Introduction

How can we identify a continuum robots? What differentiates continuum robots from other robot types?

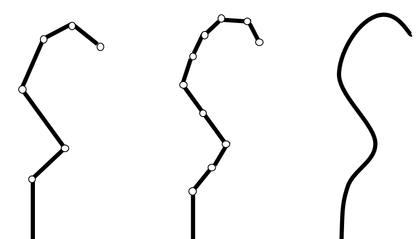
In this module, we look at continuum robots and how it compares to common robot types.

When thinking about a robot, what comes to our minds are usually manipulator arms, i.e., serial robot arms, doing repetitive tasks in automation and manufacturing, or humanoid robots, i.e., human-like walking robots interacting with their environment in everyday tasks. Those robots are inspired by the human anatomy as they resemble a similar structure in terms of rigid-links and joints. These rigid-link robots usually have similar degrees-of-freedom as their human counterpart. Naturally, the tasks and use cases are those that a human would typically do, such as welding, moving objects, etc., but with the additional speed and repeatability of a robot. Another typical robot type is mobile platforms, i.e., wheeled robots. A prominent example is a vacuum cleaning robot that many of us might deploy in our homes.

Robotics is revolutionizing automation in the manufacturing sector and the number of industrial robot deployed worldwide is expected to increase from about 1,828,000 units at the end of 2016 to 3,053,000 units at the end of 2020.

Robotics also found its way out of the factory into the service domain, where it has already had a significant impact in areas such as agriculture, surgery, or logistics and is growing in economic impact.

Beside the general market trends in manufacturing and service, there exist applications which are characterized by hard-to-reach areas, tortuous paths, and highly unstructured environments, for instance intracorporal or intraluminal medical applications, non-destructive inspection or in maintenance, repair and operation (MRO). These applications mostly require highly dexterous and miniaturized robots. Intuitively, one would increase the number of discrete joints and reduce the length of the rigid-links in order to increase the DOF in task space. The robot is then referred to as redundant. However, the discrete structure of rigid-links connected by joints cannot be miniaturized to any arbitrary size. In fact, the integration of the mechatronic components reaches a physical miniaturization limit.



From discrete structures, i.e. concatenation of rigid-links and joints to continuous bending structures.

To overcome this limitation, there has been a paradigm shift away from rigid-link, discrete structures to continuously bending ones. These are commonly referred to as continuum robots but also soft robots.

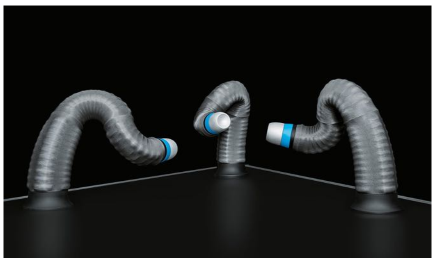
Continuum robots differ fundamentally from traditional robots, as they are jointless structures. Their appearance is evocative of animals and organs such as trunks, tongues, worms, and snakes. Composed of flexible, elastic, or soft materials, continuum robots can perform complex bending motions and appear with curvilinear shapes. The figure on the first page illustrates a continuum robot actuated by push/pull-wires to achieve bending motion.

Continuum robots have a high potential to navigate and operate in confined spaces currently unreachable to standard robots, as their diameter to length ratio can be as low as 1:300. These robots are usually developed to reach targets through complex and winding trajectories, in contrast to either standard mechanical tools or stiff serial and parallel robots.

Four Examples

Before formally defining a continuum robot, we look at three commercially available and one continuum robot on the verge to being commercially available to better understand how continuum robots look like and what they can do.

Example 1: Bionic Motion Robot



Three Bionic Motion Robots.
© FESTO. Link

The company FESTO has been pioneering continuum robots at comparable size to collaborative serial robot arms. The picture on the left shows the latest version of their pneumatically actuated continuum robot called the Bionic Motion Robot. Consisting of three concatenated segments, each of which consists of three elastomer bellows, it can extend/contract and bend by changing the pressure within the bellows. With a diameter of 13cm and length of 85 cm, the Bionic Motion Robot weighs about 3kg and can also carry about 3kg. The Bionic Motion Robot is advertised for collaborative tasks with humans as it is light-weight and safe, e.g. in assembly.

Example 2: Snake-arm Robot

Snake-arm robot.
© OCRobotics. Link

The snake-arm robot developed by OCRobotics is probably the longest among all continuum robots with 5m length. The snake-arm robot is driven by wire ropes guided through channels on the circumference of the cylinders composing the robot structure. Two wire ropes terminate at each cylinder along the robot, forming the links. As a result, by pushing/pulling on a wire rope, the respective segment can bend up to 27.5 degrees. At a diameter of 12.5cm and overall length of up to 5m (3m of which are articulated) the robot has a payload of up to 10kg. OCRobotics has been acquired by GE Aviation in 2017 to move the technology towards use in aviation industry for repair and operations.

