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• REVIEW •

Special Focus on Space Flexible Manipulation and Control for On-orbit Servicing

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# An overview of the configuration and manipulation of soft robotics for on-orbit servicing

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**Abstract** Soft robots refer to robots that are softer and more flexible when compared with conventional rigid-bodied robots. Soft robots are adapted to unstructured environments due to their flexibility, deformability and energy-absorbing properties. Thus, they have tremendous application prospects in on-orbit servicing (OOS). This study discusses the configuration and manipulation of soft robotics. Usually, learning from living beings is used to develop the configurations of most soft robots. In this study, typical soft robots are introduced based on what they mimic. The discussion of manipulation is divided into two parts, namely actuation and control. The study also involves describing and comparing several types of actuations. Studies on the control of soft robots are also reviewed. In this study, potential application of soft robotics for on-orbit servicing is analyzed. A hybrid configuration and manipulation of space soft robots for future research are proposed based on the current development of soft robotics, and some challenges are discussed.

**Keywords** soft robot, on-orbit servicing, biological inspiration, configuration, manipulation

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## 1 Introduction

On-orbit servicing (OOS) is a series of on-orbit activities to maintain space systems and includes repairing, transporting, refueling, rescuing, and upgrading of satellites following their deployment. The OOS can extend the useful life or operational flexibility of spacecraft without launching a new satellite. However, the space environment is very harsh and is often unsupportive of equipment reliability. Thus, the OOS is an attractive approach to altering current paradigms of satellite design, construction, or operation and provides reliable improvements to meet the challenges in space exploration [1–3].

Space robotics plays an important role in the OOS. Depending on the ability of space robots to function well under the long-distance effect, they can effectively assist astronauts to conduct on-orbit work and reduce the frequency of extravehicular activities. Additionally, in some situations, robots are indispensable while completing tasks that are highly difficult or dangerous. Currently, autonomous on-orbit service technology based on space systems is one of the most challenging and promising projects. Space robotics

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is successfully applied in demonstration missions including the space station remote manipulator system (SSRMS) in Canada [4], engineering test satellite-VII (ETS-VII) of the Japanese aerospace exploration agency (JAXA) [5], and orbital express by defense advanced research projects agency (DARPA) [6]. Most key elements of completed unmanned technology demonstration missions are rigid-bodied and were built on stiff components and joints. However, some technical challenges, such as capturing a tumbling satellite and operating in a confined space [7], continue to exist in servicing non-cooperative satellites.

Conventional rigid-bodied robots are used widely in the industrial community. They can be programmed to efficiently complete a single task. However, rigid-bodied robots lack adaptability, and this limits the application ability of the robots. Robots can face the following challenges especially in space applications: (1) The space environment involves micro gravity and is harsh. It is necessary for robots to adapt to unknown and confined spaces. (2) Most targets are non-cooperative, and it is not possible to identify the shape, characteristics, location, and motion of targets in advance. (3) It is necessary to satisfy safety requirements when robots interact with targets or humans. Unfortunately, it is not possible to solve all the aforementioned challenges because of the heavy structure and low freedom of rigid-bodied. The problem of vibration continues to persist although a few hyper-redundant rigid robots are flexible to a certain extent. Therefore, it is necessary to consider structural flexibility and vibration suppression for space applications [8–10].

Soft robots appear to provide a suitable mechanism for space applications. Recently, several researchers have focused on the field of soft robotics and designed various soft robot prototypes for different purposes [11–13]. Most of the robots were inspired by biological systems and exhibit optimal softness. Although soft robots are depicted in several ways, their meaning is not very clear. Rus et al. [14] define soft robots as systems that are capable of autonomous behavior and that are primarily composed of materials with moduli in a range similar to that of soft biological materials ($10^4 - 10^9$ Pa). In the present study, it is assumed that 'soft' represents a type of attribute to describe objects. Different items have different extents of softness, and rigid robots also possess a few features of soft robots. Robot manipulators with six concatenate rigid sections are softer than the manipulators with three sections, while octopus arms are considerably softer. Therefore, in the present study, it is considered that 'soft robots' refer to the robots that possess considerably improved properties of high flexibility and energy-absorption as compared with those of rigid-bodied robots.

Soft robots have important application advantages. They possess the promising ability to bend and deform to large extents. Thus they can be used in unstructured environments. Their bodies can also deform to adapt to a confined space or other different situations. Furthermore, the energy arising from a collision could be absorbed due to soft bodies, and this can improve the safety and reliability of systems. Soft robots are especially useful in applications of the OOS owing to their specific attributes [15]. This could be reflected in the following aspects.

(1) Soft robots are flexible and can adapt to an unstructured environment. The space environment is mysterious and usually involves unknown effects on robots. Space debris or spacecraft can limit the action of robots' with respect to spatial factors. Additionally, the positions and motion of targets are typically unknown and can occur anywhere, even inside the objects (such as oil fillers). In order to deal with these problems, it is necessary to equip robots with high degrees of freedom to satisfy all environmental constraints.

(2) Soft robots are deformable and can satisfy different task demands. Operating a space project is expensive, and thus it is necessary for the payload to be as light as possible. As a result, it is important for a robot to perform several different types of tasks. Soft robots provide a suitable scheme due to their deformability. Irrespective of their targets, robots can change to fit the shape of targets. The modes of robot motion can also be transformed easily for different tasks such as turning screws or grasping objects.

(3) Soft robots are safer compared to conventional robots. Rendezvous and docking of spacecraft are important functions involving the adoption of proper control to prevent the satellites from crashing. It is important to carefully use conventional rigid-bodied robots because objects are destroyed when a collision occurs. Soft robots can mitigate this problem due to their energy-absorbing characteristics. The contact force is weakened, and this can improve safety and reliability when robots interact with targets or even

humans.

Hence, soft robotics has excellent prospects with respect to OOS. Although several researchers have espoused this viewpoint, to the best of the authors' knowledge, soft robots are not applied in practical space projects to-date. Extant research on soft robots is in the preliminary stage, and different problems involving several aspects, such as actuators, sensors and control methods, continue to exist. In this study, the current status of soft robotics is first reviewed. Although most soft robots were not developed for a space environment, all the robots are valuable in developing a future design. The purpose of the present study involves learning from extant research to develop soft robots for the OOS application. In Section 2, the configuration of soft robotics is examined, and soft robots inspired by various living beings are introduced. Section 3 describes the manipulation of soft robotics and reviews recent studies on actuation and control of soft robots. Based on the investigation, discussion on using soft robotics in space applications is presented in Section 4. Additionally, a novel conceptual design of configuration and manipulation for future research is proposed, and several challenges are pointed out. Finally, Section 5 concludes this article.

