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Achieving Compliance in Mechanisms: A Comparison between Mechanical Compliance and Compliant Actuators

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Abstract: ***This article intents to compare the applicability of mechanical compliance and the use of Pneumatic artificial muscles (PAMs) as actuators to achieve compliance in robot arms. PAMs were developed by using biological inspiration from human triceps and biceps in an effort to produce a manipulator with characteristics of a human arm. On the mechanical compliance, this article focuses on how material parameters can be adjusted to achieve mechanical compliance. Furthermore a comparison in applicability of either method will show that the two will function more effectively to achieve compliance if they are used together.***

Keywords: Compliance, Pneumatic Artificial Muscles (PAMs), mechanical compliance, manipulator, flexibility

1. Introduction

There is growing need for robots that operate in close vicinity of people or even physically interact with them. These robots are expected to be tools for the humans to use, partners to humans not competitors in fulfilling the intended tasks. The most common robots are stiff and when they come into contact with humans accidentally, injury to the human occurs. Robot compliance makes it possible for humans and robots to interact safely.

Methods of achieving compliance in robot manipulators have been studied since early in robotic literature [1]. In industrial robotics accurate positioning of a manipulator or end effector is by far the most common application [2]. To achieve high accuracy is a tall order for robots operating in the same environment with people if there is to exist a danger free interaction. In order to create a safe environment for humans to work with robots, a compliant actuatorhas to be used. An alternative approach at increasing the safety level of the robot arm interacting with humans is to introduce compliance right away at the mechanical design level [1]. A compliant mechanism can be defined as a single piece of flexible structure which uses elastic deformation to achieve force and motion transmission [3]. Flexibility of links can be used as a way of achieving compliance of a manipulator without the involvement of the actuators. On the other hand, if compliance is not introduced on mechanical design stages, then it can be achieved by the use of compliant actuators. Various researches are being done towards the realization of compliant robot arms which can still achieve high accuracy and at the same time safe for humans to be in the same environment.

2. Factors that Determine Compliance

Compliance cannot be fully defined by initial material properties or geometric configuration; other factors have to be taken into consideration. These factors include, and are not limited to geometric boundary condition (location, type), the loading situation (location, type, magnitude, direction and loading history) and environmental conditions (thermal, chemical etc.) [4].

2.1 Factors affecting compliance of PAMS

In PAMs, compliance is due to the compressibility of air and as such can be influenced by controlling the operating pressure [5]. PAMs are extremely lightweight and act like nonlinear springs in their operation. Their stiffness is not constant throughout the operation period but changes with applied force. The pneumatically actuated muscle consist of an inner rubber tube and an outer cord netting, both of which affect compliance of the arm depending on the material used in constructing them

2.2 Factors affecting mechanical compliance

According to Solehuddin et al (2007), compliant mechanisms must tolerate between flexibility and stiffness [3]. In compliant mechanisms, adequate flexibility is essential to afford required displacement at the point of interest. At the same time a compliant mechanism should be stiff enough to be able to sustain external forces. The compliance of a mechanism is determined with respect to a displacement of a specific selected reference point or area of the mechanism as a result of an external force [4].

Loading situation, which are the location at which load is being applied, the type of load applied, that is whether it is a point load or distributed load, the magnitude of the load, the direction of load application and the history of loading all have an effect on the mechanical compliance of a mechanism. The environment in which the mechanism will be working will also affect the compliance, for example, in high temperature; there is a tendency of high electron excitation for some materials, which leads to weakening of bonds thereby making a material more flexible than in lower temperatures. The same goes for chemical environment in which the material will be operating. The environment can either make the material more flexible or increase its rigidity depending on the chemical reactions between the material and its environment. Fatigue affects the compliance of a material since it will determine the maximum stress at which failure may occur after cyclic load application. Creep also has an effect on compliance as it is caused by constant stress and high temperatures below elastic limit.

3. Concept of Operation

Both PAMs and structurally compliant materials are used to achieve compliance in a mechanism. In as much as compliance is achieved by using either of the two, their concept of operation differs.

