Laminar Jamming and Their Applications in Robotics

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Robots with variable stiffness links are an emerging paradigm in robotics and have captured the interest of the scientific community in fields such as soft robotics and medical devices. Laminar jamming (LJ) is a promising technology for facilitating variable stiffness in robotics.

Keywords: laminar jamming ; layer jamming ; variable stiffness ; soft robotics ; sheet jamming

1. Introduction

Robots with variable stiffness links are an emerging paradigm in robotics and have captured the interest of the scientific community in fields such as soft robotics and medical devices. The paradigm of variable stiffness considers that the structural links and joints of a robot should vary their stiffness in order to perform tasks that require different states of flexibility or rigidity, ideally combining the benefits of both rigid and soft robotics in a single system.

Laminar jamming (LJ) is a promising technology for facilitating variable stiffness in robotics [1]. The primary advantages of LJ are its potential for large stiffness variation, high speeds of stiffening and destiffening, and relatively simple operating principles. In addition, manufacturing some types of LJ structures (LJSs) may be simpler than other variable stiffness technologies.

2. Motivation and Working Principle

Multiple technologies to vary the stiffness of robot links have been investigated [2]. LJ is one of these methods that has attracted the attention of the robotics community. A compelling argument for choosing LJ over other variable stiffness methods is the large change in stiffness possible. There are LJ technologies that can achieve a stiffness variation of at least ten, which means that the maximum stiffness is ten times larger than the minimum stiffness. In addition, the speeds of stiffening and destiffening of some LJ technologies are high. Other technologies, such as low melting point materials, have larger stiffness variation, but their speeds of stiffening or destiffening are low [3]. Some types of LJ also have the significant advantage of requiring traditional and simple manufacturing processes, such as machining or laser cutting, making them relatively easy to manufacture [4]. Additionally, it has been demonstrated that LJSs can be applied in various robotic fields, as described in Section 4. For a detailed comparison of LJ with other variable stiffness technologies, readers are directed to a review article that extensively discusses various methods to vary stiffnesses in soft robotics [2].

An LJS consists of a beam that is made of thin sheets and a mechanism to lock/unlock the sheets. When the mechanism locks the sheets, the bending stiffness is high, and the whole beam behaves similarly to a rigid member. When the mechanism unlocks the sheets, they can slide between themselves, the bending stiffness is low, and the beam becomes flexible. In this state, the layers are not coupled, and they are free to slip. This working principle is the same for all LJSs regardless of the lock/unlock mechanism utilized.

The stiffness ratio in an LJS depends on the number of layers raised to the second power [1][4]. This generates, at least in theory, the possibility of obtaining very high stiffness variation by only adding more layers to the beam [4]. However, this is a theoretical value because other factors, such as friction and the efficacy of the lock/unlock mechanism, would reduce the stiffness ratio that can be achieved.

3. Lock/Unlock Mechanisms

The LJ principle is relatively simple, consisting of a lock/unlock mechanism that couples or decouples the bending stiffness of the layers to render a bending stiffness change of the whole beam. However, this locking/unlocking is not trivial and requires the development of mechanisms to facilitate this action. Several mechanisms to lock/unlock LJSs have been proposed during the last 20 years. The researchers categorize these mechanisms by the following operating principles: friction, mechanical interference, and miscellaneous principles that differ from the previous two categories.

3.1. Mechanisms Based on Friction

Friction-based mechanisms function by modifying factors determining the friction forces, such as a normal force. The following section explains these mechanisms.

3.1.1. LJ Wrapped by Shape Memory Alloy (SMA)

This locking mechanism consists of an array of SMA wires that are wrapped around the LJ. When an electric current is passed through the wire, the increase in temperature causes the SMA wires to contract, which, in turn, tightens the stack of layers and increases the inter-layer friction, incrementing the bending stiffness. Experiments were carried out with this mechanism, and the results of the experiments showed that the stiffness changed by a factor of 60 [4], meaning the maximum stiffness was 60 times larger than the minimum stiffness.

