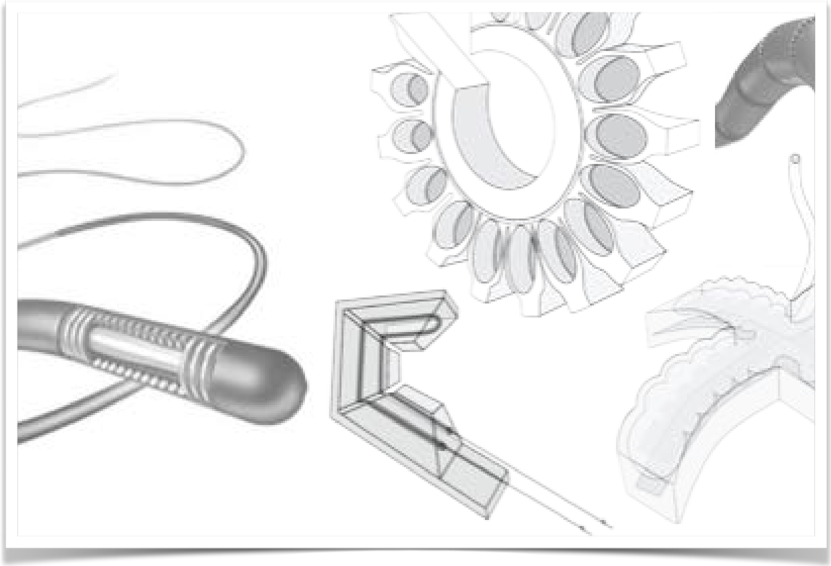


Continuum Robot Types

What are the motion capabilities of a continuum robot? How are continuum robots actuated?

In this module, we look at what types of continuum robots exist and how we can classify them.

The ultimate goal of continuum robotics is to have a continuously bending manipulator such that its shape is fully controllable. Ideally, such a robot would be appearing as a flexible cylindrical structure of soft material with its current state dictated by infinitely many actuators. Three main challenges are associated with this idealized continuum robot:

- From a mechanical standpoint, the design space to achieve continuously bending structures and compliance is very large.
- Design of robots in absence of rigid elements is unfamiliar as the vast majority of existing robots is rigid, stiff, and well defined.
- While a continuum structure may in principle have an infinite number of degrees of freedom in that it can bend, twist, contract, and eventually shear at any point along it, we will only be able to control a finite number of degrees of freedom by actuators.

In this field of tension, different types of continuum robots have emerged over the past decades. In this module, we will first look at different possibilities to classify continuum robot types and then look at the two most prevalent classes of continuum robots.

Kinematic Classification

The defining feature of a continuum robot is a continuously curving core structure, often referred to as backbone, whose shape can be actuated in some way. An almost universal additional property is that the backbone is compliant; that is, it yields smoothly to externally applied loads. Such a continuous structure has an infinite dimensional configuration or shape space - at least in principle. In fact, only a finite number of degrees of freedom (DOF) are controllable/actuatable due to mechanical constraints in building continuum robots. If a continuum robot is controlled discretely (restricting the allowable shapes of the robot to a finite set, or a shape set defined by a finite set of inputs) then it will not only be much easier to realize from a mechanical standpoint, but also be much easier to control. Nevertheless, the compliance inherent in the continuum structure still allows the robot to adapt to contact with its environment and to compensate for the limitations in its actuatable degrees of freedom.

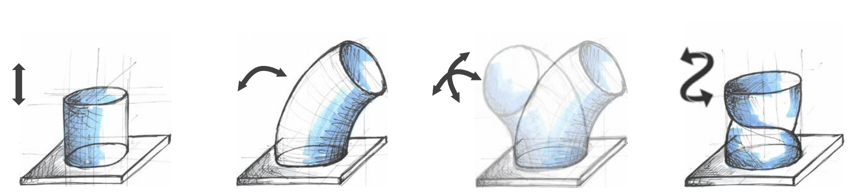
Motion Capabilities of a Continuum Robot

The motion capabilities of a continuum robot can be expressed by a set of motion primitives (depicted below)

Extension and Contraction to change the length along one axis.

