“Soft” Continuum Robots: the Interaction of Continuous and Discrete Elements

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Abstract

In this paper, we examine key issues underlying the design and operation of “soft” robots featuring continuous body (“continuum”) elements. We contrast continuum and continuum-like robots created to date with their counterparts in the natural world. It is observed that natural continuum locomotors or manipulators almost invariably rely on hard/discrete elements (in their structure and/or operation) in their interactions with their environment. Implications for the successful operation and deployment of continuum robots are identified and discussed.

1. Introduction

There are innumerable alternatives available to the robot designer. However, only a small subset of these alternatives has been realized in hardware to date. Most modern industrial robots are (human) arm-inspired mechanisms with serially arranged discrete rigid links. This is fine for industrial work where the workspace is predefined and structured. However, robots are currently generally confined to such engineered and carefully controlled environments, and kept well away from humans and their world.

A robot that must interact with the natural world needs to be able to solve the same problems that animals do. Animals come in many shapes and sizes with widely varying specialized limbs suited to their particular everyday tasks. However, most robots are built according to “general-purpose” specifications with little attention to what they will ultimately be used for. The rigid structures of traditional robots limit their ability to maneuver in tight spaces and congested environments, and to adapt to variations in their environmental contact conditions.

In response to the desire to improve the adaptability and versatility of robots, there has recently been interest and research in “soft” robots [1]. In particular, several research groups are investigating robots based on continuous body “continuum” structures. Motivation for this work often comes from nature. If the body of a robot was soft and/or continuously bendable then it might emulate a snake or an eel with an undulating locomotion [2]. A slithering robot could navigate through a variety of terrains.

An alternative solution would be to have a continuous manipulator. A robotic continuum manipulator could be similar to a prehensile tail, an elephant's trunk, or an octopus's arm.

Several different types of continuum-like robots have been proposed. Robotic snakes have been built by a few different groups [3],[4],[5],[6]. These have almost all been built using multiple discrete links. These hyper-redundant robots can move in most of the ways snakes can, but they are not as conformable. Hyper-redundant robots, like the SnakeBot [7], represent a bridge between discrete links and continuous elements [8].

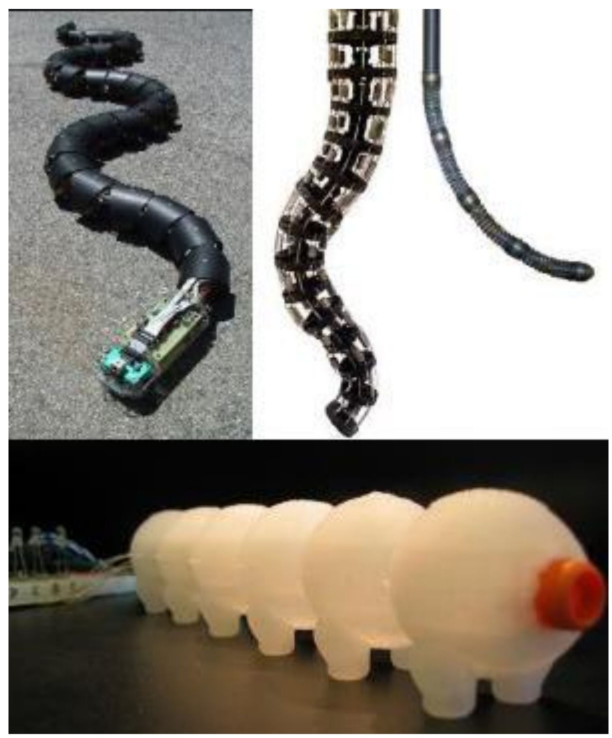

Figure 1: Robotic Snake built by Dr. Gavin Miller, Elephant Trunk Manipulator and Tendril by Clemson University, and Softbot built by Tufts University

True continuum robots, such as the Octarm [9] and the Tendril [10],[11] (Fig. 1), have continuous backbone sections which can conform around objects [12],[13],[14]. Soft robots, such as Softbot, are almost gel-like in their form [15],[16]. However, soft continuum robots are hard to build, model and control [17],[18]. Management of the malleable and compliant properties which form a great part of their appeal is proving a major obstacle to progress in this emerging field [1].