3.1.2. Elecrostatic Force

Another method to increase the friction is through electrostatic force. This mechanism consists of a stack of thin, flexible polyimide layers with patterned nickel electrodes [5]. These electrodes are connected to a high-voltage source in an alternating polarity. As a consequence, the electrostatic force between the layers generates a friction force. The final result is increment in the bending stiffness of the entire stack. The principle of using electrostatic force to lock/unlock the layers is currently known as electro-bonded lamination [6] or electrostatic layer jamming [7][8][9].

3.1.3. Vacuum Pressure

Jamming generated by vacuum pressure is the most developed technology based on friction to lock/unlock LJSs. It consists of a stack of compliant layers, an airtight chamber that envelops the layer stack, and a vacuum pump that applies negative pressure inside the chamber. When the vacuum is activated, atmospheric pressure compresses the chamber and the LJS that is inside. As a result, the friction between the layers increases, which leads to locking of the sheets and corresponding increase in the bending stiffness.

There are multiple variations of vacuum-pressure-activated LJ that have been developed to be applied in robotics [1][10][11][12][13][14][15][16][17][18][19][20][21][22][23][24][25][26][27][28][29][30]. These variations will be described in Section 4.

3.1.4. Discrete Laminar Jamming (DLJ)

Discrete laminar jamming (DLJ) is another mechanism to lock/unlock the LJS that has been utilized to build robot links with variable stiffness capabilities. DLJ does not have an elastic membrane that contains the layers. Instead, this mechanism has multiple variable pressure clamps placed discretely along the LJS. The pressure in the clamps is set by bolts [31][32] or rubber bands [33]. Furthermore, piezoelectric actuators are being considered as a method to drive the pressure in the clamps [31]. There are potential advantages of this concept in comparison with laminar jamming based on vacuum pressure, such as faster actuation, better portability, no sealing issues due to a lack of vacuum pressure, and no use of an elastic membrane, which implies a lower probability of being damaged due to contact or impact against rough edges.

3.1.5. Mesh Sheath

This mechanism consists of a spring backbone that is contained within a layer jamming structure that is formed by flaps that are sewn together. Jamming of the flaps is achieved by using a woven mesh sheath that encases the flaps. The sheath decreases and increases in radius when it is extended or contracted longitudinally by a cable coupled at its ends. When the mesh sheath decreases in radius, it tightens the flaps against a steel spring backbone and stiffens the structure [34].

3.2. Mechanisms Based on Mechanical Interference

The lock/unlock mechanism based on the principle of mechanical interference consists of an object that passes through the layer of the LJS, which prevents relative slip between the layers. Typically, there is an actuator that thrusts the object into the layers to increase the stiffness and pulls the object out of the layers to reduce the stiffness. The layers often have a cutout or slot to accommodate the object that goes through them.

3.3. Mechanisms Based on Miscellaneous Principles

At the moment, multiple research projects on LJ are exploring different concepts and mechanisms to facilitate variation in stiffness. In addition, some of these ideas are presented with various names. Therefore, defining a strict classification method is challenging because some LJ concepts are unique in terms of their working principle. This section presents lock/unlock mechanisms that do not classify as mechanisms based on friction or based on mechanical interference.

3.3.1. LJ with Heating Blankets

This mechanism consists of aluminum sheets with polymer sub-layers between them. The polymer sub-layers have ultra-thin electric heating blankets embedded in them. The aluminum cover sheets are coupled with the base aluminum sheet when the polymer layers are rigid, and the LJS bends as a whole unit. When the embedded ultra-thin heating blankets are activated by an electric current generated by a temperature controller, the increment in the temperature provokes a reduction in the shear modulus of the polymer resulting in the decoupling of the aluminum cover layers and the base aluminum layer. The ultimate consequence is decrease in the bending stiffness of the beam [35].