## 2 Configuration of soft robotics

Extant research has paid considerable attention to soft robotics due to their promising features. Inspired by lessons from biological systems, researchers used soft materials to build prototypes of robots by mimicking various animals or plants to design the configuration of robots. The development of soft materials, such as electroactive polymers (EAPs), shape memory alloys (SMAs), and pneumatic artificial muscles (PAMs), has allowed novel soft robots to possess outstanding locomotion and manipulation abilities. There are several bio-inspired soft robots that can be used for various purposes. To the best of the authors' knowledge, although a few of these robots have been developed for OOS, it is possible to learn from these soft robots to design the configuration of space soft robots. This section presents a review of different types of configurations. Specifically, this section emphasizes on soft robotic arms, soft grippers, earthworm-like robots, caterpillar-like robots, and multi-limb robots. These types of soft robots possess their own potential application prospects with respect to the OOS.

### 2.1 Soft robotic arm

Robotic arms belong to a large group of robots that are similar to a human arm in appearance. The main function involves moving an end of an arm to a desired position. A human arm can be viewed as a structure built on two concatenating rigid sections. However, soft robotics researchers prefer the softer form. Most robotic arms are inspired by elephant trunks, snake arms, and octopus arms.

Robotic arms are widely used in OOS tasks. They help in the servicing of satellites by operating an on-orbit target from a distance. Most space projects, such as SSRMS and ETS-VII, are equipped with long robotic arms. Thus, a robotic arm is a significant robotic type for the OOS. As indicated by extant research, current progress on the space robotic arm continues to remain at the stage of rigid robots. Currently, soft robotic arms are not at a sufficiently mature stage such that they can be applied to OOS tasks. However, previous studies have emphasized on developing soft robotic arms for OOS due to the promising characteristics of soft robots.

Mehling et al. [16] from NASA developed a cable-driven soft robotic arm termed as a tendril. This arm is thin and long (10 mm in diameter and 1 m in length), and thus it is similar to a natural tendril (Figure 1(a)). It can be useful to operate targets through a small gap. This feature can broaden and strengthen the abilities of robotic arms for the OOS. Walker [20] studied the field of soft robotic arms in-depth and proposed several design alternatives for future applications. Generally, studies examining soft robotic arms for the OOS are limited. However, several proposed soft robotic arms deal with other cases, and these prominent soft robotic arms could serve as a knowledge base to design a suitable soft robotic arm for the OOS.

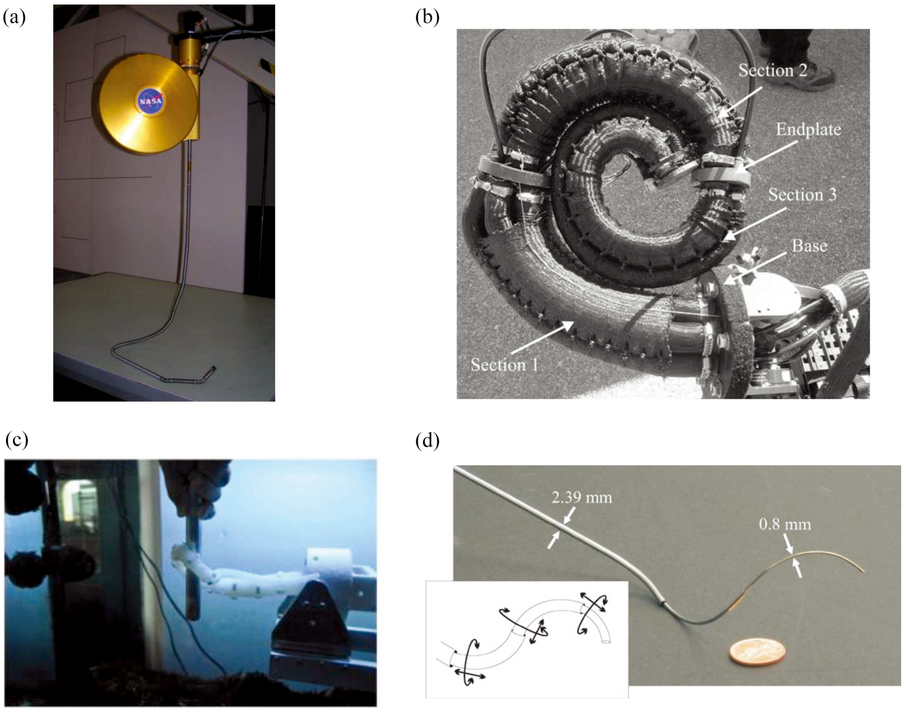


**Figure 1** (Color online) Some examples of soft robotic arms. (a) NASA's string robot [16] (@Copyright 2006 IEEE); (b) an OctArm V actuated by pneumatic extensor actuators [17] (@Copyright 2008 IEEE); (c) an octopus-bioinspired robotic arm [18] (@Copyright 2011 Elsevier); (d) a precurved-tube continuum robot [19] (@Copyright 2009 IEEE).

In this aspect, OctArm inspired by elephant trunk from Clemson University and octopus-bioinspired robots from Scuola Superiore Sant'Anna in Italy constitute representative arms. Some examples of soft robotic arm are shown in Figure 1.

OctArm robots are designed by Walker's group from Clemson University [21] (Figure 1(b)) and involve several generations. Specifically, OctArm V is studied extensively [17,22–24]. OctArm is divided into some sections (four in OctArm IV and three in OctArm V). Each section is constructed by several pneumatic extensor actuators. PAMs actuated with pressurized air are used by the robots to bend as well as extend in all directions. The robots can encircle and effectively lift objects in few seconds. Moreover, it is important to note that the robots are lightweight but they can manipulate heavy objects with different sizes. Additionally, some robotic arms are similar to the OctArm in structure but use different actuators replacing the PAM [25–28]. For example, Lu et al. [25] used SMA to build a continuum robot. Each section involved three SMA actuators. Rosenthal and Pei [26] constructed a robot actuated by dielectric elastomer actuators (DEAs), and the robot can bend through large angles.

Several scientific research institutions in Europe received support from the 'Octopus Integrating Project' of European Commission and developed soft robots based on the anatomy and mechanisms of octopus arms [18, 29–38] (Figure 1(c)). Researchers first examined the internal structure of an octopus arm. The structure is termed as a muscular hydrostat (Figure 2) and is composed of longitudinal muscles, transverse muscles, oblique muscles, and central nerve cords. With respect to robot design, longitudinal and transverse muscles are more important because the robotic arm can perform elongation, shortening, and bending mechanisms by only using these two types of muscles. Scuola Superiore Sant'Anna and Italian Institute of Technology conducted several studies. Most of studies used shape memory alloys or cable-driven arms to simulate the muscles. These robotic arms were very soft and capable of locomotion and object grasping.

The robotic arm is widely applied in medical treatment. The application scenarios are similar to the OOS tasks to a considerable extents. Soft robots are flexible such that they are compatible with the environment in human bodies, and they can mitigate the risk of causing damage to human tissues.

