DEVELOPMENT OF A ROTARY PNEUMATIC MUSCLE BASED ACTUATOR FOR ANTROPOMORPHIC JOINTS

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ABSTRACT —This paper outlines the research on the design and development of a novel rotary pneumatic actuator with applications in revolute direct drive joints of robot mechanisms. An analytical model describing the behaviour of the rotary pneumatic actuator is put forward and simulated results of this rotary pneumatic actuator are generated. The results from the simulation of the analytical model are discussed and conclusions are made concerning the model and its potential use in the model based controller for the rotary pneumatic actuator in robot systems.

INTRODUCTION

The actuation system is an essential feature of a robotic mechanism. This provides the forces, torque's and mechanical motions needed to move the joints, limbs or body. Whatever actuator is used, there are certain general requirements. The actuator should have a high ratio of power output to weight. In addition it should provide flexible control of the movement.

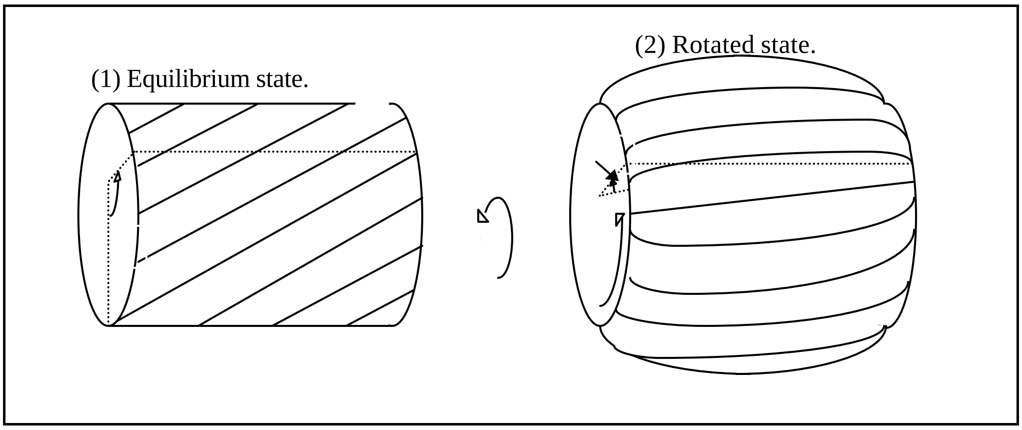
It is important in robotic applications that the weights of all components should be minimised. These components include the actuator and the energy store [1]. The actuator should be as quiet as possible if it is to be used as a general purpose robot. Above all, safety must be considered, if the robot is to be generally acceptable.

When designing actuators, it is important to consider how the power is transmitted to the link mechanism. Systems where the power is transmitted by belts, cables, straps and chains tend to suffer from friction related problems such as hysteresis, and backlash. Use of direct drive actuators can overcome this. The important issues for direct drive actuators are that they must be light so as not to adversely affect the weight of the manipulator and they must be small in size so the manipulator does not become unwieldy [2].

The quest to improve performance has seen research in different fields, stepper motors have been used because they are reasonably accurate in systems with open loop control and provide greater torque relative to other types of motors [3]. Thermal actuators make use of the fact that materials expand when heated. Thermal actuators are simple and capable of high output forces for the size of the actuator. Unfortunately, they are slow and have a very short stroke [4,5]. Shape memory alloys (SMA) are metals which return to a "memorised shape". Most of these applications of SMA have produced actuators which are reliable with high force for the size of the actuator. The disadvantages are long cycle times and low efficiency (<10%). Piezo-electric actuators use materials such as quartz [6]. When subjected to an electric current the shape of this material changes. These actuators are compact, accurate and have a fast response time. They are also very easily controlled [7]. The disadvantage of these actuators is that the stroke is very small. This has seen their use mainly in micro-robotic applications. Artificial polymeric muscles take advantage of the energy stored in chemical substances. This type of actuator has been used in proto-type robotic devices developed by the Massachusetts Institute of Technology [8]. The McKibben based muscle has been used by in a number of applications [9]-[12]. This muscle uses a rubber inner bladder with a braided outer sheathing to produce a linear contraction or elongation [14, 15].