Example 3: Multi-articulated Instruments

Multi-articulated Instruments.
© Titan Medical Inc. Link

The multi-articulated instruments developed by Titan Medical Inc. are following a comparable actuation mechanism as the snake-arm robot. To achieve bending into an S-curve the instrument is composed of two segments each of which are driven by four wires terminating at their end. Pushing or pulling on the wire pairs achieves bending in all directions. These multi-articulated instruments are part of a surgical robot system intended for use in single-port interventions, i.e. entering the human body through a single incision. The instruments are teleoperated by the surgeon, i.e. the motion of the instruments is commanded via an input device at the surgeon's console. The system is not yet commercially available.

Example 4: Soft Finger Gripper

Soft finger gripper.
© Soft Robotics Inc. Link

Using continuously bending structures to realize grippers for industrial automation applications has advantages over conventional 2- or 3-claws grippers when a wide range of objects need to be handles which are delicate or amorphous (e.g. food). One example of such a soft gripper is depicted on the left and available from Soft Robotic Inc. Each finger is composed of a soft silicone and resembles an accordion. Actuation is achieved by pneumatics: changing the pressure results in bending of a finger. The fingers can be arranged in a parallel or circular pattern depending on the objects to be handled.

While Examples 1 and 2 are showing continuum robots comparable in size to conventional serial arm robots, Examples 3 and 4 are probably the more convincing use cases. High dexterity and continuously bending is particularly useful at small scales as this is where conventional serial arm robots fail due to miniaturization constraints. In this course, we will see that small scale continuum robots have a great potential but also that the field of continuum robotics research is not yet as mature as serial arm, parallel, or mobile robotics. As a results, we have not yet seen too many continuum robots being available in commercial products.

Taking inspiration from nature: a snake wrapped around a branch.

Definition

Researchers in the continuum robot community have not yet converged to a single definition, such that there exist three major definitions, which are stated in chronological order.

Robinson & Davies, 1999

The very first formal definition of continuum robots as a class of robots was proposed by Robinson & Davies in 1999:

> Continuum robots do not contain rigid links and identifiable rotational joints. Instead the structures bend continuously along their length via elastic deformation and produce motion through the generation of smooth curves, similar to tentacles or tongues of the animal kingdom.

The definition focusses on the appearance of continuum robots and puts continuous bending and elastic deformation as key characteristics. It also explicitly excludes rigid links and identifiable joints, such that snake-like robot structures as in Example 2 would formally not qualify for a continuum robot based on this definition.

Walker, 2013

Defining a continuum robot by relating its kinematic structure to the animal kingdom was proposed by Walker in 2013:

> Continuum robots can be viewed as being invertebrate robots, as compared with the vertebrate design of conventional rigid-link robots. Continuum robots can bend (and often extend/contract and sometimes twist) at any point along their structure.

This definition follows the formalism of invertebrates, i.e. animals without a backbone or bony skeleton. According to this, continuum robots have no rigid links and joints as well. Interestingly, the structure of a continuum robot is often referred to as its backbone - even though it is continuous. In comparison to Robinson & Davies definition, Walker's definition explicitly includes extension and contraction as a characteristic of continuum robots.

Burgner-Kahrs, Rucker & Choset, 2015

To mathematically formalize the existing definitions, Burgner-Kahrs, Rucker & Choset propose the following definition:

> A continuum robot is an actuatable structure, whose constitutive material forms curves with continuous tangent vectors.

This definition generalizes the previous two in that sense that it does not make assumptions on how the continuum robot is actuated nor on the elasticity of the composing materials, but requires the representation of the morphology to be a continuous curve.

The boundary that separates continuum robots from other snake-like or hyper-redundant manipulators is sometimes obscured by manipulator designs that use continuously bending elastic elements along with conventional discrete joints in the same structure. While these robots may not technically be classified as continuum robots according to the conventional definitions, they could be referred to as pseudocontinuum robots or hybrid serial/continuum robots, as they are closely related to continuum robots and share many attributes with them.

Summary

Continuum robots are a type of robot which is characterized by its absence of rigid-links and joint and continuous appearance. The motivation behind building continuum robots is that they have certain abilities which make them distinct from other robots:

- Inherent compliance and flexibility
- Ability to perform new forms of robot motion and locomotion
- Miniaturization
- Adapt shape to maneuver within complex, tortuous environments
- Ability to avoid obstacles
- Conform to grasp wide range of objects

These abilities make continuum robots ideal candidates for a variety of applications which can typically not be performed with conventional robots. For instance, in medicine for use in surgical robotics (neurosurgery, urological surgery, lung surgery, etc.) or interventions (cardiovascular or neuroendovascular surgery, bronchoscopy, endoscopy, colonoscopy). Or in maintenance, repair, and operations of capital goods such as jet-engines, or non-destructive testing and inspection such as for cracks or corrosion in oil and gas and petrochemical industries.

Reading List

Trivedi, D. et al., 2008. Soft robotics: Biological inspiration, state of the art, and future research. Applied Bionics and Biomechanics, 5(3), pp.99–117. https://doi.org/10.1080/11762320802557865

Walker, I.D., 2013. Continuous Backbone “Continuum” Robot Manipulators. ISRN Robotics, 2013, pp.1–19. https://doi.org/10.5402/2013/726506

Burgner-Kahrs, J., Rucker, D.C. & Choset, H., 2015. Continuum Robots for Medical Applications: A Survey. IEEE Transactions on Robotics, 31(6), pp.1261–1280. https://doi.org/10.1109/TRO.2015.2489500