There is an inherent tradeoff between continuous and discrete elements. For example, continuum structures can conform to their surroundings while discrete rigid links aid precise positioning. Interestingly, continuum structures in nature seem to synergize their activities with various kinds of discrete elements, as discussed in the following section. With this in mind, we argue in section 3 that with a judicious mixture of continuous/soft and discrete/hard elements, robots can be made to perform many tasks. We conclude that the structure of soft and continuum robots should depend strongly on the task the robots will be used for and the application environment.

2. Continuous Structures in Nature

Animals in nature have a wide variety of continuum structures. Arms, tails, tentacles, and various other appendages all have important functions they perform for the animal. In the following, we classify these functions into three main classes.

Figure 2: Animals using Prehensile Tails for Balance

2.1 Balance/Stability

There are many instances in the animal kingdom of single hyper-redundant or continuous limbs being used for balance, like the tail of a kangaroo or (most probably) that of a dinosaur [19]. Some gecko species use their tails for stability when they climb. Monkeys can use their prehensile tails to hold onto branches and improve their stability [20]. A prehensile tail is often wrapped around a stable solid object at a discrete location and used as an anchor for support (Fig. 2). A caterpillar is similar in that it will anchor part of its body while the top half moves around to eat. Many other creatures, such as opossums and seahorses, have prehensile tails. The tails can be used to balance on land, in the trees, or under the sea. In this sense natural continuum structures compensate for the complexity inherent in their “softness” by essentially *environmentally grounding themselves at discrete body locations*, typically coupling with hard environmental elements. Similarly, when an animal's tail is used for balance the complexity inherent in the structure is typically handled by adopting restricted classes of movement. One example of this is running. The tail compensates for the complexity of the balancing task by making simple cyclical movements or being swung out behind to counter the animal's movements [19]. Soft continuum robots could clearly benefit from adopting similar strategies.

2.2 Exploration/Sensing

Exploration and sensing are other key functions of natural continuum limbs. Snakes have many different ways to slither. (Generally slithering refers to snakes but also describes the movement of slugs and earthworms.) The four slithering types are lateral undulation, rectilinear locomotion, concertina locomotion, and sidewinding [6]. The type of motion a snake uses depends on its environment. Lateral side to side undulation is the main way snakes move [6]. Rectilinear locomotion is how large pythons and anacondas move using their belly scales [6]. Concertina movement is how snakes climb or move in limited surroundings such as tunnels [6]. Sidewinding is used to move in the desert over loose sand [6]. Under water, eels and sea snakes can wind their way through holes in the coral to find food.

Often natural continuum elements are used as both sensors and effectors. Garden eels, brittle stars, and basket stars all sway in the ocean current to detect food. When a brittle star senses food, it can fling its arm out in the general direction of the food. Then it will coil an arm around it and bring the food to its central mouth. Once again, this flinging is not arbitrary, but is simply controlled since the arm merely unfurls in the needed direction. A similar pattern of simple control, and combination of sensing and exploration, are adopted by plants such as vines (Fig. 3) [21].

Figure 3: Climbing Morning Glory Vine

Alternative natural sensing continuum appendages are whiskers and antennae. Many animals have whiskers to help with their spatial awareness. A catfish's whiskers are used to check the muck at the bottom of a river for food. The tentacles on a star-nosed mole are very sensitive, for example the animals can even smell underwater [22].

Figure 4: Octopus Opening a Jar with its Arms [23]

Here once again, it appears the natural soft/continuum elements are seldom used in isolation of discrete or hard elements. For example, an octopus will wrap its arm around an object but uses its suckers, located discretely along the arm, for fine sensing and manipulation (Fig. 4). Millipedes have a hyper-redundant body studded with numerous discretely positioned legs. Their bodies will conform to the obstacles that they crawl over while using the fine movements of their legs for adjustments. Large anacondas use their belly scales to crawl forward silently when stalking prey [6]. These three creatures all use a combination of soft and hard(er) elements. These hybrid continuum/discrete structures *incorporate discrete elements for fine resolution*, using discrete parts for fine work and their continuum anatomy for general purpose positioning.

A robot could use a continuum appendage with sensors to probe places its main body cannot reach. This would be very useful in exploration of hazardous areas.

Figure 5: Sting Ray, Komodo Dragon tail, and Bullwhip

2.3 Obstacle Removal/Grasping

Another way to use a continuum limb is to use it to remove obstructions and rapidly grasp/manipulate the environment. A whip-like structure can be flicked out to move an obstacle from the animal's path. The movement does not have to be particularly accurate since it often just needs to be cast in the correct general direction. Many animals use their tails as weapons. Komodo dragons will whip enemies and so will sting rays (Fig. 5). If considered as a weapons system, a scorpion's tail would make an interesting model. Continuous natural appendages are also used as weapons. The tentacles of a squid are used to dart out in the direction of prey [24]. Similarly, a brittle star can fling its arms in the general direction of food and then draw the arm in to feed itself.