THE NEED FOR A ROTARY PNEUMATIC MUSCLE

A new variant on the McKibben muscle has been developed in this research. This produces a rotary action. As most joints are rotary, the advantages of a rotary pneumatic muscle is that it can be used directly as the joint of a robot to act as a direct drive mechanism. In addition the use of pneumatics also enables the use of a cheap power source, with high output power and low weight actuators so that a high power to weight ratio is obtained.

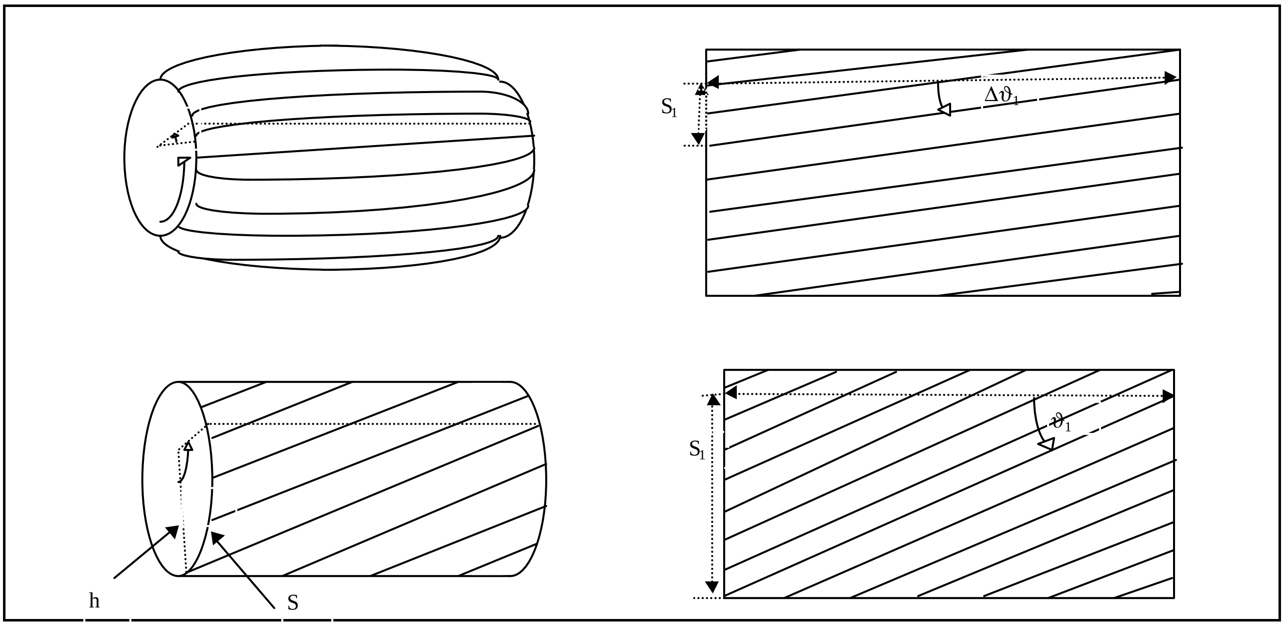


(1) Is the rotary muscle in the uninflated state. (2) The muscle after it has been inflated.

Figure 1 - Diagram of the rotary pneumatic cylinder

CONSTRUCTION OF ROTARY PNEUMATIC MUSCLE

The pneumatic muscle is constructed from two metal cylinders held together with a bearing in the middle. This forms a single cylinder where each end is able to rotate in opposite directions about the longitudinal axis. A rubber bladder is attached at each end of the composite cylinder. Nylon fibres at a predetermined angle to the longitudinal axis are bound at each end to the cylinder to form an outer sheath. The sheathing is located on the outside of the rubber bladder (Fig. 1).



ϑ is the angle between the fibre and the effective length of the two dimensional representation.
h is the radius of the rotary pneumatic muscle.
k is the length of the cylinder.
l is the effective length. In this case it is the same as the cylinder length.
S is the arc length of the angle of rotation of the rotary pneumatic muscle with radius h.

