Mimicking the thigmotropic behaviour of climbing plants to design a tactile-based grasping device for the space environment

Type of activity: Standard study

1 Background and Study Motivation

Over the last several decades the research on robotic manipulators has focused mainly on designs that resemble the human arm. The designs are based on discrete rigid links serially connected by joints. If we examine the manipulators available in nature, we will see a plethora of other possibilities. Animals such as snakes, elephants, and octopuses can produce motions from their appendages or bodies that allow the effective manipulation of objects, even though they are quite different in structure compared to the human arm. Moving from the animal to the vegetal world, we can also find some example of grasping structures [Jaffe and Galston 1968].

Climbing plants are capable to grasp objects by extending themselves and then use the objects as support by coiling around them. The goal is to achieve maximum vertical height for rich sun exposure while avoiding the energy expenditure of developing a supporting trunk [Isnard and Silk, 2009]. This big group of plants have continued to fascinate biologists from Darwin's time into the 21st century. Among all the known climbing strategies, we can define a small group of plants possessing long, filiform, and irritable organs called tendrils. They are specialized to grasp and climb the surrounding environment. Unlike the examples in the animal kingdom, climbing plants do not rely on vision to attain the support, but drive their tendrils using only the contact sense.

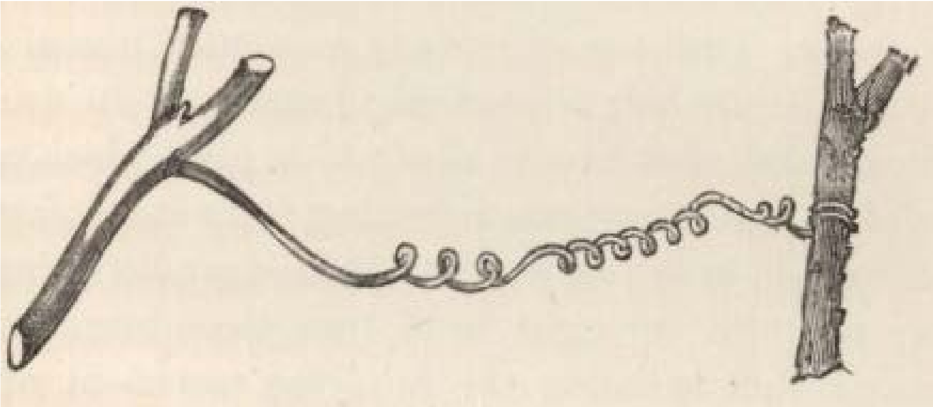

Fig. 1 – Drawing of a caught tendril of Bryonia dioica, spirally contracted in reversed directions [Darwin 1865].

There are many physiological studies of tendrils [Jaffe and Galston 1968; Putz and Holbrook 1991] which well identify and describe their three main movements:

1. Circumnutation - an endogenous movement which increases the probability of contact with supports.
2. Contact coiling - the stimulated tendril coils around a support.

3. Free coiling - the tendril develops helical coils along its axis to drag the stem closer to the support providing a spring-like elastic connection.

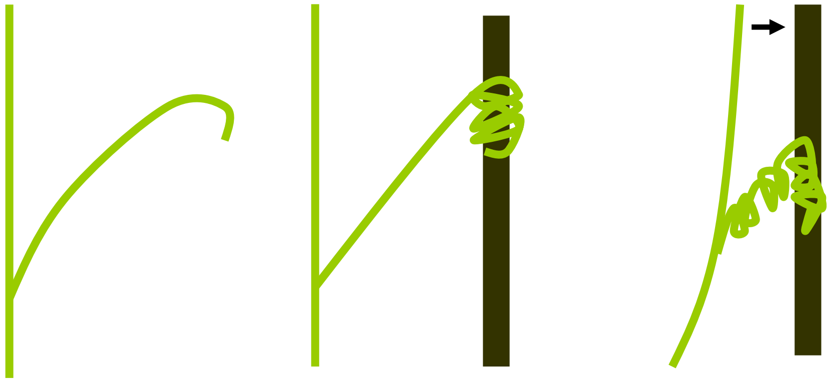

Fig. 2 – Schematic picture of the three main phases of a tendril

These relatively small structures can be used to support a vine weighing many times their mass. Usually climbing plants develop many of these attaching points so that the force is distributed between several adjacent attached tendrils, thus protecting the plant from being torn away from their support during a stormy weather.