Octopus arms, which are formidable weapons as well as effective manipulators, appear to be similarly discretely directed in the direction of objects of interest rather than having their shapes closely controlled [25]. Elephants also simplify control of their trunks by moving them within a plane oriented towards objects they desire to grasp [26]. Brittle stars manipulate objects in a similar manner as octopuses, but unlike octopuses the brittle star does not have strong suction cups on its arms. Each arm is like a snake's tail and can be used to wrap around objects. They can slither or crawl depending on the terrain. Their arms are quite dexterous and can be used to grab food and move it to the star's central mouth.

Humans can also be very effective when augmented with continuum tools. Whips, lassos, and chains are all flexible tools that can be used in a variety of ways. In the movies, Indiana Jones has used his whip to swing across gaps [27]. If a robot could do this, then it could transport itself to places it could otherwise never reach, or at least get there quicker. Ropes can be made into lassos to loop around objects. Cowboys use lassos to capture errant steers. A robot could potentially use a lasso to hook rock outcroppings to pull itself up a cliff. A grappling hook is a strongly related alternative.

A common element in all the above examples is once again *discrete control*, with the problem of close control of all degrees of freedom in the continuum structure sidestepped by making simplified motions (controlled by a *discrete* set of variables) in specific directions. In many cases, only the direction and speed need to be directly controlled. A continuum limb could similarly be used swiftly to fling obstacles out of the robot's path, or form quick but effective curling grasps.

3. Implications for Soft and Continuum Robots

The examples from nature in the previous section motivate a new look at soft continuum robots. Up to this point, most development has been motivated by the desire to create "fully soft" continuum robot bodies with no hard or discrete elements, and to precisely control their shape through the continuum of possibilities, independent of their environment. However, it seems clear that many natural soft and continuum elements are successful precisely by incorporating discrete elements, simplifying their movements, or interacting in a way very specific to their environment. The key in all cases we have reviewed is complexity reduction, which leads to strong implications for robot development. Each of these issues is investigated in the following subsections.

3.1 Complexity Reduction

A key goal for soft continuum structures is adaptability: compliance to environmental constraints via an enhanced (essentially infinite dimensional) configuration- or shape-space. In robotics, almost all efforts so far have tried to achieve this via soft compliant bodies in controlled continuum contact with their environment. (The two main types of continuum manipulator today are tendon-driven [8],[28],[29] or pneumatically [13],[29],[30],[31] controlled.) However, the resulting decision space (and its requirements for sensing and planning) is vast. A key simplifying observation from the natural world is that *in nature, soft continuum limbs are used mostly for approximate positioning, strongly exploiting discrete elements in their structure, operation, or their environment to simplify and resolve their operation*. In all cases this allows complexity reduction: environmental contact and fine manipulation details are handled by discrete scales, legs, or suckers; the movement space is restricted to a given direction or plane, as in the movements of octopus arms and elephant trunks, or dynamic balancing of tails; imprecision due to environmental forces is alleviated via stabilization using tails, anchors, or tongues. All these concepts could be exploited in novel robotic counterparts.

Another issue which appears to have been rarely considered as a major issue in robotics, but which appears critical in nature, is that of the underlying nature of control. Continuous control (regulation of the system to an arbitrary shape throughout its workspace) enables precise operation. Continuous control in the above sense is the most commonly used form of control in conventional rigid link robots. This allows the control system to compensate for (indeed, take advantage of) the simplicity of the discrete rigid link structure to achieve the precise positioning desired in structured applications such as manufacturing. However, effective continuous control of continuum robotic structures is proving extremely difficult to achieve [9],[10]. The increased complexity in continuum structures is hard to either model well, or to provide sufficient actuator inputs for, to enable consistent control.