3.3.2. Sliding-Layer Laminates (SLL)

Sliding-layer laminates (SLL) consist of a stack of layers that form a beam. Each layer is composed of sections of two different materials that are arranged periodically. One of the materials is soft and the other one is rigid. When the layers are aligned, the beam is flexible because the layers bend around their soft sections. When the layers are not aligned, each soft section is accompanied by a rigid section, causing the beam to become more rigid. It is possible to obtain intermediate values of bending stiffness by sliding the layers with an appropriate proportion of overlapping between the rigid and the soft sections. The layers are slid manually before every test [36], or they are slid by the action of a linear motorized stage [37].

4. Application of Laminar Jamming in Robotics

LJSs have been applied to robotics in devices that require variation in stiffness to manipulate objects, interact with the human body, or mitigate impact due to collisions. These applications include grippers, continuum robots, wearable robots, and robotic arms.

The application of LJ to different robotics areas has driven the invention of new LJSs that combine some of the fundamental mechanisms described in Section 3. In other cases, the fundamental LJ mechanisms have been combined with other mechanisms to achieve new functions associated with each application. These combinations of mechanisms will also be described in the applications mentioned above.

LJSs have also been combined with well-known soft robot actuators in order to provide control of the stiffness of the actuator. This is the case of LJSs based on electrostatic force that have been combined with a pneu-net actuator, which is a type of soft robot actuator that has been extensively investigated. Pneu-net actuators are now part of a soft robotics toolkit that is widely used by researchers [38]. Another example is the combination of LJSs with McKibben actuators, which are a type of pneumatic artificial muscle that were invented in the 1950s and are also widely used in soft robotics [39]. These combinations of actuators will be described in Section 4.1.

4.1. Grippers and Fingers

LJSs have been applied in the development of grippers [10][15][16][40][41][42][43]. These applications aim to develop compliant grippers that can adapt their grasping postures according to object geometry without compromising the capacity to execute pinch grasps efficiently. For instance, LJSs based on vacuum pressure have been used as joints in grippers that have variable stiffness capabilities and acceptable pinch grasp forces [15]. However, use of this type of gripper has shown that variable stiffness joints have low repeatability and durability due to the materials used in the layers. Another example is the gripper presented by [10]. It consists of fingers composed of a silicone rubber substrate, a three-part LJS that is activated by vacuum pressure, and a cable routed through the substrate. This gripper is able to perform a stable grasp of large objects (ball of diameter 20 cm) and can also perform a stable pinch grasp on small objects (ball of diameter 2.5 cm).

LJSs based on electrostatic force have also been implemented in robot fingers [38]. The finger consists of a pneu-net actuator that drives the bending motion and two films (blue and red) that form an electrostatic clutch that modulates the bending stiffness. When the finger is inflated to 30 KPa and the clutch is off, the finger bends easily because of its low bending stiffness. When the clutch is on, the films of the clutch are energized, and the electrostatic force between them increases the bending stiffness of the finger.

The stiffness variation capability of LJ has been combined with other mechanisms to implement different methods of grasping that are common in robotic grippers. For example, a gripper combined an LJS with suckers located in the fingertips is described in [24].

LJSs based on vacuum pressure have frequently been combined with pneumatic actuators of positive pressure [26][27][28][29][39][44]. The LJSs control the stiffness while the positive pressure actuator controls the shape of the fingers, usually to conform with the shape of the object that will be grasped. The most common working method consists of setting up atmospheric pressure in the LJ chamber to generate the minimum stiffness, and then positive pressure is applied to the pneumatic actuator to achieve a specific shape of the finger. Subsequently, the vacuum pressure is applied to the LJS to increase the stiffness of the finger and lock the shape of the finger, which allows the gripper to hold the object. When the object must be released, the vacuum pressure in the LJS is suspended and the pneumatic actuator is depressurized to allow the finger to return to its original shape. A good example of this method is the combination of LJSs based on vacuum pressure with McKibben actuators [39].

4.2. Continuum Robots

Laminar jamming has been implemented in the design and construction of continuum robots. The LJSs that were implemented in this application are characterized by two main changes. First, the layers are flaps with diverse shapes rather than just rectangular sheets. Second, the flaps are arranged to form a cylinder rather than a rectangular beam.

