H2020-FETPROACT-2018-01

GrowBot – Towards a new generation of plant-inspired growing artefacts

Deliverable 1.2

Periodic activity report I

WP1 – Management

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Lead participant: IIT

Delivery date: 31/01/2020

Dissemination level: Public

Type: Report

GrowBot has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 824074

Revision History

Author Name, Partner short name	Description	Date
Francesca Tramacere and Barbara Mazzolai (IIT-CMBR)	Draft of the whole document	09/12/2019
Nick Rowe (CNRS)	Draft of 2.3.1 and 2.3.3.	17/12/2019
Valeria delle Cave (IIT)	Final version of 2.11.2	10/01/2020
Marc Thielen and Frederike Klimm, (ALU-FR)	Draft of 2.3.1 and 2.3.3	10/01/2020
Emanuela Del Dottore and Alessio Mondini (IIT-CMBR)	Draft version of 2.2.3, 2.5.2, and 2.6.1	13/01/2020
Nicholas Rowe (CNRS)	Final version of 10.3	15/01/2020
Yasmine Meroz (TAU)	Final version of 2.2.1 and 2.3.2	15/01/2020
Francesco Visentin and Giovanna Naselli (IIT-CMBR)	Draft version of 2.5.4	15/01/2020
Fabian Meder (IIT-CMBR)	Draft version of 2.7.2	15/01/2020
Nicola Tirelli and Mike Geven (IIT-POLBIOM)	Final version of 2.4.1 and 2.4.3	15/01/2020
Marc Segalés (Bioo)	Final version of 2.7.1	15/01/2020
Marc Behl (HZG)	Final version of 2.4.2 and 2.5.3	15/01/2020
Michele Palladino (GSSI)	Final version of 2.3.4	15/01/2020
Nicholas Rowe (CNRS), Marc Thielen, Thomas Speck, and Frederike Klimm (ALU-FR)	Final version of 2.3.1 and 2.3.3	16/01/2020
Emanuela Del Dottore and Alessio Mondini (IIT-CMBR)	Final version of 2.2.3, 2.5.2, and 2.6.1	17/01/2020
Fabian Meder (IIT-CMBR)	Final version of 2.7.2	20/01/2020
Francesca Tramacere (IIT-CMBR)	Final version of 2.1.1, 2.1.3, 2.10.1, 2.10.2., and 2.11.1	20/01/2020
Stefano Linari (Linari)	Final version of 2.2.2, 2.5.1, and 2.11.3	25/01/2020
Francesco Visentin and Giovanna Naselli (IIT-CMBR)	Final version of 2.5.4	27/01/2020
Yasmin Ansari and Cecilia Laschi (SSSA)	Final version of 2.6.2 and 2.6.3	29/01/2020

Author Name, Partner short name	Description	Date
Francesca Tramacere and Barbara Mazzolai (IIT-CMBR)	Final version	31/01/2020

Contents

1 Overview of the project

The GrowBot project proposes a disruptively new paradigm of movement in robotics inspired by the moving-by-growing abilities of climbing plants. Growth is a very interesting feature of living beings that can inspire a generation of robots endowed with new and unprecedented abilities of movement. Growth allows a strong adaptation of body morphology to environmental conditions, also called plasticity, which characterizes the Plant Kingdom. Differently from animals, plants grow to move, following nutrient gradients, water, and light, or escaping from hostile or dangerous stimuli. These features, and many others, provide disruptive ideas and new paradigms of movement in robotics.

This continuous growth is particularly evident in climbing plants. Climbing plants do not have a very sophisticated root apparatus and use other plants, vertical walls and fixed environmental features to anchor their bodies. This way, they dramatically reduce their need for internal structural support and can thus devote much energy to navigate in the environment, therefore allowing for a relatively rapid and responsive growth.

Grounded on these premises, the long-term vision of GrowBot is to propose alternative patterns of movement in robotics, which are not confined to animal-like, muscle-based movements, but are based on growing. By imitating climbing plants, the GrowBot objective is to develop low-mass and low-volume robots capable of anchoring themselves, negotiating voids, and more generally climbing, where current climbing robots based on wheels, legs, or rails would get stuck or fall.

The present document presents a detailed description of the activities carried out in the period spanning from M1 to M12.

2 Work Packages' activity report

2.1 WP1 Management

WP LEADER	PARTNER INVOLVED	DURATION
IIT	All	48 months (M1-M48)

WP objective – This WP aims at guaranteeing the smooth coordination of the research activities carried out by the partners towards the objectives of the project, in accordance with the proposed work plan (and managing possible conflicts or deviations from the work plan). This WP is also aimed at managing administrative and financial activities.

The activities related to Data Management are also part of this WP.

List of deliverables released:

- [IIT-CMBR, M8] – D1.1 Data Management Plan I
- [IIT-CMBR, M13] – D1.2 Periodic activity report I
- [IIT-CMBR, M13] – D1.3 Periodic management report I

2.1.1 Task 1.1: Scientific and Technical Management

TASK LEADER	PARTNER INVOLVED	DURATION
IIT	All	48 months (M1-M48)

During the first year project, IIT managed all the activities related to the contact with Project Officer and Commission and shared the information with the consortium.

