Force and position control using pneumatic cylinders

G. McLatchey, J. Billingsley
University of Southern Queensland – Faculty of Engineering and Surveying
West St, Toowoomba, Queensland 4350 - Australia
email: mclatchg@usq.edu.au, billingsley@usq.edu.au

Abstract: **The supporting legs of legged robots form part of multiple closed kinematic chains in which antagonistic forces can pose a problem. In this paper, methods of compliance and force control are explored to resolve this. A 'nested loop' topology of non-linear control for pneumatic cylinders is outlined and its performance in actual implementation is reported.**

Keywords: **Force Control, Position Control, Pneumatics**

I. Introduction

Statically stable walking robots have advantages over wheeled robots in rough terrain negotiation and stability in a dynamic environment with inertial and manipulator forces but their development is not sufficiently advanced to see them used in real applications [1], [2], [3].

Legged robots are complex systems to control. Multiple closed kinematic chains exist between the legs, ground and body of a legged robot. Also, legged robots operate in an unstructured environment where terrain data is incomplete and inaccurate.

Much of the existing research is limited by its fundamental method of position control. Position control in an over-constrained system with incomplete and inaccurate system data leads to antagonistic (internal) forces between the legs [4], [5]. These forces waste energy, decrease effective available leg force, cause foot slippage and increase stress in structural elements.

Existing research has attempted to alleviate antagonistic forces by wrapping a force or impedance layer around the position control loop (e.g. the quadruped Silo4 [6] and hexapod Katharina [7]). The force feedback response is thus modified to respond to positional errors according to Hook's law [6]. This approach of Active Compliance is designed to adapt position control to cope with incomplete and inaccurate environmental and system data. The increased compliance does reduce internal forces but also reduces the ability of the robot to respond to external forces (e.g. Silo4 became unstable on sloping ground [6]).

II. Pure Force Control

Supporting legs under pure force control fully comply with any changes in position (up to the kinematic limit) while applying the target force. Environmental data is now reaction force which can be easily measured and controlled. This makes over-constrained systems much easier to control [8], [9], [10] and antagonistic forces can be easily recognised and minimised which leaves full force available to balance external forces.

III. Actuators

Position control rather than force control has remained popular in legged robot control, however, due to the prevalence of electric motors. Electric motor-based actuators are commonly used due to their low weight, size and cost, high power and ease of integration. However, they are difficult to use in force control because of their high stiction and reflected inertia [9].

Fluid based actuators such as hydraulics and pneumatics are well suited for force control because controlling fluid pressure controls force. Hydraulic actuators are capable of large forces, however their large weight limits their use to heavy robots e.g. ASV [11]. McKibben artificial muscles are not attractive for control due to their non-linear response, hysteresis and small stroke. Pneumatic cylinders are cheap, light, have a compact footprint and are naturally compliant. However, they can have high stiction, making small forces difficult to attain, and they are low in power density. Also their natural compliance makes position control difficult [12], [9].

Researchers who have used pneumatic cylinders in legged robot designs have pursued control strategies other than force control with poor results. For example STIC [12] and Robot III [13] required physical assistance to walk.

IV. Nested Loop Control

This paper reports on a new method in leg control using pneumatic cylinders. It is suitable for a cylinder with four valves controlling fluid flow from the pressure line and venting to atmosphere on both sides of the cylinder. This arrangement allows full compliance control over the cylinder as pressure can be increased on both sides to stiffen the system.

The control loop consists of four nested loops of classical proportional control of position, velocity, force and pressure (see **Fig. 1. Nested Control Loop**). The Position Error becomes the Velocity Demand. The Velocity Error becomes the Force Demand and the Force Error becomes the Pressure Demand. This technique allows a seamless transition between the four types of control allowing position control to be used for a relocating leg and force control for a supporting leg.