Figure 2 Rotation of a 2D cylinder.

When the muscle inner bladder is inflated, the angle of the nylon fibres to the longitudinal axis changes as the fibres are pushed outwards thus causing the rotation.

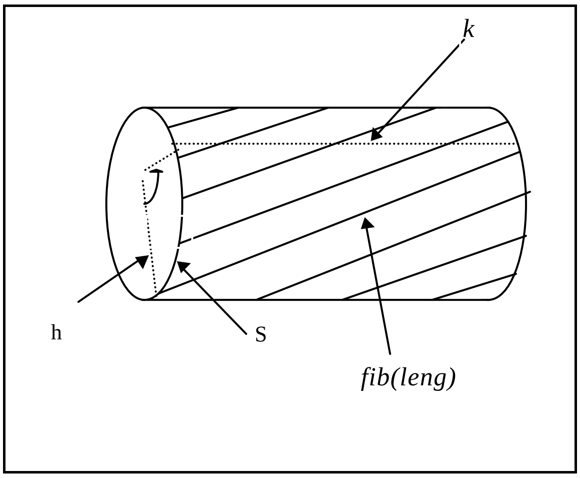
MODELLING OF THE ROTARY PNEUMATIC MUSCLE

The rotary pneumatic muscle converts pneumatic energy into mechanical energy by transferring the pressure applied on the inner surface of the bladder to radial tension. In order to find the tension as a function of pressure and actuator rotation without considering the geometric structure, a theoretic approach using the principle of energy conservation is described as follows:

Input work is done when the inner surfaces of the bladder is inflated by gas.

$$dW_{in} = \int_{si} (P - P_0) dI_i \, dS_i \qquad \textbf{Equation 1}$$
$$= P' dV$$

where
$(P\text{-}P_0)$ is the relative pressure.
S_i is the surface area.
dI_i is the inner area change.
dV is the volume change.



ϑ_1 is the angle between the fibre and the effective length of the two dimensional representation.
S is the arc length of the angle of rotation of the rotary pneumatic muscle with radius h.
h is the radius of the rotary pneumatic muscle.

Figure 3- Muscle uninflated.

Figure3 is the muscle at angle ϑ_0, where ϑ_0 is the angle when the muscle is un-inflated. The output work (W_{out}) is the work done when the actuator rotates with changes in the volume where F is the axial tension and dJ is axial displacement. From the view of energy conservation, the input work should equal the output work if a system is lossless and without energy storage. Assuming this ideal state, the virtual work argument is:

$dW_{out}=dW_{in}$,

equating Equation and Equation 2 gives-

$$FdJ = P'dV$$

$$F = -P'\frac{dV}{dJ}$$ **Equation 2**

The estimation of dV/dJ, the change in volume of the bladder with respect to axial displacement requires some geometric assumptions.

It is assumed that when there is no pressure in the muscle and the muscle is uninflated, the fibres lie in a certain orientation (ϑ_0). If the muscle were not constrained about its length and was lying in a flat two dimensional plane this would appear as Figure 2.

Next an assumption is made about the two dimensional representation of the rotary pneumatic cylinder. Given that the length of the cylinder is fixed, if an increase in the pressure occurs, a change in ϑ_0 must occur. The assumption is that if these changes in the real cylinder were applied to the two dimensional representation where the length was not constrained, the change in ϑ_0 would increase the effective length of the two dimensional representation and cause a change in the angle ϑ_1, as shown in Figure 5.

A rotation about the longitudinal axis produces a change in ϑ_0 and ϑ_1, Using these geometrical approximations the effective length and angle the fibre makes with the longitudinal axis can be found if the rotation of the cylinder is known. The equations describing this are given below.

$$hJ_0 = S$$ **Equation 3**

Assuming the fibre length is known and ϑ is the angle to the datum position, then by basic trigonometry, this trigonometry is shown diagrammatically in Figure 5.

