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Continuum robots and underactuated grasping

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Abstract. We discuss the capabilities of continuum (continuous backbone) robot structures in the performance of under-actuated grasping. Continuum robots offer the potential of robust grasps over a wide variety of object classes, due to their ability to adapt their shape to interact with the environment via non-local continuum contact conditions. Furthermore, this capability can be achieved with simple, low degree of freedom hardware. However, there are practical issues which currently limit the application of continuum robots to grasping. We discuss these issues and illustrate via an experimental continuum grasping case study.

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1 Introduction

Grasping has been a core topic in robotics since the inception of the field. The classic “pick and place” strategy for robot manipulators is core to many industrial applications. Typically, in this situation grasping is achieved using a parallel jaw gripper at the end of the manipulator. This is a simple and reliable strategy, but limits the set of graspable objects to those that fit into the shape and scale of the gripper.

Researchers have long sought to improve the versatility and dexterity of robot end effectors. Typically the strategy has been influenced by the readily available case study of the human hand. A great many multi-fingered hand designs have been proposed, constructed, and analyzed through the years. An extensive survey conducted over 30 years ago is reported by Kato and Sadamoto (1977). A more recent survey of the field is given by Bicchi (2000).

However, despite steady improvement in the performance of multi-fingered robot hands, the industrial standard today remains the parallel jaw gripper. This is in part due to the inherent complexity of the human hand that multi-fingered robot hands seek to emulate. It is difficult to produce a dexterous yet reliable hand at the scale desired for most applications. This difficulty is amplified by the need to mount the hands at the end of robot manipulators, which in turn imposes significant restrictions on hand weight and packaging.

In response to the above challenges, researchers have been considering innovative solutions, both in hardware and grasping strategies, based on simpler, under-actuated strategies.

The underlying concept is to “do more with fewer inputs”. For example, the three-fingered Barrett Hand (www.barrett.com) features the (quite non-anthropomorphic) design of rotating one finger around its “palm”, so it can serve at times as an opposable thumb, and at other times as a conventional finger. Numerous other approaches to hardware complexity reduction, such as coupling of joints to reduce the number of controlled degrees of freedom, have been adopted (Kato and Sadamoto, 1977). On the theoretical side, a significant body of work has considered the underlying nature of machine manipulation, concentrating on situations where analytical understanding (for example of non-holonomic conditions in rolling contact) can be applied to simplify the input space. An overview of this work is given by Bicchi (2000).

In this paper, we consider a different approach to underactuated grasping. Instead of using the human hand for motivation, we adopt concepts from biological “tongues, trunks, and tentacles”. This results in robot grasping based on “invertebrate” continuum robots as opposed to “vertebrate” fingers in conventional robot hands. This leads to simpler, lower degree of freedom designs. Rather than analyzing special classes of grasping, we seek to widen the range of graspable objects via the judicious inclusion of inherent compliance in the hardware.

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Figure 1. Octarm Continuum Robot.

The following sub-sections briefly review the state of the art in continuum robots and related literature on underactuated manipulation with continuum contacts. The potential and reality of continuum robot grasping are explored in the next two sections, followed by discussion and conclusions.

2 Continuum robots – potential

The idea of creating "trunk and tentacle" robots, (in recent years termed continuum robots (Robinson and Davies, 1999)), is not new (Anderson and Horn, 1967). Inspired by the bodies of animals such as snakes (Hirose, 1993), the arms of octopus (Walker et al., 2005), and the trunks of elephants (Cieslak and Morecki, 1999; Hannan and Walker, 2003), researchers have been building prototypes for many years (Fig. 1). A key motivation in this research has been to reproduce in robots some of the special qualities of the biological counterparts. This includes the ability to "slither" into tight and congested spaces, and (of particular interest in this work) the ability to grasp and manipulate a wide range of objects, via the use of "whole arm manipulation" (Salisbury et al., 1988), i.e. wrapping their bodies around objects, conforming to their shape profiles.

Much of the effort thus far has concentrated on medium-scale (length roughly 1 m) continuum manipulators, and on simple grasping with single continuum bodies on that scale. However, some initial work in combining multiple continuum bodies into "multi-fingered" versions has been demonstrated (Suzumori et al., 1991; Lane et al., 1999). In the following sections, we will discuss the fundamental advantages and disadvantages of continuum contact in grasping, covering both cases.