Pneumatic cylinders are naturally compliant due to the compressible nature of air. This can be controlled by controlling the absolute pressure in both sides of the cylinder relative to atmosphere. Holding one side at maximum air pressure and adjusting the other side according to Pressure Error can produce a very stiff system (0% Compliance Strategy). Conversely, holding one side at zero air pressure and adjusting the other side according to Pressure Error will produce a very compliant system (100% Compliance Strategy) (see **Fig. 2. Variable Compliance Strategy in a Pneumatic Cylinder**).

This new method is able to control the system compliance anywhere in between these extremes by inserting a

Compliance Offset (see **Fig. 1. Nested Control Loop**). A Compliance Offset equal to supply air pressure would produce the 0% Compliance Strategy, while a Compliance Offset of half supply pressure and zero would produce a Compliance Strategy of 50% and 100% respectively.

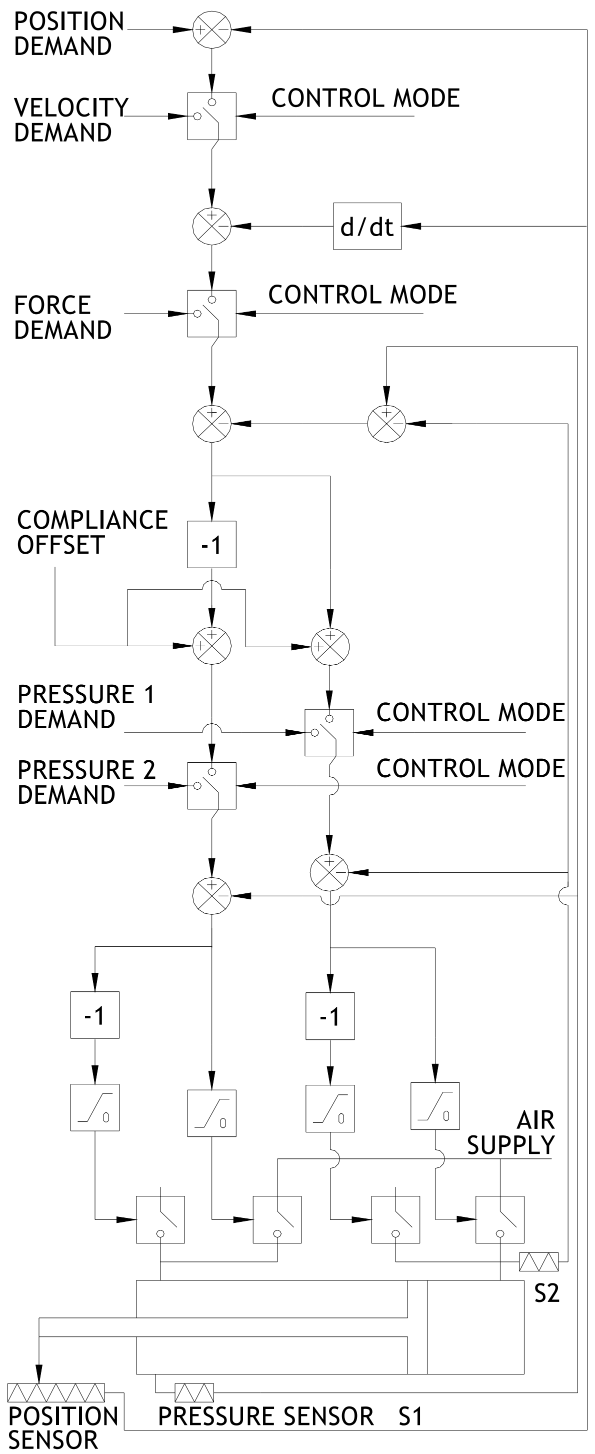

Fig. 1. Nested Control Loop

V. Experimental Set-up

The nested control loop was implemented on one of Robug IV's legs, which consist of three revolute joints named abductor, hip and knee. Each joint is actuated with a double acting pneumatic cylinder, which is controlled using four valves (two on each side of the piston, controlling inlet and exhaust). Two SenSym pressure sensors are used to measure the pressure on each side of the piston and allow the force applied by the cylinder to be calculated. Cylinder extension for hip and knee joints is measured using a linear potentiometer. A rotary potentiometer is used to measure the angle of the abductor joint. These values are included in their respective control loop as the "Position" variable. The "Velocity" variable is calculated by the finite difference approximation (1).