Vacuum-pressure-activated LJ has been implemented as a method to change the stiffness of continuum robots. For instance, an LJ device has been developed to make a snake-like manipulator that is composed of Mylar films [12]. These films are cut to form flap patterns that are overlapped and assembled in a cylindrical shape. Then an elastomeric membrane wraps around the inside and outside of the tube. When vacuum pressure is applied, and the air inside the membrane is removed, the membrane compresses the structure of the flaps that are inside, increasing the stiffness of the manipulator. The manipulator has three nitinol wires that are used as actuators placed every 120 degrees about its central axis. The scalability of the technology is not particularly substantial, but it allows the creation of a continuum robot with characteristics compatible with various minimally invasive surgery applications [3].

4.3. Wearable Robots

LJ has been applied in wearable robots for different parts of the human body, such as the wrists [17][45], lower limbs [46], back [17][22], and upper limbs [11][17][22]. A device known as a sliding linkage-based layer is a variation of a vacuum-pressure-activated LJ. It is used in wearable robots for rehabilitation or injury prevention [17]. The advantage of this mechanism is that it can provide variable stiffness in the axial direction of the layers as well as variation in stiffness in bending.This allows the LJSs to fulfill the requirement of wearable robots on body parts like the waist, wrists, and ankles.

LJSs based on electrostatic force have also been implemented in wearable robots [38] and haptic gloves [47]. The LJS consists of two films that are partially overlapped and connected to an electronic circuit. The overall device works as a clutch, and it is mounted on the elbow of a mannequin. When the LJS is activated at 125 V and the films are in contact, they lock, which increases the bending stiffness and reduces the angular displacement of the elbow when loaded under its own weight. When the clutch is not activated, the films slide past one another until they are no longer in contact and the elbow bends downward because the bending stiffness of the wearable elbow is minimal [38].

Another variation of a vacuum-pressure-activated LJ that has been used in wearable robots is known as a soft layer jamming brake (SLJB) [11][48]. The SLJB consists of two end caps and a set of layers attached to each cap in such a way that both sets overlap, with everything fitting into an outer housing made from silicone material. A tube is connected to the housing and a vacuum pump. When there is air in the device, the layers are unlocked and the end caps can move freely in the axial direction. When there is vacuum pressure, the layers are locked and the end caps are constrained or partially constrained in the axial direction. This variation of LJS is also known as a double-link-based LJ mechanism [17] or interlocked layer configuration [13].

Vacuum-pressure-activated LJ has also been applied in exoskeleton gloves to achieve variable stiffness capabilities in the fingers. Experiments conducted with this glove showed that LJSs can be used for the rehabilitation of impaired patients by regulating the force required to retain a desired grasp shape by increasing the resistance to hand opening or adjusting the force to bend the fingers [18]. Gloves with LJSs were also developed as haptic devices [21][47][49].

The development of haptic gloves has also driven the invention of a method to vary the stiffness that combines two fundamental LJ mechanisms that were described in Section 3. These methods are vacuum pressure and mechanical interference. The glove consists of multi-material layers that are covered by a sealed shell. There are two micro-teeth clutching structure layers that are separated by a sliding film boundary layer. When the pressure in the sealed shell is the atmospheric pressure, the micro-teeth are disengaged, the two micro-teeth layers can bend independently, and the whole structure has low bending stiffness. When vacuum pressure (negative pressure) is applied to the sealed shell, the micro-teeth layers engage each other to form a unified beam and the whole structure has high stiffness [50]. The sliding film boundary layer is a smooth, soft, ultrathin plastic film. It has two functions: (1) it prevents the engagement of the micro-teeth layers when there is atmospheric pressure inside the sealed shell, and (2) it allows a smooth switch engagement and disengagement of the micro-teeth layers. This results in a smooth transition between the low-stiffness and high-stiffness states.