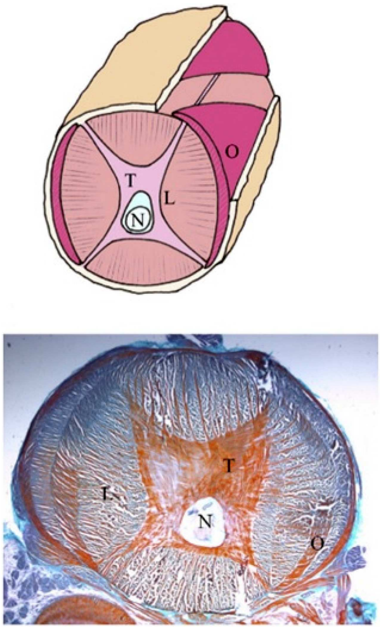


**Figure 2** (Color online) The structure of a muscular hydrostat (@Copyright 2011 Elsevier). (L) Longitudinal muscles; (T) transverse muscles; (O) oblique muscles; (N) nerve cord [18].

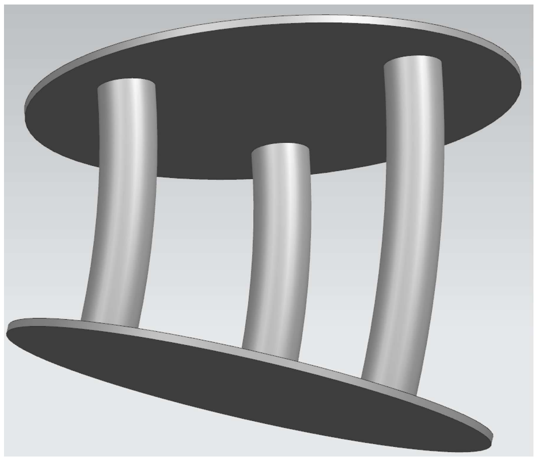

**Figure 3** An intrinsically actuated robotic arm. The bent cylinders represent actuators. They are mounted to a plate at each end.

Several previous studies used cable actuators to develop snake-like soft robots for minimally invasive surgery (MIS) or endoscope design [39–45]. Shape memory polymers (SMPs) present another attractive actuation option for medical treatment [46, 47]. Chen et al. [48] created a soft robot called ColoBot for MIS. The ColoBot is similar to the OctArm, and it uses PAM to bend the robotic tube. Webster et al. [19, 49] at Vanderbilt University designed a flexible robot with an interesting structure. The robot is also called the active cannula and is composed of telescoping, concentric, and precurved superelastic tubes. The tubes can be axially translated and rotated relative to each another (Figure 1(d)). As a result, the robot can exhibit diverse shapes simply by changing the positions of the tubes.

The fore-mentioned studies can inspire the configurations of future space soft robots. Currently, most designs of soft robotic arms can be classified into three categories [50], namely, intrinsic, extrinsic and hybrid actuation strategies. The concept of intrinsically actuated robotic arms is shown in Figure 3. As shown in the figure, the section is composed of several actuators connecting two plates at each end. The actuators can change their lengths such that the section can bend in all directions due to differences in the actuator lengths. Several concatenate sections compose a highly flexible robotic arm similar to the OctArm. In contrast, octopus-inspired robots typically involve extrinsically actuated robotic arms. This type utilizes tendons, such as steel cables, to change the shape. The major difference between these two types is that the lengths of cables can be arbitrary while intrinsic actuators involve limits on length. Irrespective of whether the actuation strategy is intrinsic or extrinsic, the robots display excellent performances with respect to flexibility, and both robots are good choices for the OOS tasks. With a section that is capable of bending in all directions, the robots can achieve various desired postures by concatenating several sections in a line. With respect to the OOS application, the soft robotic arms have larger workspaces when compared with traditional rigid space robotic arms. Thus, they exhibit a better performance in terms of linking the servicing satellite and the target. In the authors' opinion, soft robotic arms with these configurations can be directly used for the OOS tasks provided that the robots are not exhausted in the space environment.

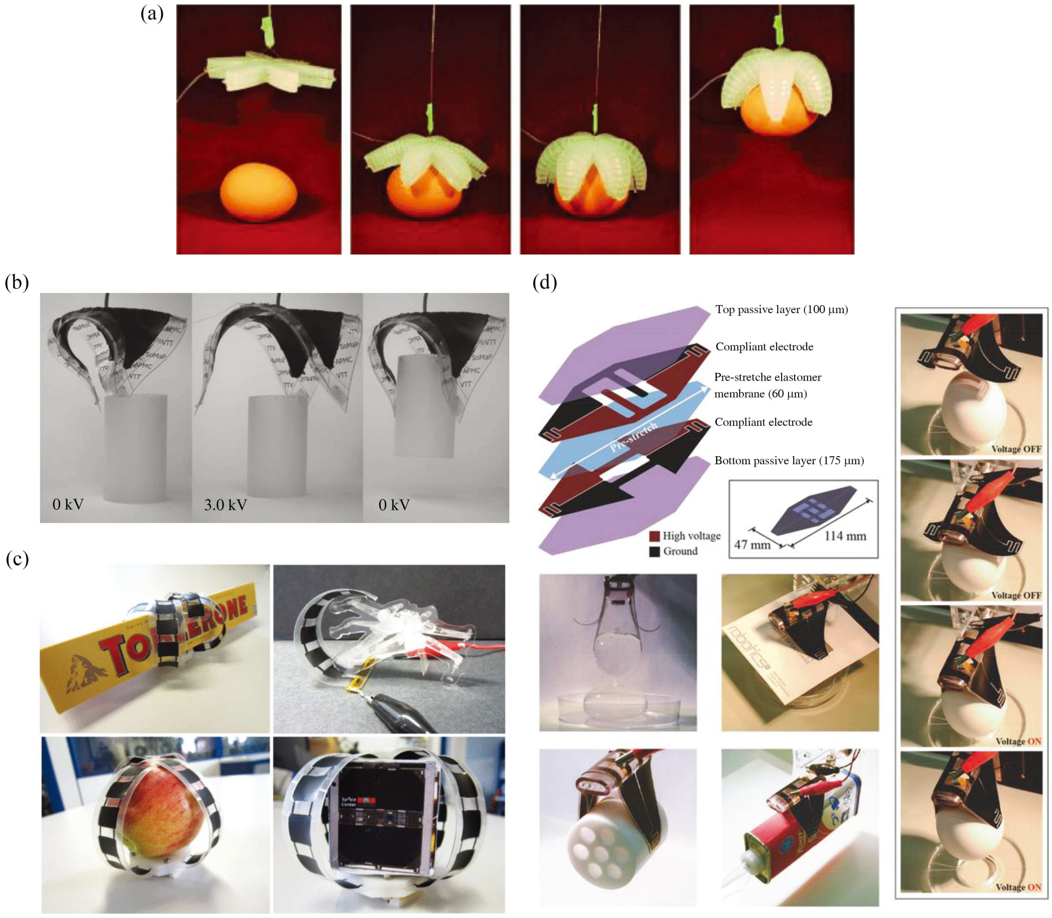


**Figure 4** (Color online) Some examples of soft grippers. (a) A soft gripper actuated by PAMs with six fingers [51] (@Copyright 2011 John Wiley and Sons); (b) DEMES for grasping objects [52] (@Copyright 2007 AIP Publishing LLC); (c) a rollable multisegment gripper using DEMES [53] (@Copyright 2015 IEEE); (d) versatile soft grippers with intrinsic electroadhesion [54] (@Copyright 2016 John Wiley and Sons).