$$Velocity(t) = (Position(t + \Delta t) - Position(t)) / \Delta t \quad (1)$$

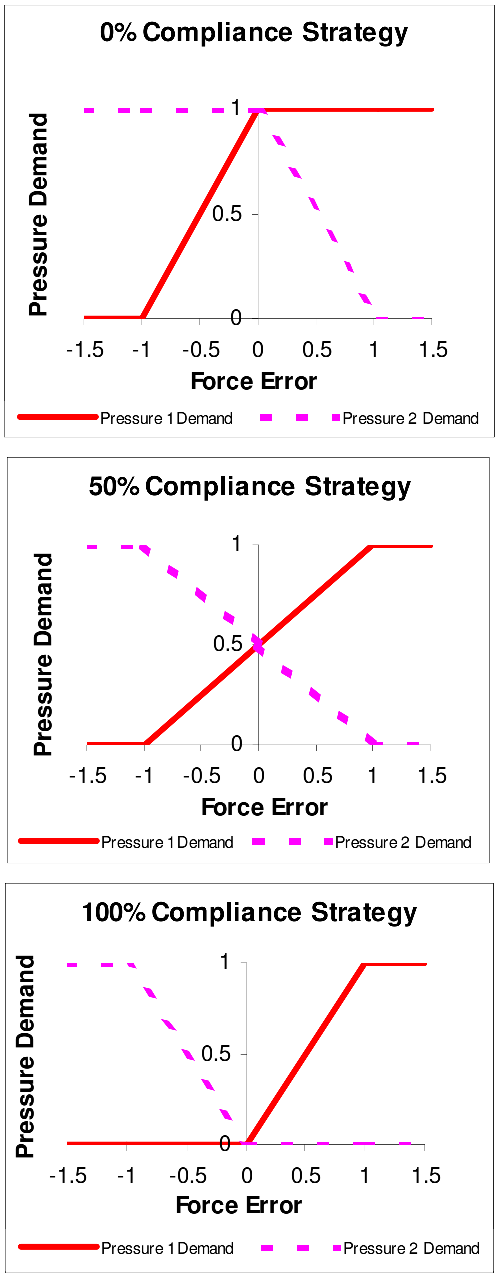

Fig. 2. Variable Compliance Strategy in a Pneumatic Cylinder

VI. OBSERVATIONS

The control loop was simple enough to be implemented on low processing speed microcontrollers without PWM (in a Bang-Bang style). Control input consisted of choosing the desired Control Mode, issuing a target for that Control Mode and choosing a Compliance Factor (between 0 and 100%).

Smooth position control was shown to heavily depend on the accuracy of the position sensor. The abductor velocity signal proved too noisy for control as it was calculated from the rotary potentiometer, which was noisy itself. Bypassing the velocity loop and coupling the position loop directly to the force loop resolved position control. This did, however, remove velocity control. Sporadic jitter that persisted under position control due to erroneous position sensor data was removed by decreasing compliance thereby stiffening the system. This did not affect the response of the system.

It is important to note that the Nested Loop form allows non-linear control techniques such as limits. For example position limits can be placed in software rather than relying on hardware stops, and velocity can be limited to improve safety and decrease effects of system dynamics.

VII. BENEFITS OF FORCE CONTROL

Force based methods have many advantages in legged robotics. Some of these have been recognised by researchers and investigated theoretically. These include foot-force distribution and force based stability criterion.

Foot-force distribution control is regarded as essential for optimal traction, minimal internal forces [4], [14], [15], reducing energy use and actuator torque and sharing forces evenly between the supporting legs [1], [16]. However, most existing methods are too complex for real-time control [1], [16] and/ or are only suitable for a minimum number of three supporting legs [3]. This is further hampered by implementing foot-force algorithms on systems with position or impedance control (for example, Silo4 [3]).