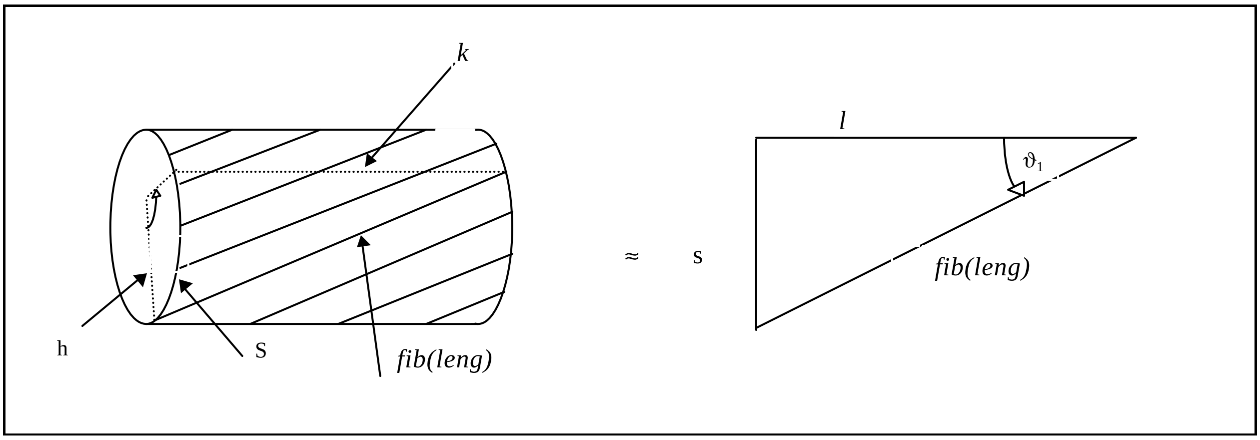


Figure 5 - Fibre angle changes with rotation.

$$J_1 = \cos^{-1}\frac{l}{fib(leng)}$$ **Equation 4**

ϑ_1 results from the angle of the fibre and is related to ϑ_0 by

$$\frac{s}{fib(leng)}\sin^{-1} = J_1$$

$\Rightarrow$ relation is

$$\frac{hJ_0}{fib(leng)}\sin^{-1} = J_1 \qquad \textbf{Equation 5}$$

If a cross sectional view of the rotary pneumatic muscle were taken, the muscle surface from one end of the cylinder to the other takes the shape of an arc. This is termed the arc length (*l*). Furthermore the assumption is made that the arc length is approximated by the effective length of the two dimensional representation of the muscle.

Hence if we know the rotation undergone by the rotary pneumatic muscle we know the effective length and the arc length of the rotary pneumatic muscle.

From this we next attempt to find the volume of the muscle. This is found by revolving the shape about the x-axis.

The problem then reduces to finding the equations describing the curve of the arc.

We know points, A and B and the arc length, but the problem cannot be solved directly and requires a numerical solution or a further approximation. If we assume that the radius is large and changes very little with *l* we can treat the radius R as a constant.

We then obtain the volume of revolution by

$$V = 4p\int_0^y y^2\,dx \qquad \textbf{Equation 6}$$

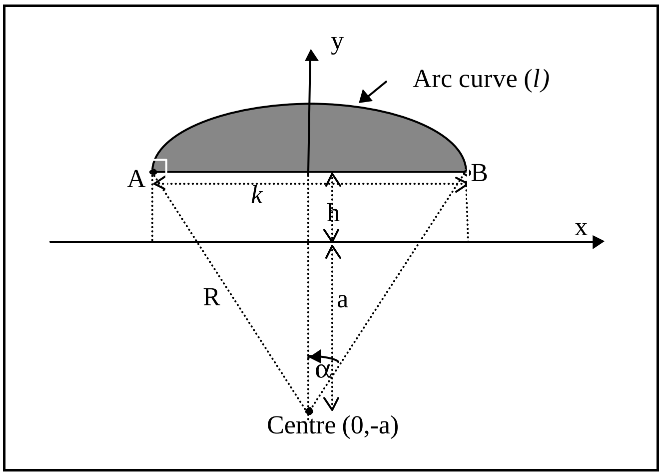


Figure 6 - Terminology for the volume calculations.

