Programmable Springs: Developing Actuators with Programmable Compliance for Autonomous Robots

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Abstract

Developing real robots that can exploit dynamic interactions with the environment requires the use of actuators whose behaviour can vary 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 easily configured using a high level programming interface to emulate complex multimodal spring damping systems. The types of behaviour that our actuator can exhibit are explored, including antagonistic actuation, cyclic behaviour and hysteresis. This system is intended as the basis for a cost effective 'off the shelf' component for robotics research and development.

Key words: Actuators, Programmable Compliance, Passive Dynamics, Autonomous Robotics.

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1. Introduction

Motion control in robotics is a long established and well understood field and forms the basis of most modern manufacturing technology. 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.

These design and control principles can be seen in the advanced humanoid robots being developed in Japan, for example ASIMO and QUIRO produced by Honda and Sony, as well as robots used in research and the emerging hobby and consumer markets.

In contrast to these approaches some research has shown that perturbations introduced from the environment can be beneficial to the behaviour of some robotic systems. McGeer [2] 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 at Sussex [4] 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 [1] 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 briefly outline the concept of the Series Elastic Actuator, developed at MIT [3] as a force controlled actuator, and then our patented prototype design for a 'Programmable Spring' which takes the Series Elastic Actuator design as a basis for a low cost and versatile building block for autonomous robots.

The key feature of our design, and the main topic of this paper, is our high level programming or behaviour specification system that provides a high level unified method of specifying actuator behaviour in terms of Force, Position and Velocity.

2. Series Elastic Actuators

In order to address some of the issues of actuator compliance the Series Elastic Actuator was proposed [3]. 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 Fig. 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. To date a number

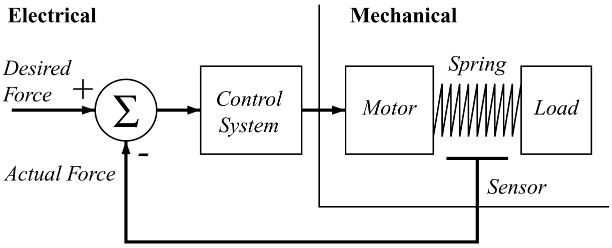

Fig. 1. Schematic diagram of a Series Elastic Actuator.

of different actuators have been developed and employed including both linear and rotary versions to drive robotic arms and other compliant mechanisms [5].

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 [3].

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. Their ability to make use of a wide variety of motor and gearbox configurations, including low cost motors or other non electrical actuation devices such as pneumatics, makes it a preferred solution for us when compared to other compliancy mechanisms such as direct drive motors. 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. The Programmable Spring Actuator

The following sections describe our prototype actuator and control system, followed by some experimental results. This provides an introduction to the particular control method we have implemented and the ways in which we can use it to rapidly and easily configure the actuator to exhibit a variety of complex behaviors. The intention here is to describe in general terms our approach to the design of variable compliance actuators and our high level programming system. We will not explore in detail the specific performance characteristics of our prototype system.

3.1. *Integrated angle sensing*

The Series Elastic Actuator provides a means of regulating force but it does not directly introduce any angle or position based control. To date, applications for series elastic actuators have employed angle sensing as a separate sensor modality within the construction of the robot [5] and as such rely on a centralized control system or an additional layer of distributed control to regulate force with respect to angle.

Our approach has been to concentrate on the development of an integrated actuator containing force and angle control within a single unit. This is combined with an embedded 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 with minimal engineering complexity. Whilst the following sections describe an actuator with a rotary output, producing angular measurements, we can apply this system equally well to an actuator with a linear output.

3.2. *System schematic*

A block diagram of the proposed actuator is shown in Fig. 2 and contains two coupled electromechanical systems. The first system is a Series Elastic Actuator comprising a motor and gear train coupled to a rotating output shaft via a rotary elastic force transducer. This system incorporates a microcontroller based PID controller that will drive the motor to maintain a specified force. The second system comprises an angle sensor at the rotating output of the mechanical system that produces both angle, and angle velocity signals. These are read by a microcontroller that outputs a force value to the series elastic actuator. The microcontroller also incorporates a number of external inputs and outputs, these include an RS232 serial interface, a CAN bus interface, a set of digital input and output ports and two pairs of analogue inputs and outputs.