3.1 PAMs: Description and Working Principles

The Pneumatically actuated muscles are made of a braided shell surrounding a rubber inner tube [6]. These pneumatic actuators have a dual structure of an internal membrane and an external shell [7]. When the internal bladder is pressurized, it expands and pushes against the inside of braided mesh sleeve forcing the diameter of the braided mesh to expand. The physical characteristic of the mesh sleeve is that it contracts in proportion to the degree its diameter is forced to increase. This means when an air muscle is inflated, it contracts, its diameter thickens equally along its length and causes the muscle to shorten. This produces the contractive force of the air muscle.

The muscle is either stretched or in loaded position when it is inactive in order for it to work properly. If not there will be little if any contraction when activated since the air muscle must be stretched in order to produce a working contraction when it is activated. Typically the air muscle can contract to approximately 25 percent of its length. A source of pressurized air is a prerequisite for PAMs and can be supplied by a compressor or a motor pump depending on their intended use. Alternatively, air tanks can be used and refilled when empty.

PAMs can be fast and have a length-load ratio dependence similar to that of human muscle, but possess only one actuation mode: contraction and expansion mode when pressurization changes. Thus in a sense, they are an analogue to a single muscle fibril. Using them for complex movements requires multiple actuators working in series and in parallel [8]. PAMs have high power-to-weight ratio and can be directly coupled to the joint without a heavy complex gearing mechanism. Two PAMs put into antagonism define rotoid actuator based on physiology model of biceps-triceps system [5]. Two muscles can be connected by means of a pulley or a sprocket. The torque is produced by the force difference between the agonist and the antagonistic muscle [3].As one of them moves the load, the other will act as a brake to stop the load at its desired position. To move the load in the opposite direction the muscles change function.

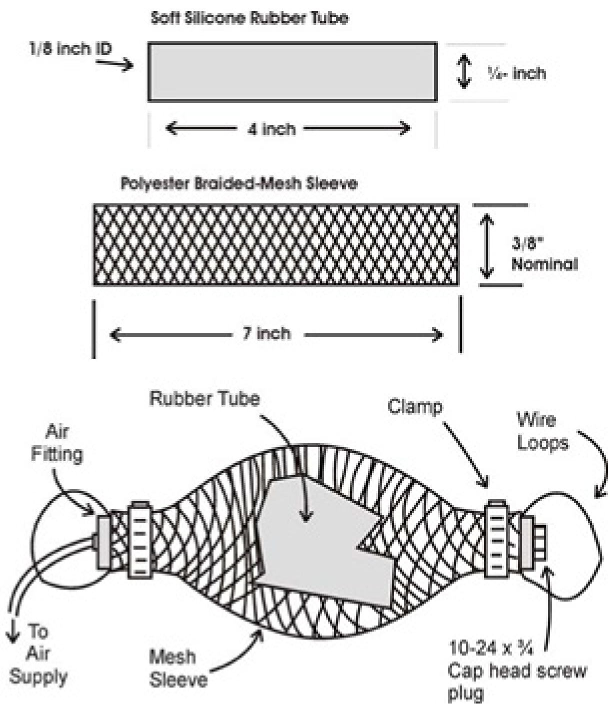

Figure 1: Artificial Muscle: Extract from Bio robotics–Build Your Own Robotic Air Muscle

Because the generated force of each muscle is proportional to the applied pressure, the equilibrium position of the end effector driven by the antagonistic couple will be determined by the ratio of both muscle gauge pressures.

PAMs do not have passive tension because of the inextensibility of the braided shell. The equilibrium length of a PAM at static condition will be determined by the pressure level, the external load and the volume-to-length change of that particular muscle [3]. All pneumatic actuators show a compliant behavior because of the ability of gas to be compressible. PAMs have their dropping force to contraction curve as a second source of compliance: even if the pressure is maintained at a fixed level, the muscles act spring like due to the change of force with regards to length [3]. Pneumatic artificial muscles can be readily replaced since it only takes uncoupling the muscles from the tubing. The use of PAMs causes no pollution and they are not hazardous as regards to fire or explosion. Another advantage of using antagonistic pneumatic system is the passive stiffness provided by the compression capability of the air fluid. However PAMs do have some operational drawbacks. In general, the PAMs have only a small amount of natural damping. The output force is clearly a function of length, but changes in velocity have a small effect on output force. They also have hysteresis introduced by friction which makes PAMs difficult to control, and it has substantial threshold pressure, before any force is generated [9].