One notable feature of continuum structures is that, while kinematically redundant versions have been developed (Hannan et al., 2003; Chrikjian, 1992), many prototypes have been designed to be under-actuated (in terms of numbers of independent actuators) with respect to their anticipated tasks. This is partly due to the desire to keep the body structures (which, unlike in conventional rigid-link manipulators or fingers, are required to directly contact the environment) "clean and soft", but also to exploit the extra control authority available due to the continuum contact conditions with a minimum number of actuators (Trivedi et al., 2008). It is in this sense that we use the term "under-actuated grasping" in this paper in the context of continuum robots.

3 Continuum contact and under-actuated manipulation

The ability to exploit continuum contact – particularly line contact – to restrain and manipulate objects is well-established. Consider for example the example of spinning tops by pulling on strings initially wrapped around their bodies (www.anirudh.net/courses/emch520/html/), or the dynamic manipulation of objects using whips (Bernstein et al., 1958). The physics of these activities, and related activities such as flycasting (Robson, 1990), are well established. The situation of manipulation of objects using ropes has also been the subject of interest in the robotics community (Donald et al., 2000).

The above real-world examples demonstrate situations in which low (often single) degree of freedom inputs, when well planned and executed, are sufficient to control higher-dimensional behavior of the manipulated environment. It is clear that the ability to "wrap around" an object presents a significant mechanical advantage, which if exploited carefully, can afford a complex behavior from a simple, low degree of freedom actuation strategy. A key issue for developers of continuum robots is to what extent this concept can be used in practice to perform useful grasping with under-actuated systems. This is the main issue explored in the following sections.

4 Continuum grasping – concepts

In grasping, as discussed above, the key attribute of continuum robots is their capability, via their inherent ability to bend at any point along their structure, to adapt their shape to conform to the perimeter of objects to be grasped. In theory, this ability could be exploited, if the continuum robot were sufficiently long and powerful, to "wrap around an object in all directions and completely constrain it". This suggests an alternative to the traditional way of thinking about grasp analysis as the net effect of a finite number of (local) contact locations. Conceptually, continuum (line) contact can be viewed as placing an infinite number of fingers in a tunable line around the surface of an object to be grasped. The inference is that the object can be "surrounded" by contacts over a sufficiently wide range of its surface to achieve, for

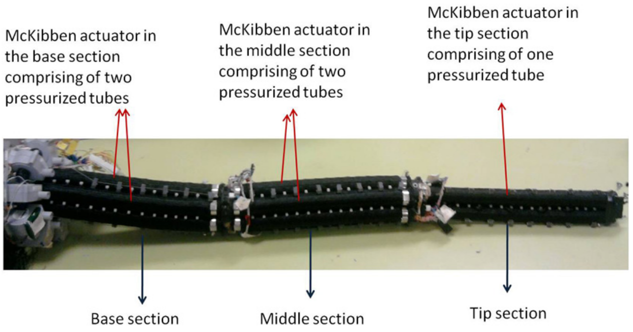

Figure 2. Picture of Octarm VI with sections and actuators marked.

example, full force- or form-closure (Bicchi, 2000), and thus stable grasping.

The engineered situation however can never be quite as above. While continuum contact can be maintained around the complete perimeter of an object, it is not feasible to apply arbitrary forces at given points on the perimeter, as if there were "infinite fingers". To do this would require in general an infinite number of actuators, corresponding to the infinite number of degrees of freedom theoretically available in the robot structure. In practice, although there are numerous different design strategies (Trivedi et al., 2008), continuum robots possess a small finite number of actuators, with the remaining (infinite) degrees of backbone freedom determined at each instant implicitly, via a combination of backbone materials properties, actuation forces, and external loading (Trivedi et al., 2008).

Despite this, continuum robot grasps do indeed tend to be quite robust to external disturbances (Trivedi et al., 2008; McMahan et al., 2006). The passive compliance inherent in almost all continuum manipulators causes them to "squeeze" around the perimeter of the continuum contact, evenly distributing the force resulting from even a single degree of freedom of actuation.