Force based stability margins are promising because the stability criterion directly uses environmental data already found (with a minimum of processing) which is accurate and complete, without using a system or environmental model. Stability margin results can also be directly mapped to the control being used, meaning the stability margin goes from merely observing system status to influencing system control [3].

Force based methods show great promise in real applications for legged robotics because they are suited to over-constrained systems. Environmental data in the form of reaction force is accurate, complete and able to be used in several algorithms with a minimum of further processing. System dynamics are measured rather than predicted making system and environmental models redundant and streamlining control. Also, the consistency between several force-based algorithms operating concurrently supports their integration.

VIII. REFERENCES

[1] Lin, B.S. and S. Song, *Dynamic Modeling, Stability, and Energy Efficiency of a Quadrupedal Walking Machine.* Journal of Robotic Systems, 2001. **18**(11): p. 657 - 670.

[2] Warren, H., *Clawar Task 19 - Barriers to Commercial Exploitation of Mobile Robotics.* 5th International conference on Climbing and Walking Robots, 2002: p. 917.

[3] Gonzalez De Santos, P., *Silo 4, A True Walking Robot for the Comparative Study of Walking Machine Techniques.* IEEE Robotics and Automation Magazine, 2003. **1070-9932/03**: p. 23.

[4] Jiang, W.Y., A.M. Liu, and D. Howard. *Foot-force Distribution in Legged Robots*. in *4th International conference on Climbing and Walking Robots*. 2001.

[5] Kar, D.C., *Design of Statically Stable Walking Robot: A Review.* Journal of Robotic Systems, 2003. **20**(11): p. 671-686.

[6] Garcia, E. and P. Gonzalez de Santos. *Controlling Dynamic Stability and Active Compliance to Improve Quadrupedal Walking*. in *8th International Conference on Climbing and Walking Robots*. 2005.

[7] Palis, F. and V. Rusin, *Adaptive Impedance/ Force Control of Legged Robot Systems.* 4th International conference on Climbing and Walking Robots, 2001: p. 323.

[8] Zielinska, T., *Synthesis of Control System - Gait Implementation Problems.* 4th International Conference on Climbing and Walking Robots, 2001: p. 489.

[9] Pratt, J., B. Krupp, and C. Morse, *Series Elastic Actuators for High Fidelity Force Control.* Industrial Robot: An International Journal, 2002. **29**(3): p. 234-241.

[10] Colbrunn, R., G. Nelson, and R. Quinn. *Modeling of Braided Pneumatic Actuators for Robotic Control*. in *2001 IEEE/ RSJ International Conference on Intelligent Robots and Systems*. 2001.

[11] Ridderstrom, C., *Legged Locomotion: Balance, Control and Tools - from Equation to Action*, in *Machine Design*. 2003, Royal Institute of Technology: Stockholm, Sweden.

[12] Cubero, S., *Force, compliance and position control for a pneumatic quadruped robot*, in *Faculty of Engineering*. 1997, University of Southern Queensland: Toowoomba.

[13] Kingsley, D.A., R.D. Quinn, and R.E. Ritzmann. *A Cockroach Inspired Robot with Artificial Muscles*. in *International Symposium on Adaptive Motion of Animals and Machines (AMAM'03)*. 2003. Kyoto, Japan.

[14] Fielding, M.R. and G.R. Dunlop. *Omni-directional Hexapod Walking and Efficient Gaits using Restrictedness*. in *5th International conference on Climbing and Walking Robots*. 2002.

[15] Celaya, E. and J.M. Porta, *A Control Structure for the Locomotion of a Legged Robot on Difficult Terrain.* IEEE Robotics and Automation Magazine, 1998. **5**(2): p. 43-51.

[16] Kar, D.C., *Minimum Energy Force Distribution for a Walking Robot.* Journal of Robotic Systems, 2001. **18**(2): p. 47-54.