3.2 Mechanical Compliant Mechanisms

The deformability of structures is primarily characterized by their stiffness which is a measure of the ability of a structure to resist deformation due to the action of external forces [4]. For compliant mechanisms, functionality is based on deformability. In humans, most motor behaviors exploit the compliance of each component of musculo-skeletal system

[10]. Compliant mechanisms rely upon elastic deformation to perform their function of transmitting and/or transforming motion and force [11]. When a compliant mechanism is deformed to transmit force and motion, some of the input energy is stored in the mechanism in the form of strain energy, while the rest is transferred to the output load [12]. In robots, compliance has a number of benefits such as lower inertial forces and lower reflected impedance, greater shock tolerance and potential for efficient (elastic) energy storage and restitution [10].

Generally compliance can be constant or variable, although constant compliance is impossible in nature [4]. Most mechanisms achieve their compliance through the use of compliant joints, which can have either concentrated or distributed compliance. With concentrated compliance, the joints have small deformable area with reference to the dimension of the mechanism. On the other hand, joints with distributed compliance include a larger area of deformable part. In case the deformation-behavior is chosen as a criteria for classifying compliant mechanism, two subgroups, namely dynamic and static deformation can be distinguished [4].The introduction of an elastic component in the system has typically been seen as an obstacle to positional accuracy, stability and control bandwidth. An effective damping mechanism can be used to minimize the drawbacks associated with the use of elastic elements in the kinematics of mechanisms.

4. Discussion

While both PAMs and mechanical compliance have great potential in achieving compliance, they can perform better if they are used together. For human-robot safe interaction, compliant joints are designed for use. However, with compliant joints, it is harder to place the tool at the center point in an exact position or to track a specific trajectory accurately [9]. In this case, an actuation with adaptable compliance can act stiff during precise position at low speeds (grasping and placing objects) and compliant when positioning is not as important when moving at higher speeds (moving from one position to another) [9]. By adding a little damping, which can be provided by compliant material, it is possible to create an improved actuator whose properties resemble natural muscle-like with respect to both length and velocity.

Compliance can also be incorporated into the robot by means of a passive approach thru the use of PAMs. Their force is not only dependent on pressure but also on their state of inflation, which provides a source of spring like behavior[3].Structure control modulates the effective physical structure of a spring to achieve variations in stiffness. When using a beam as an elastic element, the stiffness depends on material modulus, the moment of inertia and the effective beam length [9]. The performance of an engineering component is limited by the properties of the material of which it is made and by the shapes to which this material can be formed [15]. During operation, the stiffness can be controlled by adjusting one of the material parameters.

The mostly deformable parts of a compliant mechanism are the compliant joints [4]. This means that PAMs, which are compliant actuators, can be used as the joints. Used on their own for compliance, PAMs have hysteresis introduced by friction which makes it difficult to control. To counter this, compliant material can be used for the links such that all the compliance needed for a mechanism will not be provided by the joints only. One big advantage of using an antagonistic pneumatic system is the passive stiffness provided by the compression capability of air fluids [13].

5. Conclusion

By using specific materials and compliant actuation, the durability and safety of the robot is guaranteed. The drawbacks of PAMs can be minimized by the use of compliant mechanism, and proper selection of compliant materials. Materials with anisotropic mechanical properties along different directions or with different mechanical behavior at different forces would provide the basis for a wide range of non-linear motions. Heavy gearing of joints can be avoided by using PAMs for joints because of their high power to weight ratio of approximately 400:1.

6. Future Scope

The use of composite materials, which are, materials whose mechanical properties are designed to be superior to those of the constituent materials, in compliant mechanisms will help in having a material that has the properties needed to achieve compliance and suitable to work with PAMs. This means, for example, instead of using a traditional metal with required flexibility but which will not be corrosion resistant, a composite material, which will be made out of two traditional materials one with high flexibility and the other with high resistance to corrosion can be used.

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