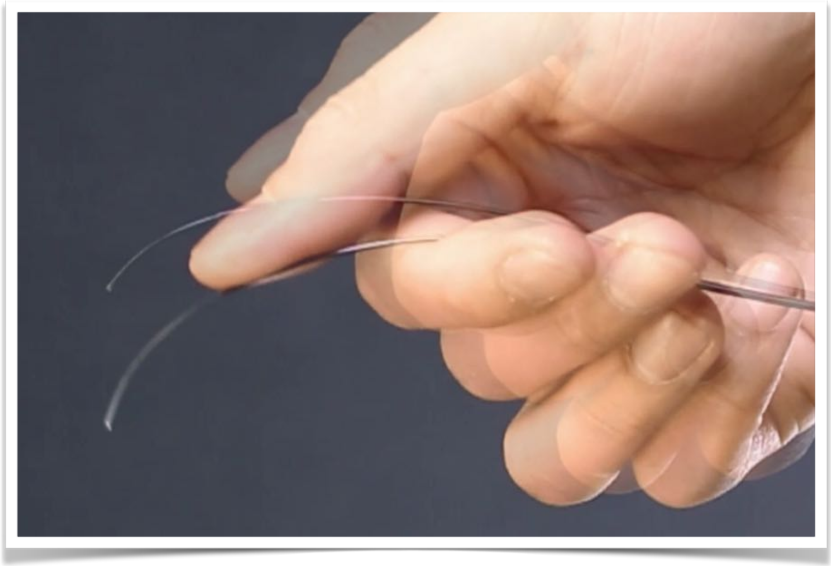


Sensing

How can we perceive information about the state of a continuum robot? What is the actual shape of a continuum

To perform their tasks autonomously, continuum robots must perceive their own position, pose, or full shape, namely proprioception, and be able to feel external stimuli, namely exteroception. Proprioception, sometimes referred to as our sixth sense, is the sense of self-movement and body position. We classify sensors as **proprioceptive** if they measure values internal to the robot (e.g., angular or linear velocities, tension, pressure) and **exteroceptive** if they acquire information from the robot's environment. Sensing the state of continuum robots is particularly challenging because they are flexible, compliant, and predominantly made of elastic materials. They further have a high number of degrees of freedom and their movement is complex. Lastly, they are often underactuated such that controlling them is non trivial.

In order to control a robot in a closed-loop manner, information on the current state of the robot has to be inferred. To some extent, this state information can be inferred from proprioceptive sensors, i.e., sensors in the actuators or drive-system such as encoder values, motor torques, tendon tension, pressure etc. In combination with a kinematic or kinetostatic model of the robot, this proprioceptive information can be used to reason about its state. Yet, the continuum robot's state may be influenced by external loads or contact with the environment, such that exteroceptive sensors are deployed in conjunction with proprioceptive sensors.

Depending on the task and application, we may be interested in obtaining information on the position or pose of the robot's tip or shape, such as the curve describing the backbone of the robot either continuously or discretely. In addition, we may require information about forces and moments acting on our robot, either just in terms of magnitude or also associated with spatial information on where those forces act to reason about contact with the environment. Or, we might be interested in obtaining information about stresses acting on our robot, i.e. torsion and shear. Lastly, sensing information about the robot's environment may be required to localize objects and obstacles and to infer information about relative locations.

In the following we will look at suitable sensors for continuum robots and the information they can provide. We categorize sensors by their locations, i.e., internal sensors, embedded sensors, as well as external sensors.

Internal Sensors

Internal methods are associated with proprioceptive sensors present in the drive-system and actuators of the continuum robots. As such, they are strongly dependent on the actuation unit design and robot type.

Common internal sensors are

- **Encoders** are linear or rotary electro-mechanical devices delivering a signal when their position changes. Encoders are either incremental or absolute. In continuum robotics, encoders will be present in actuation units with motors. Here, a rotary encoder will be on the motor shaft reporting on the angular position of the motor shaft. Depending on the drive-system this information can be transformed into linear or angular positions as well as velocities and accelerations/decelerations. Encoders provide real-time, highly accurate information and are usually used for low-level control.

- Tension is the pulling force applied to a tendon in a tendon-driven continuum robot. **Tension sensors** are electro-mechanical assemblies composed of a tension measuring element, which is a strain gauge transducer, or load-cell, in a housing. As the tension force increases, the sensor element is deflected causing a change in the voltage output signal. Tension information is used in addition to encoder information to control the tension experienced by a tendon.