The ability of tendrils to allow plants to climb is anatomical surprising. Some ecological studies prove the evolutionary success of climbers. Their strategy constitutes a key innovation allowing them to succeed with the ability to ascend over would-be competitors. This immediate advantage over their neighbours is at the cost of relatively small energetic investment.

Tendrils are produced rapidly within the apical meristem of the plant and elongated maximally before coiling. As the stem circumnutates, the tendrils touch potential surfaces for grasping. When the tendril reaches sufficient maturity, stimulation of the touch response sets in place a series of morphological changes so that the tendril begins to coil around the object showing a positive thigmotropic behaviour (thigmotropism is a directional movement in which an organism moves or grows in response to a directional touch stimulus).

The distal portions of tendrils are highly touch-sensitive, in some cases greater than the human's counterpart. Some studies report that a 0.25 mg thread drawn along a tendril can be enough to evoke a response [Simons 1992], and Darwin documented tendril responses to stimuli in the range of 1–5 mg [Darwin 1865].
Touch stimulation leads to a rapid onset of tip coiling, and this enables a secure attachment with the object. However, if the tendril loses the touch stimulation, it can reverse the movement by uncoiling [Jaffe & Galston 1968] and be ready to coil again upon another stimulation.

After the mechanical stimulus has been perceived by epidermal cells of the tendril, plant hormones serve as mediators of the coiling response. They are released by epidermal cells and are diffused along the structure. This leads to a growth arrest on one side of the tendril and a promotion of growth on the opposite side, together with a swallow and shrinkage of cells [Jaffe & Galston 1968].

Using this basic sensory-motoric loop without centralized sensing and control, plants can blindly rely on organs that will coil around supports, providing a successful grasping method. In addition, they are flexible to adapt to the shape of the object that they are grasping.

How can tendrils be imitated and what are the advantages in imitating them? Robotic grasping is a complex task and poses some very intricate problems. One of the main difficulties is to be able to generalise to variations of object position, orientation and shape. For this reason, most of the robotic grasping known assumes a grasped object and all information needed for the grasping to occur. Alternatively, they rely on vision to obtain relevant information about the objects. [Takahashi et al. 2008; Cannati and Maggiali 2005].

Plants lack of a nervous system, and therefore, the exploration of the mechanical environment and the execution of mechanical actions rely efficiently on simple reflex-like behaviour. This reflex-like behaviour is key feature for the successful grasping of objects of unknown shape and position driven only by the tactile information. An interdisciplinary approach to the functional morphology, kinematics, and physiology of tendril design will be beneficial both to biologists and engineers. The sensory and actuation system may be less dynamic than our human senses and muscles but still have the advantage of greater autonomy. The biomimetic of the tendril may be extremely valuable for use in autonomous robots. Some of the potential space applications can be: controlling the length of momentum exchange tether or electrodynamics tethers, grasping debris to facilitate their removal, terminal docking, space refuelling and self-assembly and, in general, all those missions where grasping or controlling a thether length [Kruijff 2011] could offer a solution to a space engineering problem .

2 Study Objective

The objective of this study is to develop a tendril-like flexible mechanism that best mimics the behaviour and the flexibility of a tendril by performing mechanical grasping and pulling while maximizing the degrees of freedom.

Research groups are invited to submit one or more proposed solutions together with an evaluation of their features and a basic demonstration of their feasibility (proof of concept).

The research project is proposed to develop in the following steps:

- Understand the biomimetic behaviour of a tendril from an engineering point of view in order to reproduce the natural characteristics of its hypothetic mechanical equivalent
- Assess the scope and framework of the model
- Model the behaviour of the tendril mechanism with a kinematic and dynamic simulation in order to characterize the key model parameters, which influence the grasping behaviour.
- Construct a 3D simulated model of the mechanism incorporating the interacting forces and reactions.
- Evaluate the performance of the grasping and pulling of objects (symmetric along the longitudinal axis and long enough to allow for multiple coiling) in microgravity. The objects will be of defined size, mass, material, and various cross sectional shapes.

Evaluate the robustness of various aspects of the mechanism (e.g. single point failures).