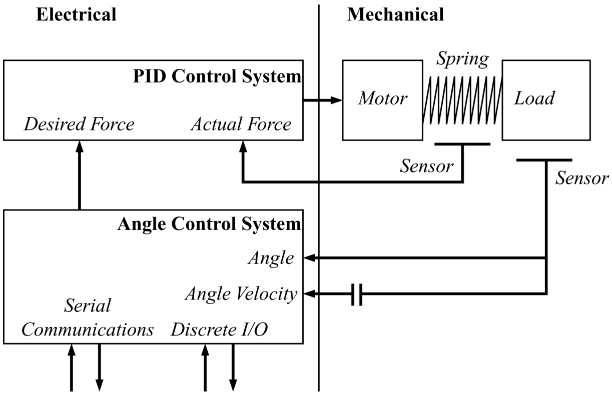

Fig. 2. Schematic diagram of a Programmable Spring.

Fig. 3 shows a photograph of our prototype system. Our choice of physical embodiment is intended to facilitate easy construction of a variety of robot morphologies with minimal engineering complexity and as such we have chosen to produce a system with a double ended rotary output shaft at one end of the actuator. This will enable us to use the actuators to directly construct robotic joints rather than using mechanical linkages to transfer power to the joint.

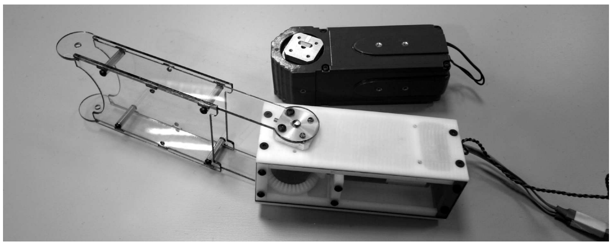

Fig. 3. A photograph of the prototype actuator used in our preliminary work (bottom) with a lever attached to the output and (top) the next generation prototype. The approximate size of the actuator is 50 x 50 x 160mm.

4. Dynamically Controllable Springs

An existing method for using a Series Elastic Actuator to generate compliant actuation has been employed on robots such as COG [5] and involves a PD (Proportional, Derivative) control loop operating with an angle sensor and generating a force target for the Series Elastic Actuator. In this system an angle target is specified and an error signal is then generated by subtracting this value from the actual angle. This error is multiplied by a gain variable to produce a target force for the Series Elastic Actuator. The velocity of this error can also be computed, multiplied by a gain variable and added to the error to produce damping.

The resulting system behaves as if the robotic joint is held in a certain position by a damped spring. Actuation can be achieved by altering the position target for the system and the stiffness and damping of the system can be controlled in real time by altering the proportional and derivative gains.

This method of control provides a simple and dynamically controllable variable stiffness actuation system and provides a potentially useful mode of control for the actuator however, it does not exploit its full potential.

The intention behind our design is to provide a functional module that can be deployed rapidly in the development of experimental robots. As such it should provide a means of specifying the actuator's behaviour that provides a high level of control and configurability without requiring the user to directly program the microcontroller at the code level.

4.1. *Force profiles to define complex spring systems*

The system outlined above is limited to linear spring damping systems. If we wished to specify non linear springs we would need to add mathematical functions to compute this non linearity. Whilst for some functions this might be trivial there will inevitably be a computational load on the system when more complex functions are used.

Our solution is to define the spring system as a look up table of force values, referred to from here as a profile, for each angle that the system can measure. This allows us to define any arbitrary spring system as opposed to those that can be defined by mathematical functions. We also apply this method to produce damping behaviour with profiles that define a damping factor for each angle and in each direction of motion.

Fig. 4 illustrates two force profiles. The first demonstrates a system with a linear spring that will hold the output at the equilibrium point with a spring force defined by the slope of the profile. This system is functionally equivalent to the PD system described above where the proportional error and velocity gains are equivalent to the slope of the force and damping profiles.

The second force profile shown illustrates the versatility of our system in its ability to define arbitrary spring systems within the actuator's range of movement. This example shows a number of different spring systems that apply at different angles; these include constant force springs, non linear springs and zero force or fully compliant zones. Fig. 5 illustrates the system in action using the simple linear spring shown at the top of Fig. 5. No damping has been specified. The actuator was manually deflected away from the equilibrium point before being released. The result is a plot of the angle with respect to time and the inset photographs show the starting and finishing positions of the actuator. This serves to illustrate the 'spring like' behaviour that the system is capable of. In its current form our actuator is designed to test and demonstrate the profile control system but has not been refined and calibrated to the degree required to do a proper analysis of its potential spring properties.