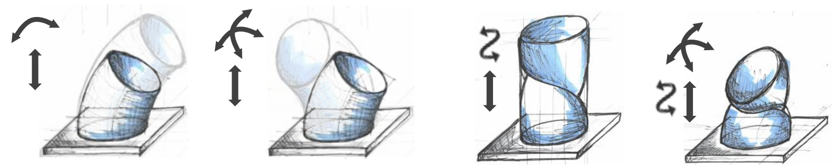
Bending in one plane (i.e. rotation about one axis) or spatially (i.e. rotation about two axes).

Twisting about its longitudinal axis (i.e. turning or torsion)



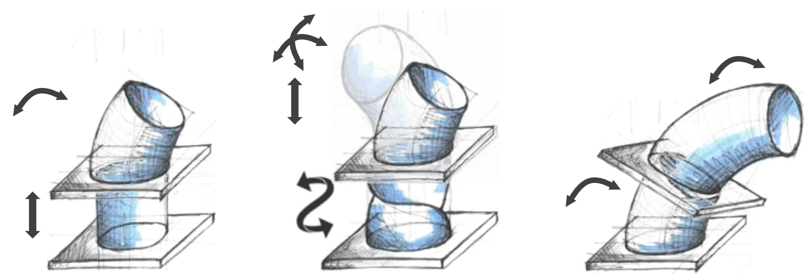
Motion primitives: change of length, bending in one planar or spatially, and torsion.

These motion primitives can be combined and realized in a single continuum robot segment. The Figure below shows some examples. For instance, a continuum robot segment can bend in one plane and change its length or bend spatially and change its length.



Examples of motion capabilities for a single continuum robot segment.

To increase the range of motion of a continuum robot, we can stack multiple of these segments, i.e. arrange them in series.



Composing a continuum robot of multiple segments.

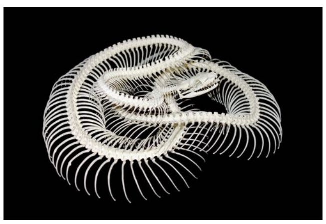
Joint, Configuration and Task Space

In continuum robotics, we differentiate between degrees of freedom in joint space, configuration space, and task space. The **joint space** dimension is determined by the physical actuators present in the robot's actuation unit, e.g. number of rotational or linear degrees of freedom. For instance, in a cable-driven continuum robot the actuation may result from pushing/pulling independently on 9 cables using linear stages such that the degrees of freedom in joint space is 9.

The configuration space is the set of independent variables that fully defines the state of a continuum robot. The dimension of the **configuration space** is the number of variables needed to fully describe the configuration of the continuum robot, i.e. every point on the robot. We will see in Module 3 that the state of most continuum robots can be approximated as a series of circular arcs. Each arc can be fully described by its length, curvature, as well as its bending plane - so at most with 3 parameters. The configuration space dimension is then $3m$ where m is the number of arcs. The most general expression of a continuum robot's state in configuration space is by a continuous function $\mathbf{X}(s) \in \mathbb{R}^6$ parameterized by arc length s using exponential coordinates to express the local coordinate frame and its position at each point.

The dimension of the **task space** may be described as $\mathbb{R}^2$, i.e. position in the Euclidean plane, $\mathbb{R}^3$, i.e. position and orientation in the plane, or $\mathbb{R}^6$ position and orientation in Euclidean space. The dimension of the task space is solely dependent on the task and how it can be expressed. For instance, if a continuum robot should move within a plane from pose A to B, the task space is of dimension 3. The task space is independent of the continuum robot type and its appearance.

Continuous vs. Discrete



A hyper-redundant snake robot which can be classified as a quasi-continuous continuum robot. © higyou

The backbone of a continuum robot does not necessarily have to be continuous. The biological counterpart, e.g. snakes, have a continuous external appearance, but are vertebrates with an internal segmented backbone comprised of many very short rigid-links.