## 2.2 Soft gripper

A robotic gripper is designed to perform specified operations on targets. Robotic grippers usually need to deal with complex tasks to satisfy the demands of automation. With respect to the OOS application, the gripper can be required to grasp objects, screw bolts, or remove debris. It is important to ensure that the robotic gripper is soft to enable the gripper to adapt to different shapes of targets and deal with fragile objects. Therefore, a soft gripper is useful for the OOS tasks. In the field of designing soft grippers, this presents a useful mechanism to construct robots by imitating human hands. As shown in Figure 4, there are a few excellent examples of soft grippers involving ingenious configurations, and these examples can promote the development of soft grippers used for the OOS application.

Previous studies used various actuators, such as pneumatic actuators or SMAs, to build hand-like soft grippers [55–57]. The grippers could catch or hold a large range of objects similar to human hands. Specifically, Harvard University developed soft grippers that are actuated by pneumatic artificial muscles [51] (Figure 4(a)) with six fingers. Each finger is composed of elastomers embedded with a series of parallel chambers. The finger bends when it is inflated. With this structure, the robots are similar to a six-finger hand. Experiments indicate that the grippers can handle fragile objects, such as an uncooked chicken egg and a live mouse, without damage.

There are also some unusual but powerful soft grippers. Brown et al. [58, 59] demonstrated an interesting but effective approach for developing a soft gripper. The body of the gripper includes an elastic bag filled with granular material. The body is soft, and the material flows around the target and conforms to its shape when it is pressed onto an object. The granular material evacuated air from the gripper to contract and harden to catch the object. The operating principle involved is that the robot possesses an ability to transfer conditions between a deformable state and a rigid state.

Recently, dielectric elastomer actuators are widely studied in the soft robotics field [60] and are well applied in designing soft grippers. Kofod et al. [52, 61] proposed dielectric elastomer minimum energy structures (DEMES). A minimum energy structure refers to a structure without any external force. The dielectric elastomer as a soft gripper is prestretched and included a minimum energy structure in the form of clenching. The gripper opens when an electric field is applied such that it possesses the ability to grasp objects (Figure 4(b)). École Polytechnique Fédérale de Lausanne conducted several studies on DEAs. Based on DEMES, Araromi et al. [53] developed soft grippers for debris removal (Figure 4(c)) wherein in a similar manner, the grippers open to capture the target when they are actuated by applying a high voltage. This study is relevant to the OOS tasks. It explores the application abilities of soft grippers for the OOS.

Shintake et al. [54] from École Polytechnique Fédérale de Lausanne composed another novel soft gripper with DEAs albeit using a very different method (Figure 4(d)). The robot includes two fingers, and an electroadhesion force was produced at the tips during operation. Thus, the gripper can catch the target more easily. When the gripper is asked to grasp an object, the two fingers are actuated by DEAs to close around the object while the electroadhesion force is simultaneously generated. The object is then picked up. An advantage of this design is that even flat objects including paper can be handled. In contrast, other soft grippers are unable to handle the fore-mentioned task.

Based on the status of soft grippers, a few of the latest grippers already possess many desired properties. They are soft and can grip a wide range of objects. Additionally, the grippers can hold targets firmly and can easily transfer the states between catching and releasing. The characteristics completely satisfy the requirements of the OOS tasks. Soft grippers can manipulate the served targets by their abilities to effectively catch and release. Moreover, the soft feature allows the robot to handle diverse objects or non-cooperative targets. However, it is also necessary for grippers to adapt the space environment. The OOS application of grippers actuated by gas [51, 58, 59] is questionable since bringing an air tank to a space environment is usually uneconomic and air pressure is another important issue. A gripper that uses electroadhesion [54] also may not be suitable. The cosmic radiation can disturb the electroadhesion force and affect the performance of the robot. The grippers using DEMES can be a good choice for the OOS tasks. However, it is necessary to examine the properties of dielectric elastomers in a space situation.

### 2.3 Earthworm-like robot

Peristalsis is common in small limbless animals such as earthworms. This motion mode can enable robust locomotion in a confined space. Robots inspired by earthworms can be used in planet exploration or endoscopy. Mangan et al. [62] created a peristaltic endoscope actuated with PAM. The endoscope consists of three sections in a series. Each section can contract by air pressure, and thus peristalsis is performed. Some earthworm-like robots use SMA actuators [63–65]. Kim et al. [66, 67] designed a Meshworm also actuated by SMA (Figure 5(a)). The distinctive body consists of an elastic fiber mesh tube. Circular and longitudinal SMAs are arranged on the body to control the length and radius of the robot. Radial SMA contraction in a segment causes radial change in the surrounding body, and propulsion is derived from peristaltic waves of ground contacts. The Meshworm possesses effective locomotion abilities and is robust when hit with a hammer. Onal et al. [70] developed a snake-like soft robot to mimic the crawling locomotion of snakes. The body consists of four bidirectional fluidic elastomer actuators in a series. The robot can crawl forward fast by bending its body.

An earthworm-like robot has special applications in the OOS tasks. The OOS robot is capable of exploring the inner space when it is necessary to perform a repair inside the on-orbit object. Peristalsis is an excellent motion pattern in the unstructured and rugged terrain. Therefore, the earthworm-like robot can be used to reach the target by passing through a narrow and complex environment. These types of robots can be applied in other space tasks such as planet exploration. However, this is beyond the scope