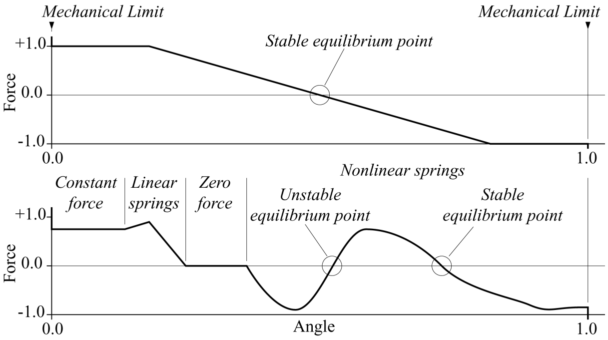

Fig. 4. (Above) A force profile used to define a simple linear spring system with a central equilibrium point. (Below) An example of an arbitrary complex spring profile that includes regions of zero force, constant force, linear and non-linear springs. Positive force values will, in the absence of an equal or greater opposing force, increase the system's position whilst negative forces will decrease it. A force value of zero will produce total compliance. The force and angle units used in these diagrams have been normalised to a range of -1.0 to 1.0 for force and 0.0 to 1.0 for angle. This range represents the torque and angular limits of the system.

4.2. *Actuating with force profiles*

This profile system makes it possible to program complex spring behaviours into the actuator but it does not directly provide a method of actuation. If we want to impart motion into the actuator rather than letting it behave

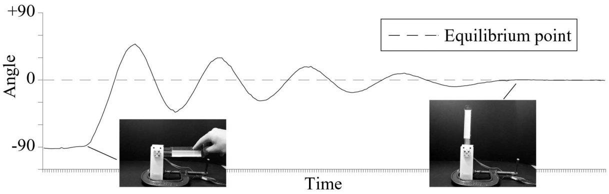

Fig. 5. A simple linear spring system in action showing the angle with respect to time as the system is manually deflected away from the equilibrium point before being released. The inset photographs show the actuator in its start and end positions.

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.

In order to achieve actuation efficiently we have included biasing and scaling factors to modify the force and damping profiles. Fig. 6 illustrates these methods applied to the horizontal scale of a force profile that defines a stable equilibrium point between two springs. The bias value allows us to effectively shift the force profile along the angle axis, producing movement at the output, whilst the scaling factor allows us to expand or contract the force profile along the same axis and vary the stiffness of the spring forces.

In the case of scaling we need a point of origin around which the scaling will occur. If we were to scale the system around angle zero we would also produce movement at the output as the equilibrium point shifts along the angle axis. To control this we have an additional variable called the scaling origin that defines the angle around which the scaling occurs. In Fig. 6 the scaling origin has been set to the equilibrium point implied by the force profile. This point is always referenced to the profile's biased position. The example above illustrates profile biasing and scaling along the horizontal or angle axis. We have also defined identical variables for the vertical axis such that the profile can be biased and scaled along the force axis.

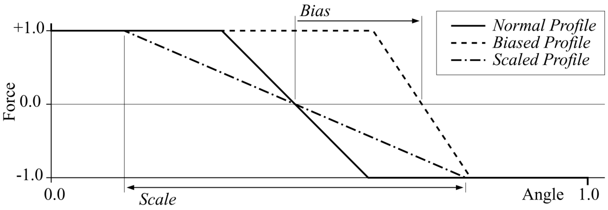

Fig. 6. Profile biasing and scaling used to produce variable compliant actuation. A bias will shift the current profile along the position axis and the scale will expand or contract the profile along the same axis.

4.3. *Damping profiles*

Damping profiles are defined in the same way as force profiles with a look up table of values relating to each angle the system can measure. We have included two sets of damping profiles each of which apply to one direction of movement. This allows us to apply damping in one direction only, and over specific angles. The damping profiles and force profiles operate as one unit with respect to the bias and scaling values so that applying a bias to shift the force profile will also shift the damping profiles.

We have also included a second type of damping referred to as uniform damping which applies to all angles and in both directions of motion.

The values for all the damping systems can be specified as negative or positive values, this has some interesting and possibly beneficial uses. With the correct degree of negative damping the system can negate some effects of friction. Specifying a larger negative damping value can also be used to produce oscillations as any perturbation introduced into the system will be amplified.

5. Profile Groups for Multimodal Behaviour

In order to achieve our aim of a unified and general purpose method of specifying complex behaviour within the actuator we have taken the force and damping profiles and their biasing and scaling variables or modulators, and combined them with a number of conditional triggers. These triggers are activated when certain variables exceed their thresholds, for example an angular or velocity threshold, and can cause a pre-defined change in actuator behaviour, for example switching to an alternate set of profiles.