Internal sensors provide information on the continuum robot's joint space. As such, the sensing information can be used to infer information on the robot's position, pose, or shape using the kinematic or kinetostatic model. For instance, as we can infer the displacement of each tendon in a tendon-driven continuum robot from the relative position of the linear axes actuating them. Then we use these displacements as an input to our robot dependent mapping to infer the arc parameters and the space curve.

But as continuum robots are continuously bending due to their elastic nature, state information obtained from internal sensors is subject to uncertainties and external disturbances such as contact with the environment. Unmodelled effects in the robot model such as friction can also greatly affect the actual robot state. In fact, the robots' shape and position can be passively changed by unknown external loads. For instance, if a concentric tube continuum robot, whose actuators control the tubes' displacement and relative rotation, is subject to an external force acting on its body, the internal measurement of the encoder values will remain constant, whereas the actual state in terms of the robot's shape is far off. Therefore, it is usually desirable to obtain additional state information which is associated with the task space.

Embedded Sensors

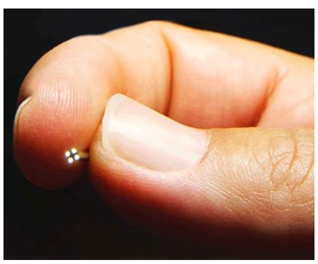
Embedded sensors have to be integrated into the continuum robot's body at the cost of eventually taking up valuable space.

Most prominently, these are imaging sensors, fiberoptic sensors, or electro-magnetic trackers.

Image-based Sensing

Using a camera embedded into the continuum robot usually means that the camera, either mono- or stereoscopic, is located at the tip of the robot. This is also referred to as **eye-in-hand configuration** in robotics.

The most common use case is for gaining visual feedback in a teleoperation setting. The user observes the robot's motion as a result of his/her input directly in a video-stream from the camera(s). Another use case is leveraging the view from the continuum robot to reason about its environment, detect objects and obstacles, determine distances, etc. Such quantitative information can then be used for visual servoing, also known as vision-based control, to control the motion of the continuum robot. This also allows to estimate the pose of the camera w.r.t. the scene, making it possible to have an estimate of the 'internal' state of the continuum robot.



Chip-on-the-tip camera with LED lighting (Image Credit: Toshiba Imaging).

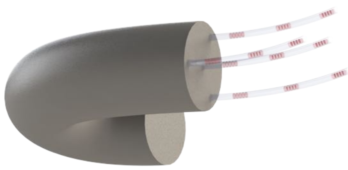
In terms of camera hardware, it can be challenging to integrate with a continuum robot, particularly if the robot has a small diameter. While small cameras exist, such as chip-on-the-tip cameras at sizes of one cubic millimetre or less, the resolution of the images is usually low and the signal may be noisy. As a continuum robot has a larger diameter, better cameras can be fitted as well.

Embedding of a camera does also involve adding a sufficient light source, either fibre optic lights or small-scale LEDs, as continuum robots are usually foreseen in applications requiring deployment in cluttered environments or within a human body in medicine such that ambient light is insufficient.

Using embedded image-based sensing is a common way to obtain information of the robot's surrounding and relatively cost-efficient. Sampling rates for typical cameras are between 30-6-Hz. The expense usually lies in the image-processing if more than pure image information is required, which also reduces the sampling rate eventually. Estimating the state of the robot or its environment from images is its own area of research and goes beyond the scope of this course.

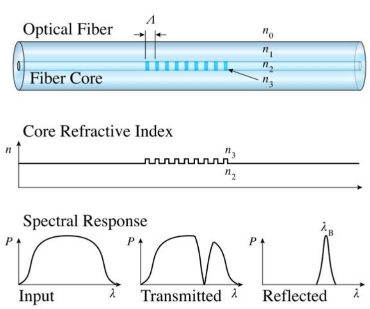
Fibre-optic Sensing

A promising technology are optical fibres with inscribed fibre Bragg gratings (FBG). Each grating can be seen as an optical strain gauge. By inscribing several FBGs into one single optical fibre, it is possible to measure strain at various locations along its centreline. Arranging several fibres in a known geometrical configuration creates a sensor array with a high spatial sensor density and small physical dimensions. The sensor array can either consist of several distinct optical fibres or of a single multicore fibre with several fibre cores, each containing various FBGs as depicted in the figure on the left. Often, the fibres are arranged in parallel to the centreline of the sensor array, which is referred to as a longitudinal arrangement. With the help of the known geometrical relations of the array's cross-section, the shape of the deformed array can be reconstructed.