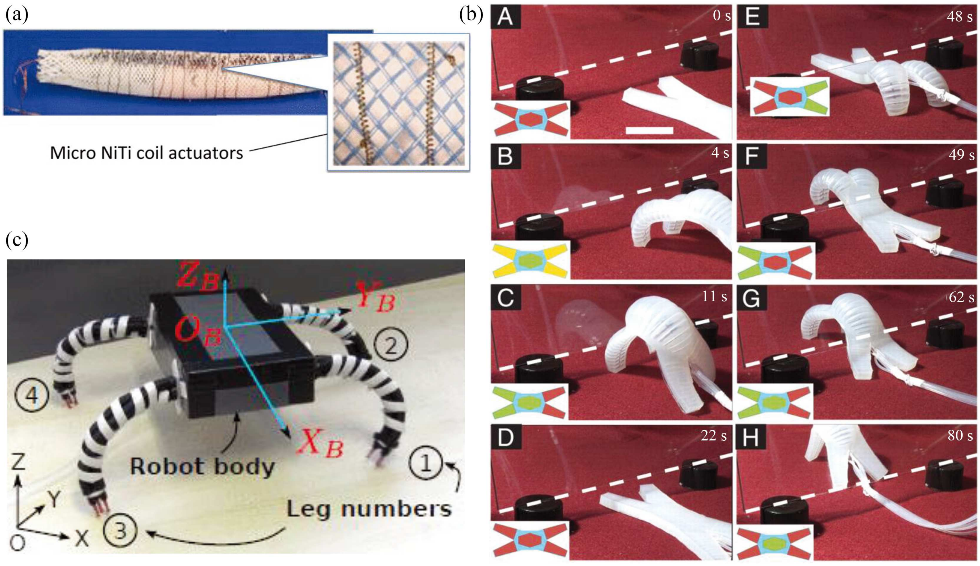


**Figure 5** (Color online) Other typical soft robots. (a) An earthworm-inspired robot with a mesh structure and SMAs [66] (@Copyright 2010 IEEE); (b) multigait soft robot actuated by pneumatic nets [68] (@Copyright 2011 PNAS); (c) a robot with four soft pneumatic legs [69] (@Copyright 2012 IEEE).

of this study.

### 2.4 Caterpillar-like robot

In a manner different from earthworms, caterpillars include more types of locomotion. In addition to peristalsis, caterpillars can cantilever their body across a gap and climb over objects. Inchworms, are known for their 'omega' shape and big prolegs. An inchworm can climb a vertical surface, crawl on a narrow stick, and travel through small cracks. Inspired by this, Koh et al. [71] built a robot termed as an Omegabot. The robot actuated by SMA can crawl and steer in a manner similar to an inchworm. Trimmer's group from Tufts University examined soft caterpillar-like robots and proposed a soft robot called a GoQBot [72, 73]. The robot included a narrow body, and SMAs are arranged under the body. Actuated by SMAs, a GoQBot can be deformed into a circle and produces ballistic rolling locomotion.

There are diverse species of caterpillars with various motion patterns. Researchers build soft caterpillar-like robots because they exhibit strong adaptability in nature. Most caterpillars have a tube body and several prolegs that can be realized by a soft robotic arm and a soft gripper, respectively. With respect to the OOS application, the overall configuration of a soft robot can also learn from caterpillars. For example, the body shape of an inchworm and its Omega motion can be utilized to develop a soft space robot. The robotic 'prolegs' can grasp the on-orbit targets or the servicing satellite, and the robotic 'tube body' can bend into different shapes. With the body and prolegs, the robot can move among space objects and perform the OOS tasks.

### 2.5 Multi-limb robot

A limb is an important component of a body. For example, mammals use their legs to walk and run. Researchers investigated various body structures of animals and built several multi-limb robots. Inspired by turtles and starfish, George Whitesides' group from Harvard University developed a series of soft robots with pneumatic nets [51, 68, 74, 75]. As shown in Figure 5(b), a four-limb robot was introduced in a previous study [68]. Four limbs and a trunk were constructed with a pneumatic net. The robot is flat in normal times and can stand up and walk with pressure inputs, and this allowed the robot to pass through a 2 cm high gap. Otake et al. [76] used EAP and gel to create a starfish-inspired soft robot. The body could bend and turn over when an electric field is applied. Pei et al. [77] designed electroelastomer roll actuators and used the actuators to create a six-legged robot called the MERbot. Shi et al. [78] built a walking biomimetic robot with eleven soft limbs. The limbs are composed of an ionic polymer metal composite (IPMC), which is a type of ionic EAP. Two SMA actuators are used to change the motion attitude of the robot. This structure allows the robot to be equipped with several motion modes including walking, swimming and grasping. Godage et al. [69] made a robot with four pneumatic limbs (Figure 5(c)). It also exhibited good locomotion performance.

The advantages of multi-limb robots are similar to those of earthworm-like robots as both types of robots are good at moving in a complicated terrain. Thus, multi-limb robots can approach an on-orbit target located at an unusual location (such as under the surface of other objects or other confined spaces). Multi-limb robots move by using their limbs while the earthworm-like robots move by using their own bodies. It can be easier to plan motions for multi-limb robots although the body size can be larger than that of earthworm-like robots.

## 3 Manipulation of soft robotics

Soft robots are highly flexible and deformable. Soft robots possess abilities to deal with various tasks since they are actuated by soft actuations. However, complex motions increase the difficulties involved in the manipulation of soft robotics. This section discusses ways in which soft robots are manipulated. Two main aspects, namely actuation and control, are reviewed. With respect to the OOS application, a few particular issues in these two fields are also discussed.

### 3.1 Actuation

Actuators are devices that transform an input control signal into motion. They play an important role in designing soft robots. Specifically, a new wave of research on soft robots has come into existence owing to the development of new soft actuators. Actuators applied in soft robots are used to replicate the functionality of muscles in the animal body to enable the robots to move and change their body shape. Diverse styles of energy are utilized. In order to be applied in OOS tasks, it is necessary to consider as to whether or not soft actuations can adapt to the space environment.

#### 3.1.1 *Electroactive polymers (EAPs) actuation*

EAPs are a class of soft materials that exhibit a change in size or shape when stimulated by an electric field [79]. An increasing amount of research attention is focused on EAPs due to their properties of large deformation and high response speed, and thus EAPs are widely used to fabricate actuators [80]. Specifically, EAPs can be generally divided into two classes, i.e., dielectric EAPs and ionic ones. The main difference between these classes is that dielectric EAPs are activated directly by DC voltage while ionic EAPs require a wet ionization environment. The difference in mechanisms results in dielectric EAPs requiring high voltages when compared with ionic EAPs that only require 1–2 volts.

Currently, dielectric elastomers are representative of the dielectric EAPs. The characteristics of dielectric elastomers are studied extensively [81] and massive systems based on dielectric elastomers have demonstrated their advantages [60, 82, 83]. Dielectric elastomer actuators are promising for future space applications. The soft gripper proposed in a previous study [53] for debris removal can support this viewpoint. However, it is necessary to consider the high voltage requirement and to improve the reliability. With respect to ionic EAPs, an ionic polymer-metal composite is typical [84, 85] and exhibits a good performance in a space environment constructed in laboratory [86]. Activating IPMC only requires several volts although it involves a few problems that should be solved. The force produced is relatively low, and encapsulation is required to keep the actuators wet.

#### 3.1.2 *Cable actuation*

In early stages, several hard hyper-redundant robots used cable actuation to move. Currently, cable-driven actuators are also frequently used to design soft robots and especially to design soft robotic arms.