We refer to these sets of profiles, modulators and conditionals as profile groups and each actuator can be preprogrammed with a number of these groups. With the ability to apply conditions upon which the actuator will switch between different groups we can configure the system to produce a large variety of behaviours including latching or hysteresis, oscillations and reactive or reflex behaviours. These various modulators and conditionals can also be linked to the various analogue and digital inputs and outputs that our hardware provides, facilitating inter-actuator modulation and conditional triggering.

5.1. *Modulators*

The biasing and scaling variables outlined above allow the force and damping profiles to be altered dynamically whilst the system is running. There are several methods of adjusting these variables and they include serial control commands sent via the RS232 or CAN bus interfaces. In addition to this method each of the bias and scale variables can be controlled by analogue to digital inputs provided in the hardware. In this way it is possible to allow a variety of input devices to modulate a profile group.

In a similar fashion it is also possible for system variables like the angle or force to be mapped to one of the two analogue outputs provided. When used in combination with the analogue input it is possible to link two or more actuators together and allow, for example, the angle variable of one actuator to set the horizontal bias of a second actuator.

5.2. *Conditionals*

A number of conditional variables exist that can be configured to trigger an event when a variable goes above or below the defined threshold. Each conditional element has a threshold variable that determines at which point the conditional trigger is activated plus a target variable that determines what the system will do with that event. The conditional triggers relating to system variables that we have included in our actuator are angle, angular velocity and force. In addition it is possible to configure the digital inputs provided by the hardware to trigger an event when their state changes.

The events that can be triggered by any of these conditionals include switching to a different profile group, enabling or disabling any other conditional trigger, and activating a digital output.

An additional and specific conditional variable has also been included. This is a motor enable threshold that allows the system to suppress motor activity if the measured force is below a certain level. This element of the design allows the user to 'lock out' the active compliance of the system below certain force levels and instead rely on the passive spring within the force transducer. This can be of particular benefit in some cyclic tasks such as maintaining a static stance or hopping where, in combination with a naturally high impedance gearbox, the system can use the passive springs in the torque transducer to either maintain some compliance or to store kinetic energy. This provides a much more power efficient method of producing certain behaviours than using active compliance alone.

There are a large number of possible behaviours that can be created using these conditional triggers. To generate a system with latching or oscillating behaviour we can employ a simple linear spring profile with an angular threshold that, when passed, will cause the system to swap to a new profile group with an opposite spring and threshold. If the spring profile in each group pushes the system away from the threshold then we can produce latching behaviour and if they push the system towards the threshold then the system will oscillate.

The potential for inter-actuator communication can also be used to facilitate some autonomous behaviour within groups of actuators. By making use of the various input and output ports on the actuator we can produce more complex multi-jointed systems. An example relevant to robotics research would be to configure a group of two actuators to function as a single leg, with one actuator providing forward and backward (stepping) movement and a second to raise and lower the leg (lifting).

The actuator's can be coupled electronically such that perturbations in the stepping actuator that push it beyond a threshold will trigger the lifting actuator to raise the leg. When the leg is lifted off the floor the spring forces in the stepping leg will cause it to swing forward, until a second threshold is reached and the lifting leg drops back down to support the robot. When combined with a number of identical leg units and a set of communication channels to prevent more than one leg stepping at once, the robot that will respond to perturbations by walking.

5.3. *Failsafe Modes*

The combination of digital inputs with conditional triggers provides some methods of configuring a variety of safety modes for the actuator that may be of value in the safe operation of autonomous devices around humans. It is possible, for example, to define a profile group specifically for certain fault conditions which the system can jump to when necessary. The trigger for this could be a limit switch to guard trap points within a mechanism and prevent a person's fingers getting crushed, or equally a serial command indicating a failure in another part of the robot.

5.4. *Profile Summation*

In addition to the ability to switch between profile groups we have also included in our specification a method of using two profile groups together. This is designed principally to emulate the antagonistic style of actuation found in biological systems and involves the concurrent use of two profile groups whose force and damping outputs are summed. With this system it is possible to define a pair of spring damping systems, each working to push the output in opposite directions. By employing the bias variables in each group these two groups can be either drawn apart, leaving the joint compliant, or drawn together to create a stiff joint. By biasing both profiles at the same time it is then possible to move the resulting equilibrium point around.

5.5. *Function Generators and Neural Oscillators*

Some additions to our profile group control system that we plan to explore but have yet to implement are several methods of generating signals and modulating variables within the actuator. The types of behaviour we hypothesize might be beneficial to an actuator designed for autonomous robotics are various oscillatory behaviours that might be employed to produce walking or other cyclic behaviour.

The first and simplest method is to include a set of software function generators with each profile group. These could be used to produce waveforms that modulate profile parameters and are modulated by other profile parameters.