5 The Octarm VI continuum manipulator – kinematics and operation

The Octarm is a biologically inspired continuum manipulator that resembles an elephant's trunk (McMahan et al., 2006). Octarm VI has three sections each comprising of three independently actuated pneumatic actuators also known as McKibben actuators positioned at an angle of 120 degrees with respect to each other (see Fig. 2). These actuators comprise of latex tubes (two tubes per actuator in the base and middle sections and one tube per actuator in the tip section) covered with a plastic mesh sheet that is wound in a double helical manner.

When all the three actuators of a section are pressurized with equal amount of pressure, the section extends along the direction of length of the actuator tubes. When the air pressure in one of the actuators is reduced, the section bends with constant curvature (illustrated in Fig. 3) . Thus by varying air pressures in the three actuators in suitable proportions determined by an inverse kinematics mapping procedure (Jones and Walker, 2006a), the section can be made to bend in different directions. Thus each section can bend about two axes (x and y) and can extend along a third axis (z) resulting in three degrees of freedom. This gives a total of nine degrees of freedom for the whole manipulator (three per each section).

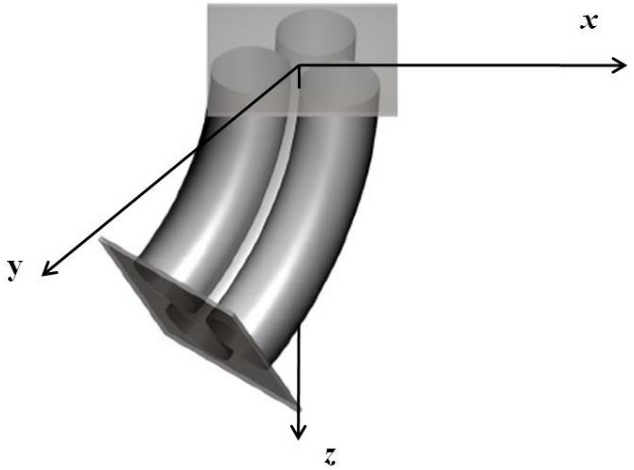

Figure 3. Bending of a section due to difference in actuator pressure levels (Jones and Walker, 2006a).

Each continuum section of the Octarm has three internal parameters – curvature κ, direction of curvature φ and section length s (shown in Fig. 4). The forward kinematics of a section of the manipulator has been developed by approximating each section of the continuum arm to a conventional rigid link robotic arm, noticing that the net transformations are the same and then by expressing the D-H table parameters as a function of the internal parameters of the manipulator (Jones and Walker, 2006b). The homogeneous transformation matrix (Jones and Walker, 2006b) expressed in terms of the internal parameters of the continuum arm is as follows,

$$\mathbf{A}=\begin{pmatrix} \cos^2\varphi(\cos\kappa s-1)+1 & \sin\varphi\cos\varphi(\cos\kappa s-1) & -\cos\varphi\sin\kappa s & \frac{\cos\varphi\cos(\kappa s-1)}{\kappa} \\ \sin\varphi\cos\varphi(\cos\kappa s-1) & \cos^2\varphi(1-\cos\kappa s)+\cos\kappa s & -\sin\varphi\sin\kappa s & \frac{\sin\varphi\cos(\kappa s-1)}{\kappa} \\ \cos\varphi\sin\kappa s & \sin\varphi\sin\kappa s & \cos\kappa s & \frac{\sin\kappa s}{\kappa} \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

From the co-ordinates of the end point of the section, the internal parameters can be calculated using geometry of the section (Csencsits et al., 2005). In such calculations, singularities occur in two configurations – when the curvature is zero and when the tip of the section is at origin. An inverse kinematics mapping procedure for converting the internal parameters (s, κ and φ) of a section to actuator lengths and thereby to air pressures in the three actuators of a section was developed by Jones and Walker (2006b).