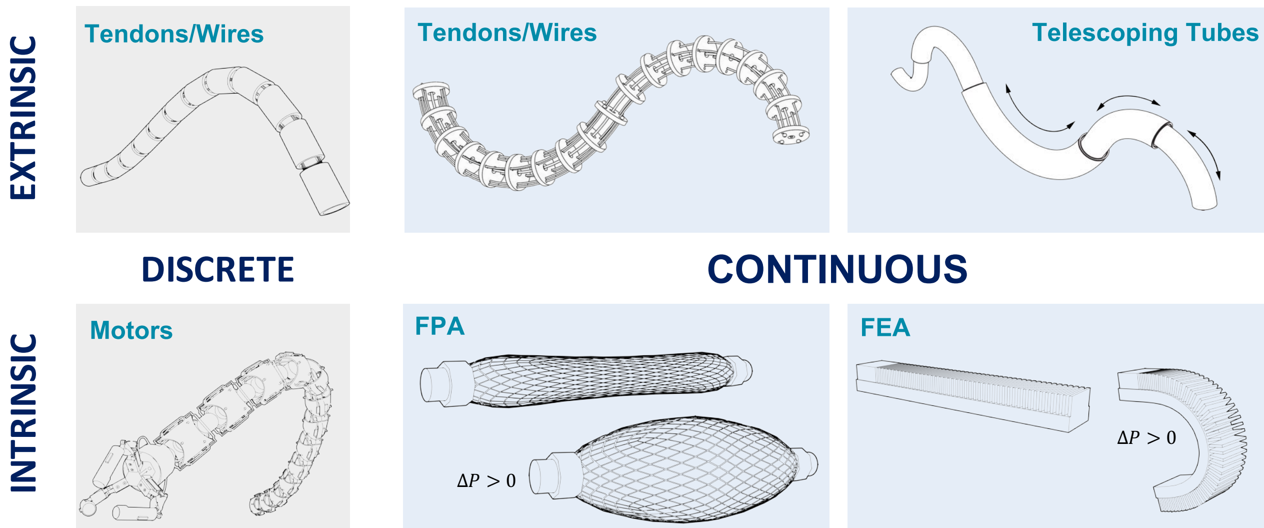
A similar paradigm can be applied to compose a discrete continuum robot. As in a serial robot arm, this can be achieved by concatenating multiple links connected by revolute joints. By keeping the link length short, the appearance of such a serial robot arm is resembling a continuous structure. In robotics, this type of robot is commonly referred to as a hyper-redundant robot, as it exhibits a high number of degrees of freedom in joint space. Those highly hyper-redundant robots can also be referred to as quasi-continuous or pseudocontinuum.

This course focusses on continuum robots classified as continuous.

Extrinsic vs. Intrinsic Actuation

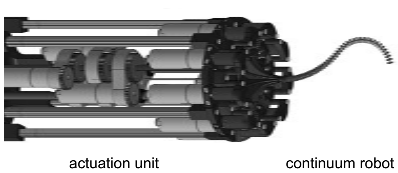
Continuum robots can be classified according to the method and location of their actuation. In extrinsic actuated continuum robots, the mean of actuation is external (remote) and is transferred into the manipulator by some mechanical linkage. In contrast, intrinsic actuated continuum robots are characterized by actuators which are located within the manipulator itself and form part of the mechanism. There also exist hybrid continuum robots which use a combination of both.

We will look at extrinsic an intrinsic actuation more deeply in the following.



Classification of continuum robots by structure (discrete vs. continuous) and mean of actuation (extrinsic vs. intrinsic).

Extrinsic Actuation

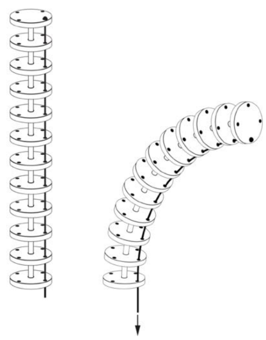


To reduce the size and weight of a continuum robot manipulator, the mean of actuation can be extrinsic, i.e. external to the manipulator. We commonly refer to the components of extrinsic actuation as the actuation unit or actuator package, which is located at the robot's base. Extrinsically actuated designs have the advantage that by locating the actuators outside the robot workspace, the backbone itself can be simplified and streamlined.

You may notice that continuum robots are usually depicted without their actuation unit. This is due to the fact that the actuation unit is much larger than the continuum robot manipulator itself, such that depicting both in a picture would change the scale.