**Table 1** Several frequently used actuation techniques and a brief summary of their advantages and disadvantages

| Actuation | | Advantage | Disadvantage |
|---|---|---|---|
| EAPs actuation | Dielectric elastomer | Has large deformability; response speed is high | Requires high voltage; reliable needs improvement |
| | Ionic polymer-metal composite | Has large deformability; response speed is high; requires low voltage | Requires encapsulation to keep wet; force is little |
| SMA actuation | | Force is relatively large | Requires robust temperature control |
| Fluidic actuation | | Force is large; has large deformability | Requires fluid supply systems |
| Cable actuation | | Has large deformability; has high efficiency | Mechanical structure is complex |

Various cables are embedded in the bodies of robots. The cables are dragged in order to shorten them, and thus robots can change their body shape. This actuation method is successfully used in a few soft robotic arms [27, 43, 87] such as octopus-inspired arms [18]. Cable driven actuators possess an advantage of high efficiency because energy transformation is not involved in actuation. They also can cause large deformations because the cable lengths are arbitrary in theory. However, a large number of cables are necessary to make robots sufficiently flexible. Hence, the mechanical structures of robots are complex.

#### 3.1.3 *Shape memory alloy (SMA) actuation*

A SMA is an alloy with shape-memory effects that can return to its pre-deformed shape when it is heated following deformation. SMAs are popular choices for soft actuation [88] and have a significant feature that enables the production of a large force. The shape of the SMA coils is often used to amplify the overall strain. Therefore, a large number of soft systems are successfully constructed due to the advantages of SMAs. However, temperature control is a challenge especially in space environments with large temperature differences.

#### 3.1.4 *Fluidic actuation*

Fluidic actuators are another type of popular actuators. They use compressed air or pressured liquid to perform actuation. In the 1950s, Mckibben actuators were composed and were considered as the oldest pneumatic artificial muscles. Similar PAMs are developed by a few firms including Bridgestone, Shadow, and Festo [89, 90]. A new style of fluidic actuation is widely studied [91]. Pneumatic networks were proposed by Harvard University [92]. The actuator consists of a series of chambers that can bend rapidly by inflation.

To-date, several successful soft robots are designed by using fluidic actuators. Although fluidic actuators are powerful and possess good flexibility, they require fluid supply systems that are heavy and complex. This can limit their application ability.

#### 3.1.5 *Discussion of actuation on OOS*

Advantages and disadvantages of the several types of actuation are listed in Table 1. Each type of actuation has its scope of application. It is necessary to carefully select these actuators for OOS application.

A fluidic actuator is not applicable for OOS. First, it is actuated by pressure produced by fluid. It is necessary for a robot to possess high quality skin because the space is nearly vacuum. Second, it requires a heavy and complex fluid supply system, and thus fluidic actuators can occupy large amounts of resources including room and weight. Hence, they are not desirable for space application. Furthermore, fluidic actuators are typically big. This also involves certain limitations.

EAPs, shape memory alloys, and cable driven techniques are suitable for future application although it is necessary to adequately resolve problems. EAPs should be developed further since they exhibit excellent properties albeit requiring improvements if they are used for OOS. The technology of SMA is relatively mature but it is necessary for the temperature control to be reliable and effective. A cable driven actuator is also appropriate and the structure of robot should be carefully designed.

## 3.2 Control

The control problem is challenging because it is hard to establish the model of a soft robot. Additionally, even soft materials mechanisms are not completely mastered. Fortunately, it is feasible to model the category of multi-segment robots such as OctArm. These robots correspond to typical continuum robots. Several researchers proposed techniques involving kinematics and dynamics control for continuum robots. However, the control for general soft robots is characterized by a paucity of research. Particularly, the problem is considerably more difficult in the OOS application.

### 3.2.1 *Control for continuum robots*

Continuum robots can be studied by analyzing each of their segments. Each segment is actuated by changing the lengths of actuators as indicated by the analysis in Subsection 2.1. Therefore, the shape of robot can be easily described by each length of the actuators. Walker's group conducted studies on kinematic model that is based on OctArm, which corresponds to a pneumatic continuum robot [24,93,94]. With respect to cable-driven continuum robots, Camarillo et al. [43] studied a mechanics model. Xiao et al. [95] proposed an algorithm for continuum robots to plan planar motions. This enabled the robot to grasp objects in an uncertain environment. Giorelli et al. [96] studied a 2D inverse kinetics model of a cable-driven soft robot. A continuum geometrically exact approach for kinetics model and a Jacobian method for inverse kinetics were proposed. The approaches were applied in the octopus-inspired arm. Giorelli et al. [87] used feed-forward neural network learning to deal with inverse kinetics in three-dimensional space. Following training, the network could acquire the relation between the arm tip and the forces generated by cables.

The dynamic control of continuum robots can be designed by learning a dynamic model of hard hyper-redundant robot [97,98]. Gravagne and Walker [99] studied a dynamic model of a cable-driven continuum robot called as a Clemson Tentacle Manipulator. They used a PD plus feedforward controller to control the robot. Based on muscular hydrostats, Yekutieli et al. [100, 101] established a 2D dynamic model of the octopus-inspired arm. Tatlicioglu et al. [102] developed a dynamic model of a planar extensible continuum robot such as an OctArm. Based on the model, Braganza et al. [103] used a neural network feed forward controller to control the OctArm.

### 3.2.2 *Control for general soft robots*

Control for soft robots (with the exception of continuum robots) is challenging. Most studies use a model-free open-loop control strategy. This implies using a sequence of motion commands to control robots to complete a specified action. Soft robots can adapt well to the environment, and thus it is not typically necessary to control soft robots precisely. Therefore, robots continue to exhibit excellent capabilities given the open-loop control.

As shown in Figure 4(a), the pneumatic gripper can grasp objects simply through predefined air pressure. The gripper with particle jamming [59] is controlled by directly evacuating air. The grippers constructed by DEAs [52–54] are actuated by predefined voltage. They can grasp a large range of objects with a simple control policy. Meshworms (Figure 5(a)) [66] and snake-like robots [70] can crawl by manually inputting control signals. GoQBot [73] can perform ballistic rolling locomotion by experimentally designing the control signals of two SMAs. Multigait soft robots (Figure 5(b)) [68] are actuated by inflating four limbs or the trunk. The robot can walk in various environment by designing the inflation sequence.

The performance of the robots is limited with open-loop control techniques. A few researchers attempted to study motion control for soft robots. Marchese et al. [104] studied a soft spatial fluidic elastomer manipulator. The dynamic model was developed, and a control policy was proposed. The robot can grab and brace precisely and effectively with the controller.

#### 3.2.3 *Discussion of control on OOS*

Control for soft robots is challenging because the modeling is difficult. It is relatively easy to model the continuum robot, and thus a few control techniques were developed. However, control for most soft robots is still in the preliminary stages. Nevertheless, the difficulty of control is unavoidable in OOS tasks. It is necessary for space robots to approach and interact with the served target to address the OOS tasks. This requires precise control of position and action. Furthermore, reliability of control is also an indispensable property in the space environment.