4.4. Robotic Arms

Changing the stiffness of robotic arms is another application of LJ. The purpose of this application is the development of robot arm links to achieve the load capabilities and precision of a traditional rigid robotic arm with the safety of a compliant soft robot. One strategy to introduce compliance capabilities in robot arms is the implementation of variable stiffness links (VSL). The novel VSL has a dual parallel beam configuration [13][14][20]. The lateral beams are composed of a solid center support, layers on both sides, and a sealed enclosure. The solid center support is made of a rigid material, but it is compliant due to the thin sections along it. When there is vacuum pressure inside the bags, the lateral beams are in a rigid state and the link reaches high stiffness. When there is atmospheric pressure in the bags, the whole link becomes compliant since the solid center supports are not constrained to move due to the flexibility of the thin center sections. This idea of having a solid center or a *backbone* with adjacent LJSs has also been applied to build fingers of robotic grippers with variable stiffness [16]. The key role of the backbone is to increase the stiffness variation by increasing the distance between the LJSs on both sides and the neutral axis, which increases the opposing moment coming from friction forces in the LJSs.

Parallel guided beams composed of LJSs have also been implemented in robot arms to change the stiffness of the joints rather than change the stiffness of the links [19]. The construction of the joint consists of two sets of parallel guided beams that form a wrist that provides variable stiffness in two perpendicular axes of rotation.

Some types of LJ mechanisms have been developed for the construction of robot arms with VSL. That is the case for the DLJ mechanism that was described in Section 3.1.4. The trapezoidal pin mechanism is another method to build a VSL for robot arms [51]. It is a combination of the DLJ mechanism and the mechanical interference principles that were described in Section 3. The trapezoidal pin mechanism consists of a pneumatic actuator that drives a trapezoidal pin to interfere mechanically with the layers, which, in turn, changes the stiffness of the LJS. The trapezoidal pin applies normal force between the layers, which generates friction between them. The pin also generates mechanical interference between the layers. The stiffness of the LJS depends on the air pressure in the pneumatic cylinder. This mechanism is an evolution of the conical pin mechanism [52]. Both mechanisms implement another novelty, which is the location of frames along the LJS. These frames do not apply normal pressure to the layers. They only avoid the separation or buckling of the layers. In addition, changing the number of frames modifies the stiffness range that can be achieved.

There are other methods to build VSLs that have been combined with LJSs. This is the case of the VSL, which combines three types of variable stiffness methods: airtight chamber, shape morphing, and LJ [53]. This VSL consists of a cloth cover that contains two spring steel plates and a TPU (thermoplastic polyurethane) air bladder. When the air bladder is not pressurized, the VSL has minimum stiffness. When the air bladder is pressurized, the link is inflated and the cross-section becomes circular, which increases the bending stiffness. When the VSL is not pressurized, the link has a rectangular cross-section and behaves as an LJS whose layers are unlocked.

4.5. Other Diverse Laminar Jamming Robots

A notable strength of LJ as a variable stiffness mechanism is the diverse potential for its fields of application. In this section, other applications not related to grippers, continuum robots, wearable robots, or robot arms are summarised.

Soft robotics researchers have conceptualized the application of LJSs to build the landing gear of unmanned aerial vehicles (UAV). These LJSs are activated by air vacuum. The purpose of this application is to tune the stiffness of the landing gear to minimize peak forces, mitigate shock forces, and accelerate the decay of the oscillations. This application demonstrates how LJSs can be used to transform the dynamic response of rigid robotic structures [25].

The application of LJ in underwater robots has been investigated as well. An LJS based on an SLL mechanism was applied as the method of locomotion of a robot fish [37]. The SLL tail is attached to a stepper motor that generates the flapping motion, and the stiffness of the SLL mechanism is driven by the linear actuation of a solenoid. When the robot is moving in open waters, the tail is set up in its rigid state and moves at a large sweeping angle. When the robot is moving in a close channel, the tail is switched to its soft state, which allows the robot to navigate at low speed but steadily through the channel and with a sweeping amplitude that is smaller in comparison to the open water case.

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