The fundamental operations of a continuum robot are achieved by the combination of one or more actuator inputs

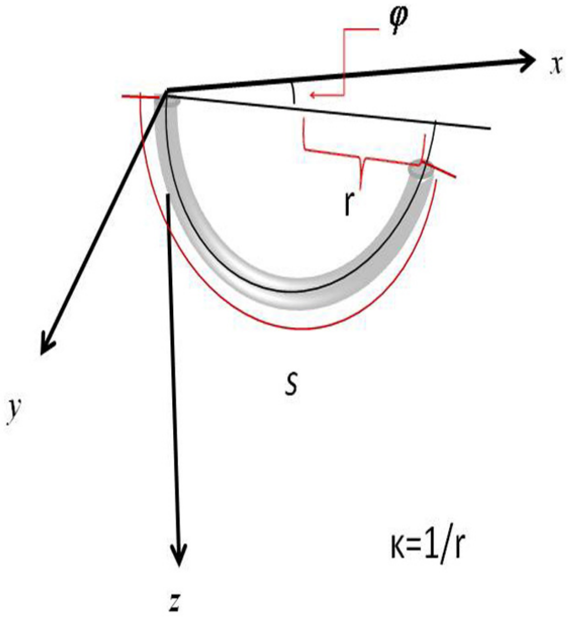

Figure 4. Kinematics of a single section of a continuum arm.

Figure 5. Octarm grasping a spherical object – continuum grasp.

in contrast to conventional rigid link robots wherein each degree of freedom is controlled by an actuator. With a motive to make the control of operations intuitive to the operator, the user-interface for Octarm VI has been designed in a way that only the high-level control operation is obtained as input from a joystick (Csencsits, 2007). A detailed description of various joystick mapping schemes employed to obtain s, κ and φ values of the selected sections from different joystick positions is given by Csencsits et al. (2005). Inverse kinematics procedure (Jones and Walker, 2006b) is implemented to determine the actuator pressure levels required for the desired position of the arm.

6 Continuum grasping – practise

In this section, we use the results of a series of experiments to demonstrate aspects of continuum grasping (that were discussed in previous sections) which are easily achievable, and some of which are less accessible at the present time. The experiments discussed below were conducted in the robotics laboratories at Clemson University, using Octarm VI.

For experiments conducted on continuum grasping and reported on in this paper, the Octarm was placed horizontally on the floor thereby restricting, for each section, one of its degrees of freedom (to bend upwards/downwards). Thus, in such a planar arrangement, each section can bend sideways and extend along its length; thereby the manipulator as a whole has six controllable degrees of freedom. This arrangement is convenient to analyze grasping of stationary as well as moving objects. Also, maximum curvature for each section is achieved when the Octarm is laid on the floor as bending of the air actuators is not opposed by gravitational effects. Due to mechanical constraints (inherent compliance), curvature limitation and sagging are unavoidable when the Octarm operates in the spatial world.

The inputs to the pressure regulators that control the pressure levels in the air actuators of the Octarm are given through a control PC having a Data Acquisition I/O board. This is a Pentium III EBX form-factor Single Board Computer (SBC) running QNX Neutrino real-time Operating System. This is connected to another PC on the operator side that is interfaced to a joystick (Logitech Wingman 3-D). The values of s, κ and φ are obtained as inputs from the joystick position. The mapping from these parameters to air pressures in each of the actuators in a section is implemented in a MATLAB/Simulink code. String encoders that are mounted on the base of the arm provide actuator lengths as feedback.

Throughout these experiments on continuum grasping, one or more number of sections were used and the curvatures were controlled using the joystick. The grasping ability of the Octarm was initially analyzed with a set of stationary objects of different shapes, sizes, textures and orientations. Depending on the size of the object, one or more sections of the Octarm were used for grasping. A firm, continuum contact was observed in grasping spherical and cylindrical objects that aligned with the curvature of the arm. A picture of the Octarm grasping a ball is shown in Fig. 5.