Nature however suggests an alternative approach to complexity reduction in control. If a continuous manipulator is controlled discretely (restricting the allowable shapes of the system to a finite set, or a shape set defined by a finite set of inputs) then it will be much easier to control. Clearly many, if not most, continuum structures in nature are controlled in a discrete (as defined above) manner, as discussed in section 2. Notice that in this case the compliance inherent in the continuum structure allows the system to adapt to compensate for the simplicity of the control. The concept of central pattern generators has been used to define the shapes and simplify the control of some snake-like robots [2]. An extension of these ideas to the wider class of continuum robots could enable practical control of behaviors similar to octopus arm or elephant trunk manipulation. Binary control (enabling "whip-like" movements similar to those discussed in section 2.3) has corresponding potential for continuous manipulators in dynamic tasks.

3.2 Design Implications

A common theme in the above discussion is the effectiveness of the combination of continuous and discrete elements. One direct way to achieve this synergy is by incorporating both types of structure on an overall robot design, a *hybrid continuum/discrete robot*.

Figure 6: Fictional Snake-Arm Robots (B-9, Sentinel, Doc Ock)

Figure 7: Real Snake-Arm Robots from OC Robotics [28]

Some hybrid continuum/discrete robot designs have previously been considered. One possibility is to have a continuous arm and simple gripper, like the trunk of an elephant which can pick up a peanut with its finger-like projections. A robot with a continuous arm and discrete gripper is generally called a snake-arm robot. There are numerous examples of snake-arm robots in science fiction, but few in real life (Fig. 6). Science fiction can serve as inspiration just as well as nature. For example, the flip-top communicators from Star Trek could have inspired the cell phone [32]. However, while there are multiple examples of fictional continuum robots, there are very few continuum robots in reality. Most real snake-arm robots are discrete, using many joints to become hyper-redundant [8]. Snake-arm robots are used in the nuclear industry and for robotic surgery [28],[33] (Fig. 7). The advantage of having a continuous arm with a discrete gripper is that it would be like having a tentacle with a hand on its end, providing impressive maneuverability with a simple, if not particularly dexterous, grasp (Fig. 8).

Figure 8: Discrete Arm with Continuous Fingers [34]

The question of whether to use discrete or continuous parts is an interesting one, with the answer depending on how the robot is desired to move and what its function will be. Let us consider an example consisting of an arm and a manipulator. When would it be best for the arm to be continuous (i.e. the snake arm approach)? Having a continuous arm would let the manipulator reach places that might otherwise be unreachable. The three most prominent continuum structures in nature are the octopus arm, elephant trunk, and tongues. Underwater animals can have soft continuum arms because they are affected little by gravity. Most tongues are short and stout so they can also ignore gravity. However, an elephant’s trunk is affected by gravity and can be seen swinging as the elephant moves its head from side to side. Adding a discrete gripper onto the end of a continuum trunk would cause an even greater sag in the robot.

Figure 9: Giraffe Using its Tongue to Extend its Reach

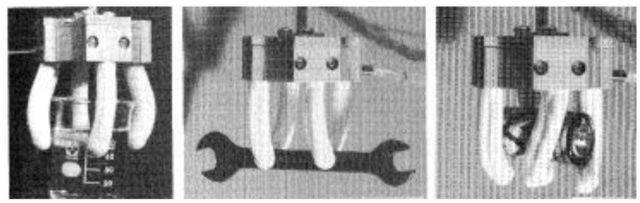

Figure 10: Flexible Microactuator [14]

An interesting alternative design approach would be to use a serial discrete link arm and a continuous end effector. This model is less frequently explored than the snake-arm robots, even in fiction. The giraffe is a natural example. The concept can be thought of as a discretely built neck with a continuous tongue as a manipulator. It could use its prehensile tongue to reach places it cannot fit its neck into (Fig. 9). Unlike the giraffe's tongue, most robotics end effectors are in the form of hands or simple grippers. One example of a hand with continuum elements is the AMADEUS dexterous underwater gripper [1]. The flexible microactuator built by the Toshiba Corporation is much smaller and could be used for more delicate tasks [14] (Fig. 10). This type of robot would be like having an octopus for a hand. It would be able to manipulate objects dexterously and do things that current discrete link manipulators can't. One issue with the manipulator is how many fingers it should have and how many joints for each. Four fingers is usually enough to manipulate objects in 3D. As with a continuous arm, continuous fingers would have sagging and torsion issues. However, this would be less than for a continuum trunk, and the continuum end effector could compensate for gravity and/or changes in the environment such as the movement of its goal, just like a giraffe's tongue can move to catch leaves blown by the wind. There are few examples of a discrete arm with a continuous end effector in nature. However, there are also few examples of the wheel and yet it is one of humanity's most useful inventions. Roboticists should not be limited by nature, but also look to their imagination for inspiration.