Once we find V we then find $\frac{dV}{dJ}$ and the force

$$F = P\frac{dV}{dJ}$$

The equations to find the volume V are given below. The terminology used below is illustrated in Figure 6.

h, k fixed

$l, a, a,$ variable

$$\text{radius of circle} = \sqrt{(a+h)^2 + \left(\frac{k}{2}\right)^2}$$

$$= R \qquad \text{say} \qquad \text{Equation 7}$$

$$\frac{l}{2} = Ra \qquad \text{Equation 8}$$

$$\sin a = \frac{k}{2R} \qquad \text{Equation 9}$$

Equation of upper semi - circle is : $y = \sqrt{R^2 - x^2} - a$

Let volume of revolution of shaded area be V

h is radius of the cylinder, k is the length of the cylinder,

R = radius of arc formed from the arc length

l is the arc length

$$V = 2p \int_0^{k/2} y^2 dx - pkh^2$$

$$= 2p\left[\frac{kR^2}{2} + \frac{ka^2}{2} - \frac{k^3}{24} - 2a\left[\frac{x}{2}\sqrt{R^2 - x^2} + \frac{R^2}{2}\arcsin\frac{k}{R}\right]_0^{k/2}\right] - pkh^2$$

from Equation 7 we obtain $a = \pm\sqrt{R^2 - \frac{k^2}{4}} - h,$ and

substituting this gives:

$$= 2p\left[\frac{kR^2}{2} - \frac{k^3}{24} - \left(\frac{Rl}{2} + \frac{kh}{2}\right)\sqrt{R^2 - \frac{k^2}{4}} + \frac{Rlh}{2}\right] \text{ since } R\arcsin\frac{k}{2R} = \frac{l}{2} \text{ by } (2) \text{ and } (3)$$

Also by Equation 8 and Equation 9, $\sin\left(\frac{l}{2R}\right) = \frac{k}{2R}$.

Differentiating with respect to l gives:

$$\cos\left(\frac{l}{2R}\right)\left[\frac{2R - 2l\, {}^{dR}\!/_{dl}}{4R^2}\right] = -\frac{k}{2R^2}\frac{dR}{dl}$$

i.e. $\frac{1}{2R}\cos\left(\frac{l}{2R}\right) - \frac{l}{2R^2}\frac{dR}{dl}\cos\left(\frac{l}{2R}\right) = -\frac{k}{2R^2}\frac{dR}{dl}$

$$= \frac{R\sqrt{R^2 - \frac{k^2}{4}}}{l\sqrt{R^2 - \frac{k^2}{4}} - kR}$$

now we know $V = p\left\{kR^2 - \frac{k^3}{12} - (Rl + kh)\sqrt{R^2 - \frac{k^2}{4}} + Rlh\right\}$ and so

$$\frac{\P V}{\P l} = \frac{pR}{l\sqrt{R^2 - \frac{k^2}{4}} - kR}\left\{3kR\sqrt{R^2 - \frac{k^2}{4}} + 2lh\sqrt{R^2 - \frac{k^2}{4}} - 3lR^2 + \frac{lk^2}{2} - 2khR\right\}$$

From equation 6

$fib(len)^2 - l^2 = h^2 J_1^2$

so $l = \sqrt{fib(len)^2 - h^2 J_1^2)}$

andusing thechainrule

$$\frac{dV}{dJ_1} = \frac{dV}{dl}\frac{dl}{dJ_1}$$

$$= \frac{pRh^2 J_1 \left(h^2 J_1^2 + fib(len)^2\right)^{\frac{-1}{2}}}{l\sqrt{R^2 - \frac{k^2}{4}} - kR}\left\{3kR\sqrt{R^2 - \frac{k^2}{4}} + 2lh\sqrt{R^2 - \frac{k^2}{4}} - 3lR^2 + \frac{lk^2}{2} - 2khR\right\}$$

usingequation3

$$F = -P'\frac{dV}{dJ_1}$$

$$= P'\frac{pRh^2 J_1\left(fib(len)^2 - h^2 J_1^2\right)^{\frac{-1}{2}}}{\sqrt{fib(len)^2 - h^2 J_1^2)}\sqrt{R^2 - \frac{k^2}{4}} - kR}\left\{3kR\sqrt{R^2 - \frac{k^2}{4}} + 2\sqrt{fib(len)^2 - h^2 J_1^2)}\,h\sqrt{R^2 - \frac{k^2}{4}} - 3lR^2 + \frac{\sqrt{fib(len)^2 - h^2 J_1^2)}\,k^2}{2} - 2khR\right\}$$