While two sections were required to encircle objects having larger diameter, objects were still firmly held by a single

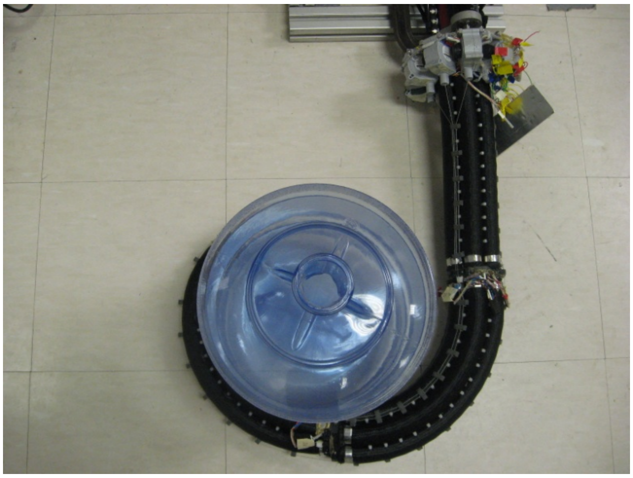

Figure 6a. Two sections of the Octarm used for grasping.

Figure 6b. The same object grasped using the tip section of the Octarm.

section by having a tight grasp, thereby realizing force closure. This is shown in Fig. 6a and b. When multiple sections were used to grasp an object having a circular boundary however, a perfect continuum contact was often not observed as all the three sections did not uniformly bend with the same curvature. This was attributed to the Octarm manipulator's construction which caused all three sections to individually bend with uniform curvatures but not as a whole. Continuum grasping was also seen in the case of soft objects which deformed their shape to confirm to the boundary of the manipulator sections.

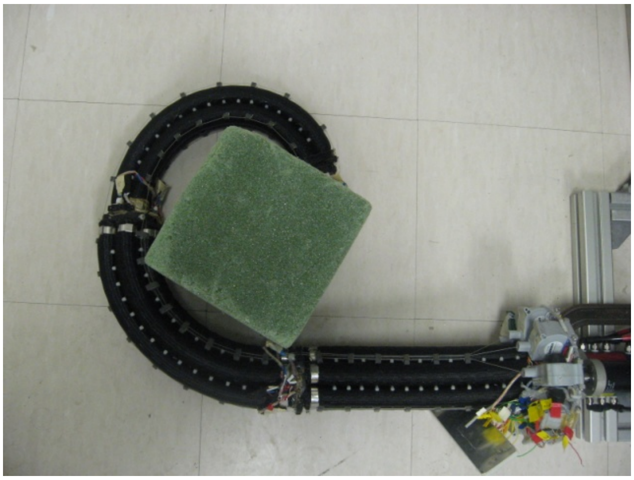

Figure 7. Object held by point contacts.

Interesting results were obtained when objects with sharp edges were grasped. While grasping objects of the shapes of cube, cuboid, etc., contacts were made at the edges or at the faces of the object. The number and location of contact points that determined the stability of the grasp were dependent on the initial orientation of the object. Although continuum contact was not possible in this case, the manipulator was able to hold objects through distributed point contacts leading to force closure in the plane (Fig. 7). An increase in tightness of the grasp on a rigid object flattened the curvature of the manipulator thereby increasing the contact surface. Thus, based on the dimensions, orientation and rigidity of the target object, grasping in practice was realized partially by continuum contacts and partially by (locally) point contacts (Fig. 8).

Continuum grasping using the Octarm is particularly attractive in grasping fragile objects (like an egg tray, glass jug) where a soft but firm hold is required (Fig. 9). Potential applications include rescue operations and safe manipulation of delicate objects. Apart from the objects mentioned earlier in this paper, there are also numerous other cases in which the parallel jaw gripper is not plausible. Multifingered robots can provide a more dexterous solution for grasping but with more complicated mechanisms. Continuum grasping, on the other hand derives inspiration from biological structures and redefines grasping by providing a novel and less complicated approach. Its versatility in handling a plethora of objects makes sense intuitively and is also proven from the above experiments.

Continuum manipulators also have an edge over their competitors by their ability to robustly grasp moving objects

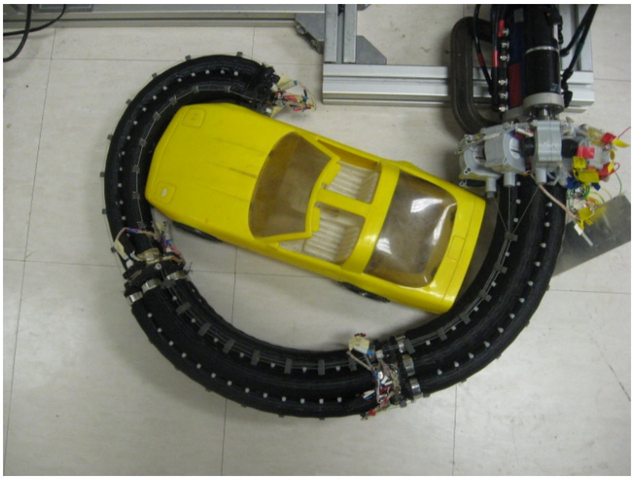

Figure 8. Continuum and point contacts.