In a manner different from the ground-based soft robot, a space robot is not fixed to the ground but instead freely floats in space. Therefore, it is necessary for a space robot to maintain its posture more steadily and perform actions more accurately when compared with a ground-based soft robot. It is also important to obtain the attitude information of the soft body to the maximum possible extent. The key to precise control may be through capturing and describing the status of the soft robot. Embedding a few rigid elements to support the soft body can be a helpful method to ease the control problem of the space soft robot.

Distributed sensing and neural networks learning can be useful to control the soft robots for the OOS. It is considered that soft robots are machines with mechanical intelligence. Thus, it is necessary to embed functions including sensing, actuation, and computation in soft materials [14, 105]. It is helpful to learn from biology systems to develop the control techniques. For example, while grasping a bottle, humans' arms possess the ability to determine the manner by which muscles can work instantly to create a proper posture. Additionally, the eyes and the brain are also used in formulating a plan to grasp the bottle. These lessons from biology can outline research ideas. A large number of sensors are distributed throughout the robot in a manner similar to the massive sensory cells all over the human body. Visual [106], tactile [107], and other sensing techniques play significant roles. It is also necessary to consider the fusion of these pieces of information [108]. Following sensing, the signals from sensors are computed, and then a response to control the robot is generated. Neural networks learning can be used to determine a map from sensing signals to control signals since the number of sensing signals is high and actuators also require many control signals. This procedure mimics the work of the nervous system and it is applied in designing the controller successfully [87, 103].

## 4 Potential application for on-orbit servicing

### 4.1 Motivation

The motivation of this section is that space robotics involved with physical interception is complex, highly risky, and noisy. Space soft robotics will play an increasingly important role in the future application of the OOS owing to its light-weighted [109–111] and versatility. The significant compliance and adaptability of space soft robotics appear to generate considerably lower vibrations when compared to that of traditional machines [8]. Intrinsically, it can reduce the risk of sudden impact when compared with 'control safe' in cluttered or unstructured environments. Additionally, it can operate efficiently in any orientation or low gravity situations [112] because of redundant degrees-of-freedom.

### 4.2 Design constraints

There are common design constraints that need to be considered. First, a space environment can affect the operation of spacecraft prior to the emergence of reliable applications, e.g., (1) vacuum, (2) large temperature variation, and (3) cosmic radiation (X-ray, Gamma or ultraviolet ray). Second, it is necessary to develop self-awareness, such as the autonomous navigational capability to a non-cooperative target while avoiding obstacles and collecting available information about the unknown target and the environment. Third, the robot should act in a resource-efficient manner to satisfy the requirement of effectiveness operation and long durations. That is, it is necessary to pay attention to resources including

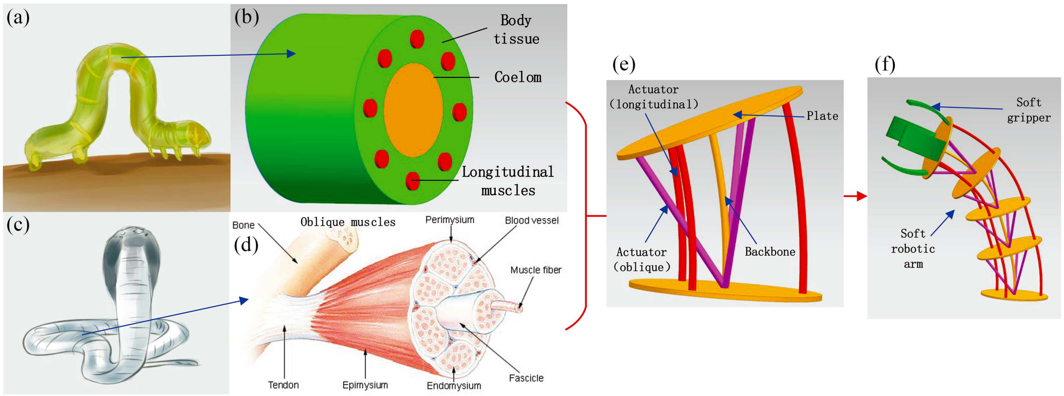


**Figure 6** (Color online) The structure of the soft robot for OOS. (a) The example picture of an inchworm. (b) The muscular structure of the tube body of an inchworm. (c) The example picture of a snake. (d) The bone and oblique muscles of a snake. (e) A segment of the soft robotic arm. Two plates are connected by three longitudinal actuators, three oblique actuators and one backbone. (f) CAD design of the robot. The structure consists of a soft robotic arm and a soft gripper. The soft arm is responsible to move the soft gripper to the desired location and the gripper is in charge of catching objects.

time and power storage. In summary, the overall capabilities of a space soft robot should be carefully examined in term of mass, size, speed, complexity, and reliability.

### 4.3 Hybrid configuration of space soft robot for OOS

In this subsection, a hybrid configuration of a space soft robot is developed for the OOS. The robot is flexible and possesses the ability to generate sufficient force with respect to the OOS target. The main concept of this configuration is accomplished by a combination of three key components, namely bone, muscle, and skin. This hybrid structure is designed to achieve stiffness variability through combining the key features of an inchworm and a snake. Specifically, the muscle systems are completed by the longitudinal muscles of an inchworm and the oblique muscles of a snake. Additionally, the robot structures of the bone and skin are learned from those of a snake. The combination of flexibility and stiffness is the characteristic of this space soft robot.

To illustrate this configuration, the special structures of inchworm and snake are presented in Figure 6(b) and (d)[1)] separately. These findings are encouraging in terms of an optimal configuration with enhanced operational capacities during environmental interaction and target manipulation. An inchworm is a caterpillar of geometrid moths. It has a soft tube shaped body and several strong prolegs. As shown in the review of soft robots, several robots are developed to mimic inchworms [71,113–115]. These robots are intended to realize inchworm-like crawling and climbing on the ground while emphasizing on its body structure. The sketch of the muscular structure inside the tube body is shown in Figure 6(b). The relationship between the bone and oblique muscles of a snake is illustrated in Figure 6(d).

Inspired by these structures, a single-segment of a soft robotic arm is shown in Figure 6(e). This robotic arm is multi-segmented. Two adjacent segments are joined by a round plate. Three actuators (longitudinal) capable of changing their lengths are distributed in the circumference of the round plate. Another three actuators (oblique) obliquely connect two plates to enhance the bending performance. Thus, a segment can bend, elongate or shorten due to the differences in the actuator lengths. The arm with several segments could possess high degrees of freedom. Furthermore, a backbone throughout the arm is used to support the body when the robot operates. This concept is derived from a snake, which has a spine. Additionally, a soft gripper [53] is implemented on the tip of soft robotic arm to deal with the tasks of OOS. This component mimics the prolegs of an inchworm.