Example optical fibre with four cores with multiple sets of inscribed FBG sensors.

FBGs are special sections inscribed in optical fibres. Each grating is characterized by a specific Bragg wavelength. It reflects incoming light with exactly this wavelength (see Figure on the left). If the fibre is subject to longitudinal stress and/or temperature change, the reflected light spectrum shifts. Assuming that the sensor array is used under stable temperature conditions, the strain can be related to the observed wavelength shift. This locally observed strain information can then be used to determine point-wise curvature information. The curvature along the whole length of the fibre can then be determined by interpolation and the shape, respectively the curve, can be determined by integrating twice.

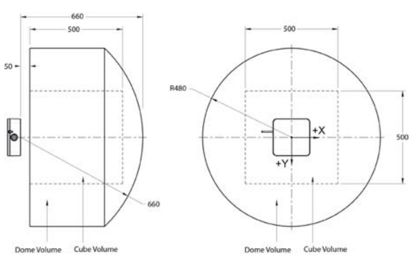


Using this underlying principle, an fibre-optic sensing system is composed of an optical interrogator, also known as measurement unit or data acquisition system, which is an optoelectronic instrument allowing the reading of multiple FBG sensors. During data acquisition, the interrogator measures the wavelength associated with the light reflected by the optical sensors and then converts it into engineering units. The sampling rate is usually about 1kHz. Post-processing is required to infer shape information from the wavelengths measurements.

Fiber-optic sensing systems have the advantage that fibres are small diameter and can easily be integrated into continuum robots. It allows for real-time acquisition of shape information in dynamic settings. While the fibres are available at affordable costs, the overall sensing system is quite expensive due to the optical interrogator which is highly specialized equipment (around $100k). The accuracy of the fibre-optic sensing is dependent on the post-processing and calibration. Placement of the fibre within the robot has to be accurate in order to rely on geometric relationships in shape reconstruction. Determining shapes that originate from bending and twisting of the fibres can be challenging as this requires special fibre arrangements.

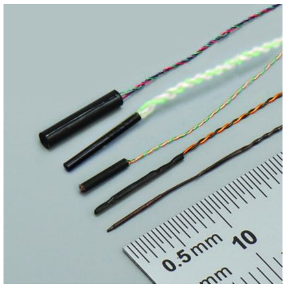
Electromagnetic Sensing

Electromagnetic (EM) spatial measurement systems determine the location of objects that are embedded with sensor coils. When the object is placed inside controlled, varying magnetic fields, voltages are induced in the sensor coils. These induced voltages are used by the measurement system to calculate the position and orientation of the object. As the magnetic fields are of a low field strength and can safely pass through human tissue, location measurement of an object is possible without the line-of-sight constraints of an optical spatial measurement system. Therefore, electromagnetic sensing is a great option for continuum robots in medical applications.



Example field size of an electromagnetic field generator. (Image Credit: NDI Inc.)

An electromagnetic tracking system is composed of a field generator which emits a low-intensity, varying electromagnetic field and establishes the position of the tracking volume, and sensors. Small currents are induced in the sensors by the varying electromagnetic field produced by the field generator. The characteristics of these electrical signals are dependent on the distance and angle between a sensor and the field generator. The sensors are small-scale and come in 6-DOF or 5-DOF versions. 6-DOF sensors report their position and orientation and are slightly larger (0.8 mm diameter x 9 mm length). 5-DOF sensors report their position and two of its orientation (pitch and yaw, except roll) which allows a smaller footprint (0.5mm diameter x 8mm length or 0.9 mm diameter x 6 mm length). The sensors are connected to a sensor interface unit which amplifies and digitizes the electrical signals and and minimizes the potential for data noise. The sensor interface unit connects to the system control unit, which calculates



Sensors for electromagnetic tracking. (Image Credit: NDI Inc.)

the position and orientation of each sensor and interfaces with the host computer. The measurement information, i.e., position and orientation, of the sensors is available at a measurement rate of 40Hz.