Figure 9. Grasping fragile objects – using a parallel jaw gripper (unsafe grasp) and the Octarm.

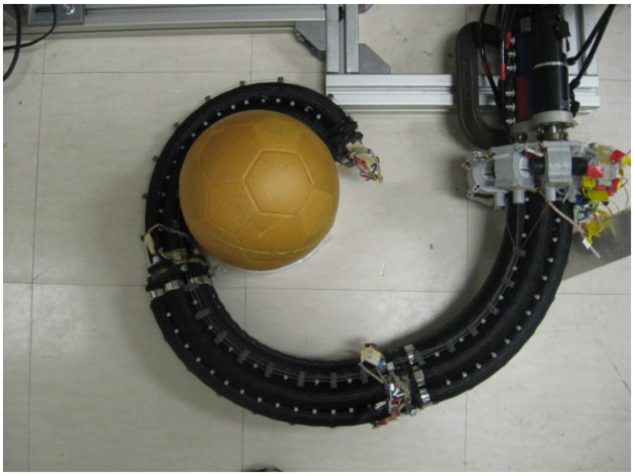

Figure 10. The Octarm - grasping and acquiring a moving object.

Table 1. Compliance of all three sections (measured in a distance perpendicular to z-axis indicated in Fig. 3).

	Compliance (in 10^{-3} m kg^{-1})		
Pressure Levels in the Actuators (in $\times10^5$ Pa)	Base Section	Middle Section	Tip Section
0.8273	0.5698	0.5835	1.1454
2.1373	0.3655	0.3699	0.8201
4.5505	0.2776	0.2876	0.5705
5.5158	0.2276	0.2302	0.4262

without the requirement of precise knowledge of the relative velocity of the moving object. The inherent structure of a continuum manipulator and its nature of grasp are advantageous in grasping moving objects. The Octarm was able to restrict the motion of and grasp passive but moving objects like a spinning ball, rolling ball and a sliding object as long as the relative motion between object and robot was towards the inner surface of the loop formed by the manipulator (Fig. 10). In the case of passive rolling objects, grasping was successful for objects that were able to drift and not sufficiently heavy to oppose the movement of the manipulator. Although a few practical problems were faced due to slow response of the Octarm relative to fast – moving objects, there exists a huge potential for grasping non-stationary objects with continuum manipulators to be explored in the future.

Another topic of interest in this context that is in line with grasping is "acquisition". Various bio-inspired strategies were developed to use continuum manipulators to grasp an object and bring it towards the base of the manipulator. This is similar to the behavior seen in animals possessing trunks and tentacles in grabbing food objects. Octopus-inspired strategies were developed for the Octarm by McMahan and Walker (2009).

Manipulation of an object grasped is achieved using the base section of the continuum manipulator. Since the Octarm was operated in a plane, manipulation of the base section was restricted to one degree of freedom only.

7 Discussion

In this section, we analyze the potential of Octarm to be used for continuum grasping by discussing various aspects of its capabilities as well as a few inherent problems that accompany grasping. The analysis is based on quantified physical data and observations made from the experiments in the previous section.

One of the major advantages of any bio-inspired soft robot is its intrinsic compliance which enables grasping of a wide variety of objects whose shape, size and orientation are not accurately known. While holding an object, the continuum arm no longer maintains its constant curvature bending configuration as it deforms to confine to the shape of the object. This passive adaptation ability of the Octarm relies on its compliance as well as the rigidity of the object that is being grasped. Table 1 gives approximate measures of compliances of the three sections of Octarm VI at different actuator pressure levels.

Table 2. Approximate curvatures of the three sections.