The topology of a space soft robot is shown in Figure 6(f). The soft arm part is responsible to move the soft gripper to the desired location. The soft gripper part is in charge of dealing with targets. The robot possesses flexibility, deformability, and energy-absorbing characteristics. High flexibility allows the

1) This picture is cited from http://www.medicalook.com/systems_images/Skeletal_muscle.jpg.

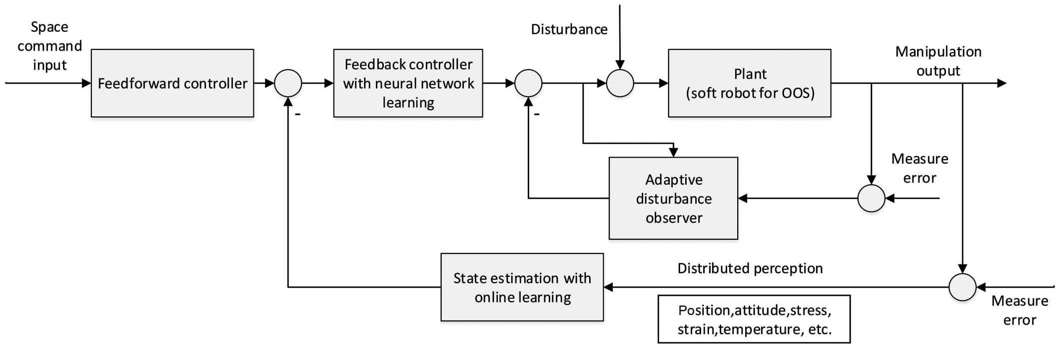


**Figure 7** The block diagram of the potential manipulation system of a space soft robot for the OOS.

robot to adapt to an unstructured space environment, and different tasks including connecting spacecraft or removing debris can be uniformly completed by the soft gripper.

### 4.4 High performance manipulation of space soft robot for OOS

A manipulation scheme is proposed in this subsection. It is necessary to control a space soft robot to complete the OOS manipulation missions including upgrading, refueling, and debris removal, etc. The scheme of the future space soft robot for OOS is also discussed in two aspects, namely actuation and control.

As mentioned in the Subsection 3.2.5, EAPs represent a type of good actuators for space applications because they are light-weight, flexible, and adaptable to the space environment. However, the force produced by EAPs is relatively low, and thus the actuation composited with novel functional material (such as EAPs) and traditional material can be a practical scheme to satisfy the OOS requirements. Specialized actuation including actuators (longitudinal and oblique) in the robotic arms and the actuators in the soft gripper can be selected. New composite material is utilized as the backbone to raise the performance involved in maintaining the shape of the robot. The backbone can passively bend by changing the length of the actuators.

Distributed perception and brain-inspired control is presented to build a high performance control system of the space soft robot for manipulation. This idea for future research is introduced as follows.

It is necessary to distribute massive sensors in the robot. It is also important to obtain the states of the robot. The position, attitude, strain, and temperature, include necessary key information. Micro-sensors, such as strain sensors or thermometers, are embedded throughout the body to obtain the lengths of the actuators or the shape of the robot. Control signals can then be tuned to actuate the robot at the desired state. Additionally, visual and tactile sensors are placed at the gripper. The perception fusion of vision and tactile information allows the robot to determine the locations of the target satellites or debris to complete the OOS tasks.

The potential control system for robotic manipulation includes a feedforward controller, a feedback controller, and an adaptive disturbance observer. Furthermore, it is necessary to update the control laws and state estimation with the neural network learning. The block diagram of the potential manipulation system of space soft robot for the OOS is shown in Figure 7. The system is inspired by that used in a previous study [116] albeit with the additions of some new elements. It is designed to address two challenging problems for the space soft robot. The first problem relates to the uncertainty of the dynamics model of the robot. The other problem involves an unknown disturbance in the space environment. As a result, neural network learning is used to design proper control laws in real time without the exact model of the robot. The learning method and the updating strategies constitute the core of the brain-inspired control. An adaptive disturbance observer is also important in resisting the space disturbance and can improve the robustness of the system.

### 4.5 Challenges

The above discussion corresponds to a concept design of future soft robots for the OOS. Future projects will involve realizing and verifying this design.

Although the hybrid configuration is an obvious key feature given its flexibility with respect to representative manipulation tasks, it requires an appropriate approach to generate the required muscle activation patterns for manipulating. Additionally, a careful design of actuation and control techniques is required to accomplish a versatile soft robot for various tasks and conditions. The underlying mechanisms are still largely unclear and require further research.

A large distance between concept design and realization continues to exist for OOS soft robots. Challenges and future directions can be summarized according to the following aspects.

(1) Actuations with increased ideal properties need to be developed. With respect to OOS, the robot is expected to be highly reliable because it is hard to repair the robot in space. The actuators should be long-lived, repeatable, and capable of adapting to the tough space environment. Furthermore, the actuators should be sufficiently soft to meet the task demands. It is also important to consider their economic efficiency.

(2) Fabrication technology requires progress. Facilities for functions including actuation, sensing, and computation should be embedded throughout the body of the robot. The facilities are small-sized and can be called micro electro-mechanical components. Therefore, it is relatively difficult to fabricate this type of a robot.

(3) The problem of control should be effectively solved. Currently, most approaches to robot control use an open-loop method to directly operate the robots. Ground-based robots perform well based on their excellent structures. However, a control system is significant for space soft robots to interact with the on-orbit target. It is necessary to develop new control schemes [117–119] for future application.

## 5 Conclusion

In this study, the field of soft robotics, which is closely related to biological systems, was examined. Recently, several studies focused on soft robots as they indicate various promising aspects in many applications. In the first section of the study, the definition of applying soft robots in OOS is discussed. Soft robots possess properties including high flexibility, high deformability and energy-absorption that enables them to deal with the problems existing in the OOS tasks, such as (1) a confined space environment, (2) non-cooperative targets, (3) multifunctional demand, and (4) safety requirements. The second section of the study reviews the configuration of soft robotics. Several soft robots are described, and the robots are divided into various categories, namely robotic arms, soft grippers, earthworm-liked robots, caterpillar-liked robots, and multi-limb robots. This section documents the immense progress in the field of soft robotics and is helpful in the future design of space robots for the OOS. Section 3 examines actuation and control for soft robotics to describe the manipulation of the soft robots. It is necessary to consider soft actuations in terms of whether ot not they can adapt to the space environment. Additionally, the control problem remains open with respect to space soft robots. Section 4 presents an analysis of the application prospects of space soft robots for the OOS. A configuration of the OOS robot for future research is also proposed. This involves a hybrid strategy inspired by inchworms and snakes. The configuration can be suitable for OOS. A potential high performance control scheme is also presented. However, several challenges continue to exist in soft robotics and include actuation, fabrication and control techniques. These challenges should be examined further given the excellent prospects of the soft robots in OOS.

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