RESULTS

A simulation of the model was developed on Matlab [13]. Simulated results of how the muscle behaves under certain conditions were produced. The conditions tested were isotonic, isobaric and isometric conditions. The simulated results is shown in Figure 7.

The isotonic test results indicate a monotonic relationship between the angle turned by the muscle and the muscle pressure. Figure 11 indicates a asymptote exists at 0 radians, which is approached when the pressure is increased. These results indicate that the force produced by the muscle increases as the angle the muscle is rotated at increases.

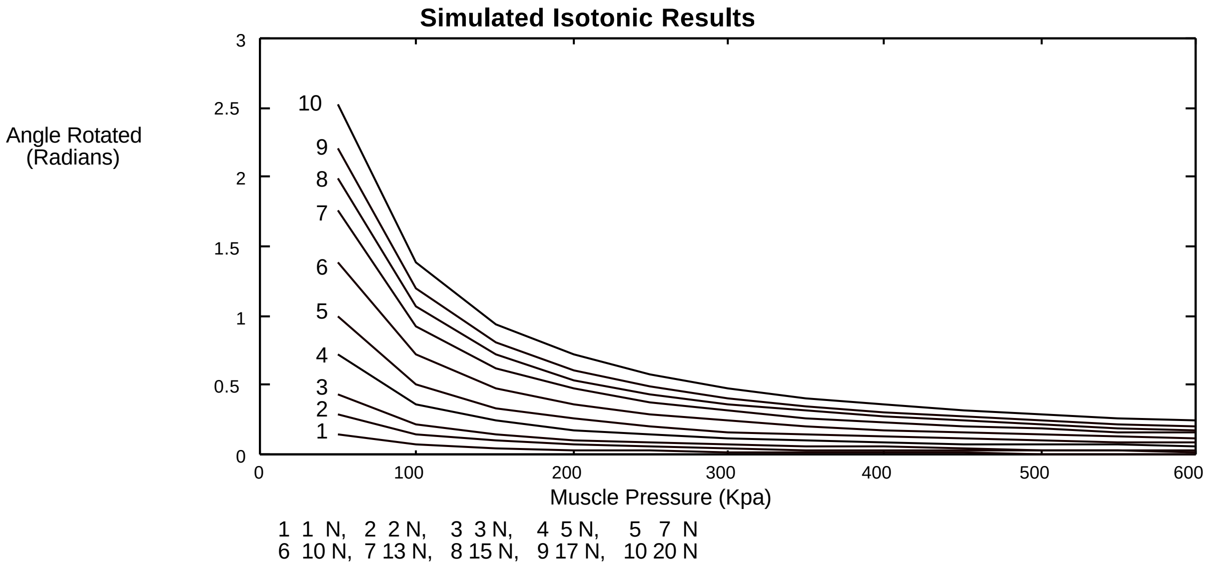


Figure 7 - Isotonic simulation results.

angle of rotation is constrained. These results indicate that the force produced by the muscle is linearly related to the pressure.

CONCLUSION

An investigation into alternative robotic actuation systems resulted in the design and development of a novel pneumatic muscle. This muscle provides a rotary action. This rotary action is useful in the design of robotic devices because often robotic joints are revolute and the rotary actuator can be used directly as a revolute joint thus creating a direct drive robot. Direct drive robots do not have the problems of friction within the power transmission system that non direct drive robots have.

Models describing the behaviour of the rotary pneumatic muscle were investigated. An analytical model describing the relationship between torque produced, muscle pressure and amount of rotation of the muscle, was developed. This model was developed using the laws of energy conservation.

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