3 Proposed Methodology

A clear understanding of the tendril from a biological and engineering point of view is essential to best reproduce the natural grasping behaviour at the base of the grasping feature. This will be done in close collaboration with the ACT researchers who can provide all the biological information.

The main focus of the applicant’s proposal should be a discussion on the intended development of a tendril-like mechanism and on the creation of a simulation model. The following points need to be understood:

- The two masses (the mass the tendril is attached to and the object to grasp) are placed in the space environment therefore they are free to move.
- The grasping phase needs to be modeled and a firm attachment created with at least two coils formed around the grasped object. A pulling phase should also be modeled as to assess the grasp firmness.
- We suggest the mechanism to have a modular structure made of single elements. Each element able to “sense” the touch and “actuate” a relative expansion/contraction which results in the overall movement of the tendril in the direction of the touch. Each element is also able to communicate with the neighboring modules.
- In the biological tendril each segment acts as an autonomous agent that decides its direction of growth according to the direction of touch stimuli. The “actuate” decisions of each single segment is transmitted to the adjacent segments and further along the tendril. Once the tendril has coiled around the object with a certain number of coils the final stage of the grasping occurs by the contraction of longitudinal fibers (cellulose G-fibers in nature). These fibers run through all the tendril elements. By contracting them, it effectively reduces the overall radius of the helix, and thus, secures the hold.
- To perform the grasping, plants work at a timescale of several hours, and although we assume that the device should be faster than its biological equivalent, we leave this feature open and linked to the material and actuators chosen for the device itself.

This study is mainly addressed to research laboratories in the fields of biomechanics, and biocybernetics.

4 ACT Contributions

The project will be conducted in close scientific collaboration with ACT researchers. ACT researchers will provide both knowledge concerning space related issues and applications and plant behavioural biology as detailed in the project description above.

5 Bibliography

Cannata, G., Maggiali, M. (2005) An embedded tactile and force sensor for robotic manipulation and grasping. Humanoid Robots, 5th IEEE-RAS International Conference.

Darwin C. (1865). On The Movements and Habits of Climbing Plants. London: John Murray.

Engelberth J., Wanner G., Groth B. and Weiler EW. (1995). Functional anatomy of the mechanoreceptor cells in tendrils of Bryonica dioica Jacq. Planta 196 : 539 – 550

Isnard S, Silk WK. (2009) Moving with climbing plants from Charles Darwin's time into the 21st century. American Journal of Botany 96:1205-1221.

Jaffe MJ, Galston AW. (1968). The physiology of tendrils. Annual Review of Plant Physiology 19: 417–434.

Kruijff, M. (2011) Tethers in space: A propellantless propulsion in-orbit demonstration Uitgeverij BOXPress.

Liss , H. , Weiler EW. (1994). Ion-translocating ATPases in tendrils of Bryonica dioica Jacq. Planta 194 : 169 – 180 .

Putz F.E., Holbrook N.M. (1991). Biomechanical studies of vines. In Putz F. E., Mooney H. A. [eds.], The biology of vines, 73–97. Cambridge University Press, Cambridge, UK.

Simons P. (1992). The Action Plant. Oxford, UK: Blackwell Publishers.

Takahashi T, Tsuboi T., Kishida T., Kawanami Y., Shimizu S, Iribe M., Fukushima T., Fujita M. (2008) Adaptive Grasping by Multi Fingered Hand with Tactile Sensor Based on Robust Force and Position Control. IEEE International Conference on Robotics and Automation Pasadena, CA, USA, May 19-23, 2008

5.1 Additional readings

Bowling A.J., Vaughn K.C. 2009. Gelatinous fibers are widespread in coiling tendrils and twining vines American Journal of Botany 96(4): 719–727.

Carrington C. M. S., Esnard J. (1989) Kinetics of thigmocurvature in two tendril-bearing climbers Plant, Cell and Environment 12, 449-454

Engelberth J. (2003) Mechanosensing and signaltransduction in tendrils. Adv. Space Res. Vol. 32, No. 8, pp. 1611-1619

Jaffe M. J., Galston A. W. (1966) Physiological Studies on Pea Tendrils.I. Growth and Coiling Following Mechanical Stimulation Plant Physiol. 41, 1014-1025