Electromagnetic tracking allows for real-time tracking of pose information with no line-of-sight restrictions and is relatively cost-efficient. In a state-of-the-art EM tracking systems (NDI Aurora v2, NDI Inc.), the stated root-mean-square-error (RMS) for 6-DOF sensors is 0.48 mm in position and 0.3° orientation and for 5-DOF sensors 0.7 mm in position and 0.2° in orientation in an environment free of electromagnetic disturbances. Any ferromagnetic material or insufficiently shielded cable may interfere with the field, lead to field distortions and as a result impact the system's accuracy. Therefore, if electromagnetic sensing is used, the continuum robot and eventually parts of its actuation unit need to be build from non-ferromagnetic materials such as medical-grade stainless steel, aluminum, and titanium. Depending on the size of the continuum robot, embedding electromagnetic sensors into its body can be challenging. As can be seen on the picture, the sensors come with a straight, stiff part which can impact the continuum robot's ability to bend continuously. While multiple sensors can be tracked at the same time, the number is limited to up to 8 and the sensors cannot be too close to one another to allow for proper tracking.

External Sensors

To sense information about the state of a continuum robot, it may be desirable to not integrate sensors to the robot, but to use readily available external sensing methods. The most used methods for continuum robots are coordinate, image-based, and laser-based sensing.

Coordinate Measurement

A coordinate measuring machine/arm is used to measure the geometry of the robot by sensing discrete points on its surface using a probe. There exist two common types of probes typically used for continuum robots: mechanical probes and laser probes.

Example of a coordinate measuring arm (MicroScribe).

Mechanical Probes: To acquire a measurement point, the robot has to be touched with the probe of the measurement arm which is usually operated manually by a user. This technique is suited to measure the position of the tip of the robot or to gather information on the shape of robot by measuring at multiple distinct locations along it.

Mechanical probes provide high accuracies - usually sub-millimetre, but as operation is user-dependent the accuracy can vary. Mechanical probes are fast to setup and ready to use. But as the robot needs to be touched, it is challenging to not deform the robot while touching, which would lead to measurement errors and inconsistencies. As we are mostly interested in obtaining information about the centreline of the robot when we want to infer the shape, a coordinate measurement on the surface of the robot is suboptimal as it induces an offset to the centreline which has to be corrected for in post-processing. Lastly, mechanical probes for coordinate measurement are only suitable for static robot configurations and requires direct access to the robot.

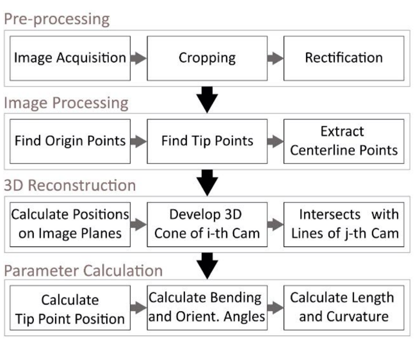
Laser Probes: To overcome the necessity of touching the robot for measuring coordinates, touch-less laser probes can be used, also referred to as 3D laser scanners. The laser probe is attached to the measurement arm and manually guided by the operator along the continuum robot. The laser probe emits a laser line and using the images from the camera within the probe, the distance of the scanned object from the probe can be determined. By sweeping the continuum robot, a point cloud of its structure can be obtained. This raw point cloud usually includes some noise as well as unwanted objects. Therefore, a post-processing step is performed to clean the data and eventually thin the point cloud in order to extract the shape.

Example of a coordinate measuring arm equipped with a laser probe for 3D scanning (FARO).

Laser scanning has the advantage of providing dense information on the robot's shape with contact-less acquisition. The precision of laser scanners is usually in the order of micrometers. This measurement technique is only suited for static cases, i.e., the continuum robot cannot move. Acquisition of the point cloud and post-processing can be quite time consuming. Lastly, this method also required direct line-of-sight, such that the continuum has to operate in free space.

Image-based Sensing

Image-based sensing employs mono- or stereoscopic cameras observing the robot fully or partially in its workspace. In robotics, an external camera is also referred to as **eye-to-hand configuration**. Using cameras observing the robot can be simply used to acquire image or video footage of robot motion in a qualitative manner, but it is more often applied to obtain quantitative measures. This requires additional processing of the images or video frames. Methods of computer vision, such as segmentation, 3D reconstruction using epipolar geometry, etc. are deployed to infer information on the robot's tip position or pose as well as its shape. This information can then be used for visual servoing, also known as vision-based control, to control the motion of the continuum robot.