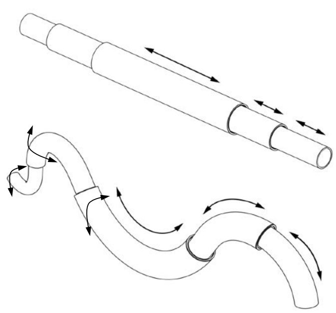
Tendon-/Wire-Actuated

Perhaps the most direct approach to bending a continuous structure is the use of remotely actuated tendons. Given a



backbone which, in the absence of external loads, consistently attains a given shape (typically straight), tendons can be used to deviate from this shape. Tendons are routed along the backbone and terminated in groups at selected points down it. Forces applied to the tendons at the base produce torques at the termination points, resulting in bending. The backbone shape resolves into a series of sections whose end points are defined by the tendon termination points along the backbone. We will study this type of continuum robot in Module 4.

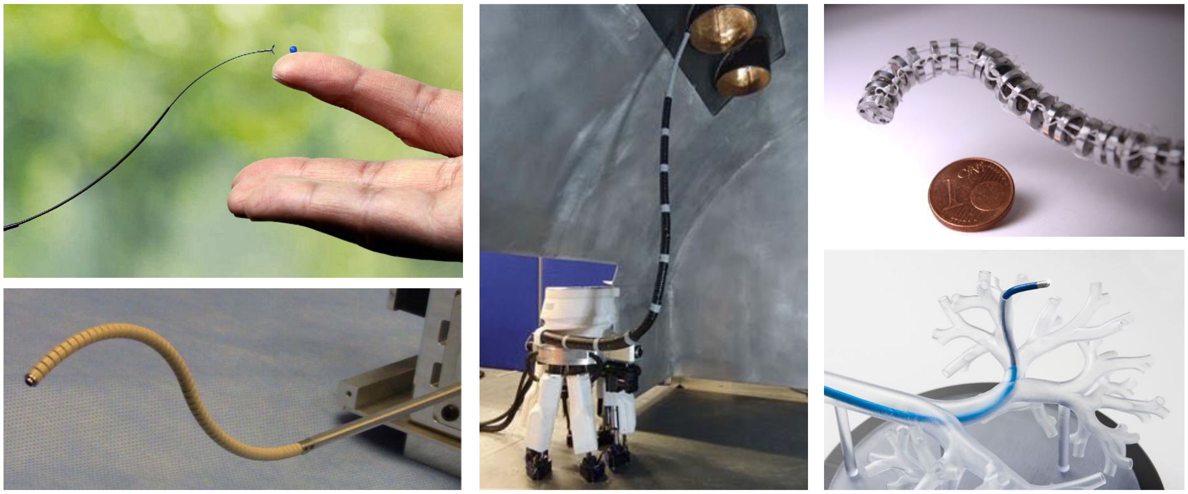
Telescoping Pre-curved Tubes



This type of continuum robot design relies on a backbone composed of multiple concentric compliant tubes. The tubes are free to move (translate and rotate) with respect to each other (subject to hardware limits) with the translations and rotations actuated at the base of the robot. The net effect is similar to a telescope: the structure can extend and contract by translational sliding of the tubes longitudinally. Telescoping tubes inherently achieve both extension and twist.

To achieve more complex motions, pre-curved compliant tubes are used. These tubes can be directly controlled in terms of extension and contraction as well as their relative rotation in respect to one another. The achievable range of curvatures of the continuum robot are defined by the elastic interaction of the pre-curved tubes as they conform to an equilibrium state. This type of continuum robot is also referred to as a concentric tube continuum robot. We will study this robot type in more depth in Module 6.

Continuum robots using extrinsic actuation are most common. Some are depicted below. One advantage of extrinsic actuation strategies is the transmission of forces from remotely located actuators, such that the continuum robot itself can be miniaturized well and light weight. Therefore, the smallest existing continuum robots are extrinsically actuated. A potential disadvantage are bulky and large actuation units. Challenges arise from friction in the mechanical transmission and scalability.



From left to right and top to bottom: Concentric tube continuum robot (© Continuum Robotics Laboratory, University of Toronto). Long tendon-driven continuum robot prototype for in-situ repair (© Advanced Manufacturing Technology Research Group, University of Nottingham). Extensible segment tendon-driven continuum robot (© Continuum Robotics Laboratory, University of Toronto). Tendon-driven continuum robot (© National Center for Image Guided Therapy, Brigham and Women's Hospital and Harvard Medical School). Telescoping tendon-actuated endoscope for bronchoscopy (© Auris Health, Inc).