Section	Maximum Curvatures (in m^{-1})	
	planar (2-D) operation	spatial (3-D) operation
Base section	3.98465	2.28228
Middle section	4.16693	3.79449
Tip section	8.33072	8.07598

Table 3. Payload of Octarm.

Weight of Octarm VI (Approx)	6.93996 kg
Payload (Lifting against gravity)	0.90718 kg

Table 4. Actuator parameters.

Section	Time taken for the pressure levels to increase from 0 Pa to 5.5158×10^5 Pa in all the actuators (in s)	maximum percentage of extension
Base section	5.51	27.18
Middle section	5.66	42.47
Tip section	5.78	38.5

The compliances of the base and middle sections are almost the same. The tip section having a thinner structure than the other two sections is more compliant. With an increase in actuator pressure, the stiffness of each section increases thereby making it less compliant.

There are a few potential problems faced with the operation of the Octarm in full 3-D environments which degrade its performance in grasping to certain extent. A comparison of the approximate curvatures of the three sections of the Octarm VI measured in planar (2-D with the effects of gravity eliminated) and in 3-D configurations is shown in Table 2.

The maximum curvatures of the three sections in 3-D configuration are lesser than the ones achievable in 2-D planar configuration. The maximum curvatures that can be reached also give an idea of the dimensions of the object that can be effectively grasped using one or more sections of the Octarm.

In 3-D operation, the manipulator's position deviates slightly from its kinematics which is attributed to sagging effects due to gravity and weight of the arm. Also, when the manipulator carries and lifts objects, its ability to grasp is limited by the payload capacity of the arm. The maximum load that the Octarm VI can sustain without deforming its grasping configuration is given in Table 3.

The time taken for each section to expand to its maximum possible length i.e. for the pressure in the actuators to increase from 0 Pa to a maximum value (5.5158×10^5 Pa) is tabulated in Table 4. Currently, there is no explicit mechanism to regulate the speed of operation of the Octarm. But, faster movement of the Octarm for the same curvature can be observed by varying at maximum section length (s).

Although 3-D operation of the manipulator permits an infinite number of directions of bending for grasping, the inherent design of the manipulator permits maximum curvature to be achieved only in three directions ($\varphi = 30°$, $150°$, $270°$) , when the section bends away from any one of its three actuators. Also, there is a second local maximum curvature that can be achieved in three directions ($\varphi = 90°$, $210°$, $330°$) when the section bends away from any two of its three actuators. This imposes a restriction on effective grasping operation of the arm in spatial configuration. For the experiments conducted in planar 2-D space, the Octarm is bent in the direction of maximum curvatures. The curvature values of each section reported in this paper also correspond to the directions of maximum curvatures.

In this paper, a novel idea to use a continuum manipulator for under-actuated continuum grasping has been proposed and demonstrated using the Octarm as a prototype model. Continuum manipulators can be approximated by the operations of a multi-linked under-actuated chain, but the kinematics, actuation and control strategies employed are different from the former. The Octarm lacks links and joints, but, having the air pressurized actuators arranged in a triangular pattern enables the arm to bend in an infinite number of directions. The grasp realized using a continuum arm is more qualified by its flexibility (compliance) and this compensates for the lack of accuracy when compared to rigid link robots in positioning the arm to grasp objects. The arm was manually operated and its potential to grasp was analyzed and quantified using empirical data. We are currently programming different trajectory motions for the Octarm to find a movement of the arm that increases the impact force at the contact point. Having this as the groundwork, in the short term, we intend to develop autonomous grasping algorithms to realize impulsive manipulation with continuum arms.

8 Conclusions

Continuum robot structures are designed to create continuum contact with a grasped object, over a relatively large range of the object surface. This capability arises due to their ability to adapt their shape to that of the object, and can be achieved with relatively few controlled inputs. This combination of increased contact area with fewer degrees of freedom, compared with conventional multi-fingered robot hands, offers the potential for robust and adaptive under-actuated grasping with continuum robot elements. In this paper, we discussed and demonstrated this potential via a series of experimental case study examples. However, as illustrated in the experiments, numerous challenges need to be addressed before under-actuated continuum grasping is a practical option.

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