A third alternative design would be a non-serial hybrid continuum/discrete structure. These structures might be ideal for fine manipulation. One natural model for a continuous end effector is the basket star (Fig. 11), which has similarities with the brittle star (Fig. 12). Rather than a brittle star's five limbs, the basket star has a fractal-like pattern of tentacles. It is almost tree-like in its form. A basket star would make a great manipulator if you could control it [35]. A manipulator with rigid linked fingers cannot conform to an object it intends to grasp, but continuum fingers can wrap around an object like the grasp of an octopus. This would result in a better grip with less chance of the object being dropped.

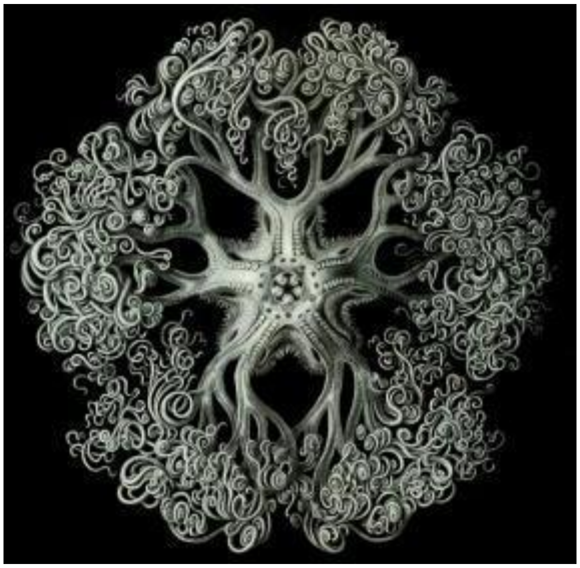

Figure 11: Illustration of a Basket star

Figure 12: Illustration of a Brittle star

A key question raised by the earlier discussion is how motions for soft continuum robots should be planned and controlled. Motivated by the examples from nature reviewed here, we argue that simplifications should be sought where possible, as discussed in the previous subsection. The strategy of restricting and controlling movements to a plane is appealing and clearly successful for many animals, and likely to be most practical for continuum robotic elements. For hybrid continuous/discrete robots, it would appear to be best for the discrete part of the robot to be controlled continuously (and vice versa) so that the discrete part is concerned with precision, and the continuum part with more global environmental accommodation. For example, the fractal-like pattern of the basket star end effector design would be hard to control continuously so discrete control of the continuum elements would be most appropriate.

Additionally, it seems clear that the structure of these new forms of robots with soft continuum elements robot should be dependent on the environment they will operate in. The traditional approach of building general-purpose robots has only been partially successful – while traditional robots are used for a variety of tasks in structured environments, typically those environments have been heavily engineered to fit the robots capabilities. Therefore robots have not significantly penetrated the inherently unstructured environments of the "real world". Soft continuum robots are explicitly intended to enter that world, and the lesson from their counterparts in the natural world is that success generally implies specialization and matching to the environment. We believe that, at least in the medium term, the same is likely to be true for continuum robots.

Finally, notice that there are other types of locomotion not discussed here for which soft continuum robots might be useful. Legged locomotion and slithering are the two main types of terrestrial locomotion, but some creatures can configure their bodies to roll around like wheels [36]. In nature the caterpillar of the Mother-of-Pearl moth and the stomatopod shrimp (*Nannosquilla decemspinosa*) are two of the few rolling animals [37]. There are many types of robots that mimic the legged locomotion of animals, but wheeled robots are more common and more practical at this time. Rolling is usually a secondary form of motion in nature with the primary form being legged locomotion. Rolling is complex to control and a non-wheeled rolling continuum robot would be hard to steer with no stable base for sensors. However, new types of modular and shape shifting robots might find this mode useful in the future.

4. Conclusion

We have discussed the design and operation of the emerging class of soft and continuum robots, contrasting the state of the art in robotics to date with the counterparts in the natural world. We note that natural continuum locomotors or manipulators almost invariably use design modifications or specialized "tricks" to simplify their operation. The complexity reduction achieved is usually based on synergy of soft/continuum with hard/discrete elements (in the structure and/or operation of the robots). We have discussed implications for the design and successful operation of novel continuum robots. A key inference is that construction of a soft continuum robot should depend on the environment it will be used in. It also appears that appropriate combination of continuum and discrete, or soft and hard, elements is likely to significantly improve the performance of these robots.

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