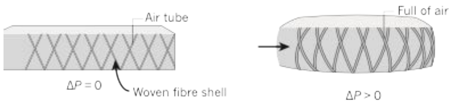
Intrinsic Actuation

Intrinsically actuated continuum robots have their actuators within the continuum backbone. In fact, the backbones of most intrinsically actuated continuum robots are largely formed by their actuators. Intrinsic actuation can also be referred to as local actuation.

Intrinsic actuation in continuum robots is mainly realized as fluidic actuation, which utilizes a pressurized gas or liquid to change elastomeric chamber volumes which converts into motion, usually contraction or bending. By arranging multiple contracting fluidic actuators radially, coordinated pressurization can be used to achieve extension and bending. We will look more closely at these fluidic actuation principles in the following.

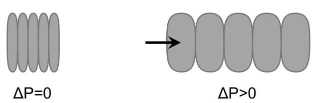
Further intrinsic actuation strategies utilize smart materials, such as shape memory alloys or electro active polymers, or magnetic actuation.

Flexible Pneumatic Actuators



Flexible pneumatic actuators (FPA) are linear soft actuators. By changing the internal pressure, the FPA expands. Depending on the type of FPA, this expansion causes a longitudinal contraction and extension.

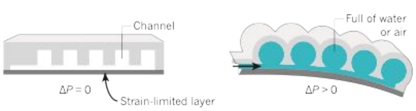
The most common FPA is a pneumatic artificial muscle, also known as McKibben actuator. These are composed of an elastomer bladder enclosed in a woven fibre sleeve or shell. An increase in pressure applied internally causes the bladder and shell to expand radially, causing longitudinal contraction. Pneumatic artificial muscles are usually grouped in pairs to achieve bending: one agonist and one antagonist.



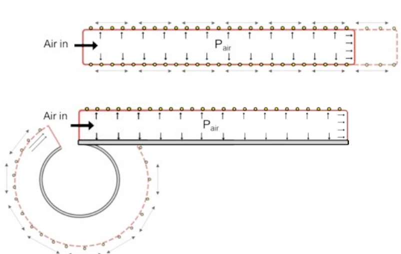
Another common FPA used in continuum robot are pneumatic bellows. When inflated the bellow structure extends and when deflated contracts back to its original length.

In a continuum robot, usually three FPAs are radially distributed to form one section. When pressure is increased or decreased in all three actuators of a straight section, the section length increases or decreases. When differing pressures are applied, the section bends into a segment with approximately constant curvature. The plane of the curve is determined by the three pressures. In general, the section extends, contracts, and changes its curvature and plane of curvature as a function of the three applied pressures.