Typical image-processing pipeline to determine tip position, length, and curvature information.

The image or video-stream processing is dependent on the desired information but usually involves multiple steps. This is particularly challenging for small-scale continuum robots as the information in the image representing the robot in terms of pixels is sparse. Consequently, the resolution of the camera and the lens have to chosen wisely. While using artificial markers on the robot to ease image processing may be appealing, this becomes infeasible if the robot has very small diameter. In recent years, the continuum robotics community has seen some efforts in learning-based image processing, but the majority of techniques relies on classical computer vision.

External image-based sensing has the advantage of being contact-less, such that it can be deployed both for static and dynamic continuum robot applications. Cameras are readily available and 3D reconstruction from stereo or multiple cameras can be highly precise (sub-millimetre). Nevertheless, processing of images in real-time or reliable reconstruction are challenging and usually not working off-the-shelf. If considering dynamic measurement, synchronization of the image acquisition needs to be accounted for. A downside of image-based techniques is that direct line-of-sight is required, such that occlusions or partial views have to be avoided and accounted for in processing.

Challenges

Ideally, one would want to use as many sensors as possible and probably combine different modalities for their strengths while mitigating their limitations. Yet, it is impossible to have a multitude of sensors in a continuum robot given that there are many challenges in electronics, sensor size and space, wiring, powering, system integration, data communication and processing. Therefore, a smart sensor design and configuration strategy is needed to keep the number of sensors required to achieve a desired sensing capability low, and to optimize the sensor configuration for the best performance. Developing a sensor configuration strategy for continuum robots is particularly challenging because of their deformable body and high number of DOFs.

As of now, there is no way to directly measure forces and moments acting on a continuum robot. This information has to be inferred from other sensing modalities as discrete strain information. Force/torque sensors are commonly used in rigid-link robots but may not be available at small enough scale. One way to approach this is by measuring the actual shape of a continuum robot, for instance from images, EM tracking, or FGBs, and then comparing the measured shape with the expected shape from the robot's kinematic or kinetostatic model. The observed deformation is a result from external forces and moments acting on the robot (assuming that the model is accurate). With assumptions on where forces/moments are acting (e.g. just at the tip), the model can be used to estimate those. While this is working in principal, the technique is still subject of ongoing research.

In this module, we have looked at the most prominent sensors used for continuum robots. Considering soft continuum robots, the development and integration of flexible and stretchable sensors is even more challenging. For instance, highly stretchable strain gauges composed of liquid metal micro channels can be directly embedded into the body of a silicone-based pneumatic actuator. They can then be used to measure the bending angle of the actuator. Yet, as soft continuum robots undergo large deformations, selecting the number of strain gauges, their location as well sensitivity is far from trivial.

Some areas of open research are concerned with continuous, real-time shape measurements of variable curvature, multi-section continuum robots, continuous force measurements along the robot's body, and tactile sensing skins.

Summary

As continuum robots are flexible bending/extending structures, sensing can be quite a challenge. The smaller the size of the continuum robot, the more challenging the sensor selection and its integration becomes. In this module, we have seen that multiple sensing modalities exist, each of which has its advantages and challenges. As no measurement technique is perfect and as no sensing modality suits all needs, the selection of sensors is a trade-off between application requirements and the particular continuum robot.

Some application areas, such as surgery, may also provide additional sensing means, such as medical imaging to reason about the position/pose or shape of a continuum robot operating within the human body (ultrasound, fluoroscopy, computed tomography, or magnetic resonance imaging). At the same time, applications may impose restrictions on which sensing modalities can be used. Think of a continuum robot for non-destructive inspection of a jet engine. Electromagnetic tracking would not be feasible in terms of range and external cameras would have no line-of-sight.

Reading List

Shi, Chaoyang, Xiongbiao Luo, Peng Qi, Tianliang Li, Shuang Song, Zoran Najdovski, Toshio Fukuda, and Hongliang Ren. 2017. "Shape Sensing Techniques for Continuum Robots in Minimally Invasive Surgery: A Survey." IEEE Transactions on Biomedical Engineering 64 (8): 1665–78. https://doi.org/10.1109/

Wang, Hongbo, Massimo Totaro, and Lucia Beccai. 2018. "Toward Perceptive Soft Robots: Progress and Challenges." Advanced Science 5 (9): 1800541. https://doi.org/10.1002/advs.201800541.

