that keep the output at a certain position. By employing a bias we can shift the position of the output by moving the profile, providing compliant actuation, and we can also expand or compress the profile along the range of motion to increase or decrease stiffness.

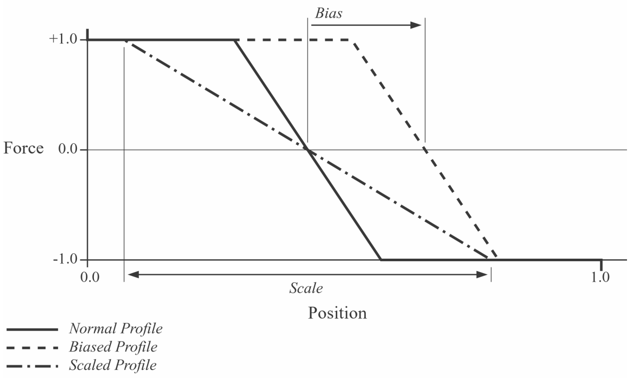

Figure 7: Profile biasing and scaling used to produce variable compliant actuation. A bias will shift the current profile along the position axis and the scale will stretch or shrink the profile.

4 Communications interface

External control of the system can be provided in a number of ways. Out prototype currently under development will provide two types of control interface, a serial communications system and a low level electronic switching interface. The microcontroller used in our prototype is a Microchip PIC18f4680.

4.1 Serial interfaces

The serial communications interface makes use of the hardware available on the microcontroller and consists of an RS232 serial communications port and a CAN Bus controller.

Either of these two interfaces can be used to send commands to the system including the loading of complete profiles or to bias, scale or swap an existing profile. The same interface can be used to request data from the actuator, for example the current force and position.

4.2 Digital logic interface

A second interface provides two pairs of digital input and output pins that deliver and accept logic level electrical signals. These can be used to implement a number of low level behaviours, for example a digital input can be used to trigger the actuator to change profiles and the corresponding output can be strobed to indicate when a trigger point has been passed. In this way a group of actuators can instigate profile changes in each other.

It is also possible to pass information in the form of pulse width modulated signals where the outgoing pulse width represents the actuators current angle or force, and the incoming pulse represents a desired force or position. This method can be used to implement a force mirror where the force and angle of two actuators reflect each other. This low level interface can also be used in parallel with the serial interface.

Figure 8 shows the proposed actuator that we are currently constructing. It employs an elastic force sensor integrated into a bevel gear allowing the output shaft to be driven at right angles by a motor and gearbox. This particular design was chosen to create a thin actuator with a double ended output shaft specifically intended for constructing elements such as leg joints for walking robots.

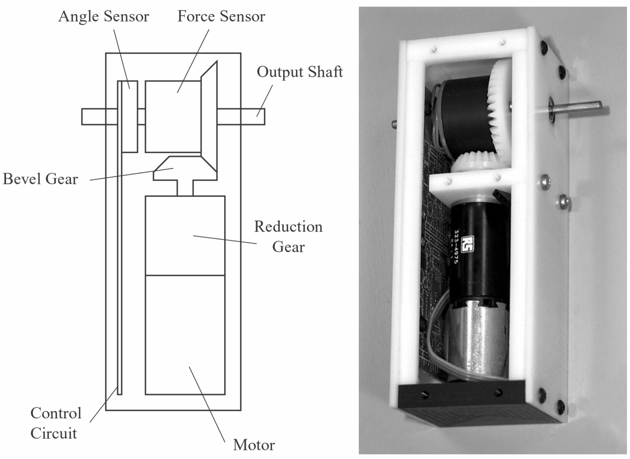

Figure 8: A Programmable Spring Actuator schematic and the prototype currently under construction. A bevel gear is employed to produce a thin actuator intended for constructing robot leg joints. The dimensions are approximately 50x50x120mm.

5 Applications beyond robotics

The potential applications for this approach to actuator design go beyond research into autonomous robotics. Consumer robotics is a rapidly growing field and cost effective compliant actuators may find many applications there and in the toy industry. The actuators could also be employed in haptic systems and computer gaming to produce force feedback devices. The use of force mirroring where one actuator reflects the force and angle states of another may also find applications in telepresence robots and in radio controlled toys.

One avenue of development we are exploring is to turn our actuator into a device for providing force feedback in radio controlled model vehicles. The existing actuators used in these vehicles, commonly referred to as the hobby servo, have been a popular off the shelf component in small autonomous robots for many years. Some manufacturers of these actuators have recognised this by producing versions specifically aimed at robotics. By developing a compliant actuator that can be applied to the radio controlled model market as a force feedback system it may be possible to exploit economies of scale and produce a range of very low cost programmable spring actuators.

6 Conclusion

The design proposed here is intended to fill a perceived gap in the market for off the shelf components intended for developing autonomous robots. Whilst it will never be possible to design a ‘universal’ actuator our system is intended to provide a wide range of functionality that can be applied to many robotic systems requiring controllable compliant mechanical elements.

We have deliberately avoided detailing specific performance characteristics of the actuator, for example the maximum torque or velocity that it can achieve, because these characteristics depend on specific design choices like the type of motor used. Instead we have attempted to outline a concept that can be easily applied to produce a range of different actuators with many different power and dynamic response characteristics suitable for a variety of applications.

Our test rig has provided a proof of concept for the design and the prototype system is in the final stages of construction before testing begins.

We plan to use Programmable Springs to develop a number of robotic systems; these include a passive dynamic biped, multi-legged robots and robotic manipulators.

The design of the actuator, in particular its variable compliance, gives it the ability to emulate the antagonistically actuated joints found in nature. This will allow us to pursue research into biologically inspired robotic systems that would normally be prohibitively expensive. The low cost and integrated control of the actuator will reduce the complexity of the engineering required to construct these types of robotic systems.

When the actuators are employed to model antagonistic joints it may prove useful to add extra methods of control to the system. These would allow the actuator to behave as a pair of antagonistic actuators and provide a method of control that reflects this model.

A key factor in the performance of the actuators will be the type of force sensing device used. We are currently experimenting with a custom made sensor that is simple to manufacture, low cost, robust and scalable. The design of the electronic control system is also important to the performance of the actuator and we are developing a mixed signal system that combines analogue and digital processing.

The inclusion of damping profiles will add to the behavioural complexity of the actuator and increase its functionality, allowing it to behave as a dynamically reconfigurable complex spring damping system.

The emphasis on the use of profiles as a method of defining the actuators behaviour is intended to provide a controlling interface that is both versatile and easy to use, enabling an actuator or group of actuators to be configured to exhibit complex dynamic behaviour with a minimal amount of engineering or programming.

References:

Alexander, R. M., (1988) “Elastic Mechanisms in Animal Movement” Cambridge University Press.

McGeer, T., (1990) “Passive dynamic walking” International Journal of Robotics Research.

Pratt, G. A. and Williamson, M. M., (1995) “Series elastic actuators" IEEE International Conference on Intelligent Robots and Systems, vol. 1.

Torres-Jara, E. and Banks, J., (2004) "A Simple and Scalable Force Actuator" International Symposium of Robotics.

Vaughan, E., Di Paolo, E. A. and Harvey, I., (2004) “The Evolution of Control and Adaptation in a 3D Powered Passive Dynamic Walker” Proceedings of the Ninth International Conference on the Simulation and Synthesis of Living Systems, ALIFE'9 Boston, September 12th-15th, MIT Press.

Williamson, Matthew M., (1998) "Rhythmic Robot Arm Control Using Oscillators" Proceedings of IROS '98.