Fluidic Elastomer Actuators

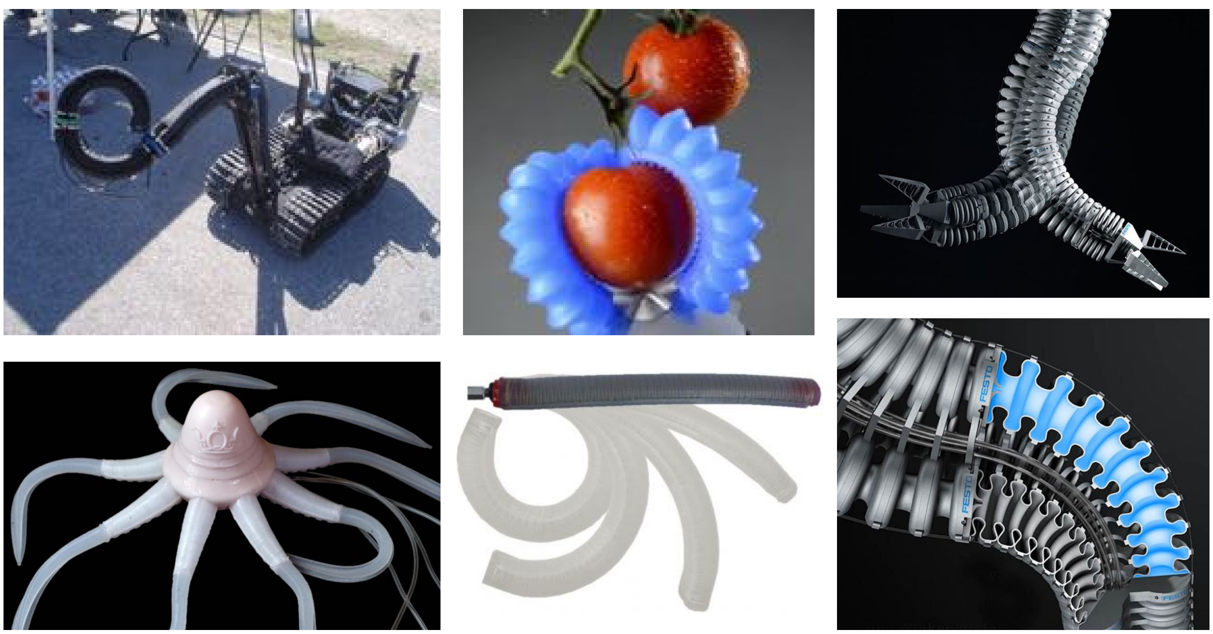


Fluidic elastomer actuators (FEAs) consist of a pneumatic network of channels in an elastomer that expand when filled with a pressurized fluid, causing the soft body to bend toward a strain-limited inextensible layer. Once pressurized, the actuator will keep its position with little or no additional energy consumption.



Another variant are fiber-reinforced FEA which use an inextensible fiber wrapping to constrain expansion of material under pressurization. The configuration of the strain-limiting components of these fiber-reinforced actuators can be such that different motions can be achieved. On the left we see an extending fibre-reinforced FEA, which is achieved by a symmetric double-helical fibre wrapping which limits radial expansion, and a bending fibre-reinforced FEA, which uses the same fibre wrapping but also employs a strain-limiting sheet of inextensible material on one side of the actuator. There also exist extending and twisting fibre-reinforced FEAs.

Continuum robots using fluidic actuation principles are depicted below. Advantages of this intrinsic actuation are light weight, absence of friction and electrical parts. Those come at the expense of pumps, valves, and pipes which cause a bulky supply to the robot prone to leakages which can limit efficiency. When more sophisticated motion capabilities are desired, miniaturization of a continuum robot with fluidic actuators is challenging. In general, the dynamics of fluidic actuation are also challenging to control.



From left to right and top to bottom: OctArm using pneumatic artificial muscles in three segments on a mobile platform © Walker, Clemson University. Soft swimming octopus with eight tentacles composed of arrangements of fibre-reinforced bending actuators © Althoefer, Queen Mary University. Soft gripper using fluidic elastomer actuators in each finger © Soft Robotics Inc. Single bending fibre-reinforced FEA and its range of motion © Soft Robotics ToolKit. Bionic handling assistant using a radial arrangement of bellows which extend under pressure © FESTO.

Summary

The ultimate continuum robot, a slender, long, and compliant structure which is controllable in terms of its shape at any point along its length, is hard to achieve. There is an inherent trade-off between continuous and discrete elements. For example, continuum structures can conform to their surroundings while discrete rigid links can be used for precise positioning. Interestingly, continuum structures in nature seem to leverage synergies with various kinds of discrete elements as well as continuous elements.

We have seen that the most prominent actuation strategies of continuum robots are extrinsic by tendons/wires or telescoping tubes or intrinsic by fluidic actuation. The finite number of actuators in a continuum robot leads to a kinematic structure with motion capabilities expressed in combinations of four primitives (extension, planar or spatial bending, and torsion). While the active degrees of freedom, i.e. those that can be controlled by the actuators, are limited, continuum robots can contain many if not infinite passive degrees of freedom. As continuum robots are compliant and often composed of soft materials, interaction and contact with the environment and resulting external forces and moment acting on the robot can deform it in various ways. For example, a continuum robot composed of a single segment whose bending can be controlled by pulling on a tendon can be forced out of the bending plane or into an s-shape.

Reading List

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

Walker, I.D., 2013. Continuous Backbone "Continuum" Robot Manipulators. ISRN Robotics, 2013, pp.1–19. https://doi.org/10.5402/2013/726506 (Section II)

Rus, Daniela, and Michael T. Tolley. 2015. "Design, Fabrication and Control of Soft Robots." Nature 521 (7553): 467–75. https://doi.org/10.1038/nature14543