A more sophisticated method is to include a small neural network that can be configured to function as a neural oscillator. Work by Williamson [5] using a simple neural oscillator to generate cyclic behaviour in a robot arm has shown that in some instances adaptive behaviour in a cyclic multi-actuator system can be achieved with simple localized oscillators. As with the function generators the network inputs and outputs can be mapped to and from various system parameters.

5.6. *Too many features . . .*

There are a large number of potential triggers that we might incorporate within the actuator, for example we could include thresholds for the rate of change in angle velocity, potentially useful for detecting collisions.

No doubt there are circumstances where other more unusual conditional triggers are of value, however there inevitably has to be a compromise between including useful features and making the system too complex or computationally demanding to be practical, or power efficient. We anticipate that applying our system to the control of real robots will illustrate what features are most useful.

In some circumstances other methods of control may prove more appropriate. In the example of antagonistic actuation we are considering adding a method of control designed to explicitly emulate the so called hill-type muscle model [6].

6. An Example of Multimodal Behaviour

To illustrate the use of conditional thresholds in conjunction with a pair of different profile groups we constructed a simple reactive system, a pin ball flipper, which reacts to a ball hitting a lever by pushing the ball away.

This control system is shown in Fig. 7 and consists of two profiles each with one angle threshold. In profile group one the system defines a stable equilibrium point between a weak linear spring and a damped constant force spring. When the system is perturbed (by a ball hitting the flipper) it is pushed past the angle threshold (A) and swaps to profile group two. Profile group two consists of a strong spring force that drives the system and with it the lever (and ball) towards a positive angle. As the system approaches the threshold for this profile group (B) a damping force begins to counteract the motion of the flipper, slowing its motion until it reaches the threshold. The system then returns to profile group one where the weak constant spring force returns it to the equilibrium point. The damping defined along this constant force zone prevents the system overshooting its equilibrium point and triggering a new cycle. Fig. 8 shows the system in action with actuator angle plotted against time.

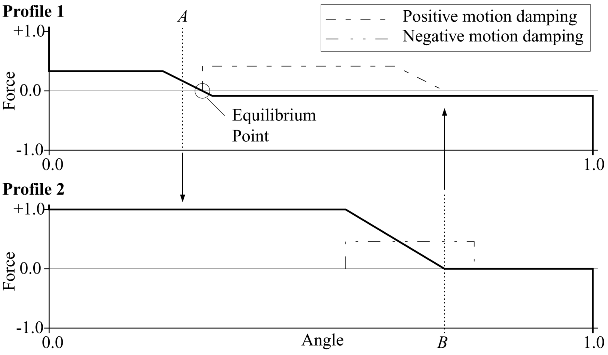

Fig. 7. The two profile groups used to create a pin ball flipper. Conditional damping for each group is also shown.

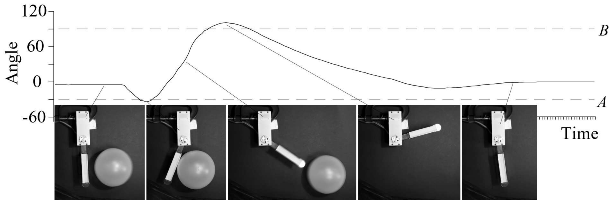

Fig. 8. The pin ball flipper in action with the actuator's angle plotted against time. Inset images show the actuator's various states. Angle thresholds (A and B) are also shown.

7. 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.

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. 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 that find their way back into the robotics market.

8. Conclusion

The design proposed here is intended to fill a perceived gap in the market for off the shelf components 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. With this in mind it would be fair to say that this research has a strong element of product design as well as scientific exploration.

The main focus of this paper has been on the control system, and specifically on the use of profile groups as a high level unified method of specifying the actuator's behaviour. We have also demonstrated some principal features of this control system in action. Whilst our approach can be used to create complex autonomous behaviour within an actuator, the profile system also provides low level direct control. Specifying a force profile with zero force across all angles, and using the vertical bias to shift it up and down the force axis, can be used to directly command the force output whilst still accommodating the conditional triggers we have outlined.

We have deliberately avoided detailing specific performance characteristics of the actuator, such as torque or velocity, because these characteristics depend on specific design choices like the type of motor used. Instead we have attempted to outline our high level control 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. We recognise that an important part of our next stage in development will be to produce a more detailed analysis of a specific actuator in action.

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 ability to emulate antagonistic actuation allows us to explore biologically inspired modes of control in these robots.

The emphasis on the use of profile groups as a method of defining embedded actuator 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.

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