During the first year, the consortium organized three project meetings. A detailed description the events is reported as follows.

List of project meetings

GrowBot kick-off meeting	
Location	*Domus Comeliana*, Pisa, Italy
Date	January, 30th-31st 2019
Organiser	IIT-CMBR
Agenda	please, refer to Annex 3.1
Project website link	https://www.growbot.eu/project/events/2-uncategorised/20-kick-off-meeting-event

The main objectives of the kick-off meeting focused on: (I) sharing partners' expertise and background relevant to GrowBot and the specific role within the project; and (II) discussing and defining contents and activities related to GrowBot Advisory Board, prizes, tutorials, and joint workshops.
Each PI gave a 25' presentation including: (I) a general overview of the institution, team members, and relevant facilities; (II) a description of scientific background and main expertise; and (III) a description of the role in GrowBot, including responsibilities as WP leader or contributing partner, and of specific activities to perform.

IIT management office presented a detailed overview of administrative and financial management of European projects.

During the first-day roundtable, the consortium discussed the following issues:

- Advisory Board (AB): a list of candidates was agreed with all the partners during the meeting and a vote was carried out in the following days via web (doodle). The candidates who got more preferences, and therefore elected as AB members, were: George Jeronimidis (plant biology expert), Sandro De Poli (representative of the industrial domain), and Antonio De Simone (mathematics and mechanics of materials expert).

- Call for ideas (GrowBot Prize): GrowBot aims at promoting initiatives to enlarge scientific and technological communities around plants science, bioinspired materials and robotics by launching calls for ideas in the form of prizes (in line with the conditions set out in general Annex K) for performing selected activities at European level. During the meeting, the consortium discussed and defined the details and topic of the first call for ideas, planned to be launched at month 3.

- Tutorial meetings: the tutorial meetings aimed at creating a common language within the consortium, which is characterized by a multidisciplinary nature. This represented *per se* an added value of the project. During the kick-off meeting, the partners discussed details related to the organization of the tutorials (planned at month 3).

- Joint workshop: the partners discussed international events relevant to organize joint workshops on GrowBot topics.

Tutorials meeting	
Location	Tel Aviv University, Tel Aviv, Israel
Date	April, 9th-10st 2019
Organiser	TAU
Agenda	please, refer to Annex 3.2
Project website link	https://www.growbot.eu/project/events/2-uncategorised/23-tutorial-meeting-event

A presentation of the results of the tutorials meetings is reported in Tasks 2.1 and 2.2 of WP2, described in the following section.

Project meeting	
Location	Gran Sasso Science Institute, L'aquila, Italy
Date	November, 11th-12st 2019
Organiser	GSSI
Agenda	please, refer to Annex 3.3
Project website link	https://www.growbot.eu/project/events/2-uncategorised/32-project-meeting-l-aquila

The meeting was in two days: the first day was dedicated to the discussion of project issues and the second day was dedicated to remotely discuss with the three members of the Advisory Board.

During the first day, the partners discussed the following issues: review meeting; report on the research activities; plan of scientific outcomes; communication, dissemination, and exploitation plan; deliverables to be submitted; and the agenda of the meeting with the Advisory Board.

During the second day of the project meeting, a Skype call with the three members of the GrowBot AB (Prof. George Jeronimidis, Prof. Antonio De Simone, and Dr. Sandro De Poli) was organized. Dr. Barbara Mazzolai, the project coordinator, introduced the project to the AB's members. Then, each partner introduced its own institute and highlighted the role in the project. In the end, the consortium established a round-table discussion with the AB.

2.1.2 Task 1.2: Administrative and financial management

TASK LEADER	PARTNER INVOLVED	DURATION
IIT	All	48 months (M1-M48)

Details are reported in Deliverable D 1.3 Periodic management report I.

2.1.3 Task 1.3: Data Management Plan

TASK LEADER	PARTNER INVOLVED	DURATION
IIT	All	48 months (M1-M48)

The aim of this task is to manage all data generated within the project, defining a balanced strategy between open dissemination of results for maximising access to and re-use of data on one side, and protection of results for future market exploitation and patenting. GrowBot participates in the Open Research Data Pilot. A first Data Management Plan was released at M8. The report was confirmed without modification at M12 and will be updated periodically (M30, M48). The consortium chose to exploit Zenodo as online repository for the data management.

Details are reported in Deliverable D1.1 “Data Management Plant I”.

2.2 WP2 Tutorials and design specifications

WP LEADER	PARTNER INVOLVED	DURATION
TAU	All	6 months (M1-M6)

WP objective – WP2 aimed at two main objectives: i) the organization of two tutorials given by biologists to engineers and by engineers to biologists, which is a very effective way to exchange systematized knowledge between researchers from different communities overcoming the difficulties inherent to the multi-disciplinary project and helping joint activities; and ii) define GrowBot design specifications and application scenarios.

The joint tutorial was organized at Tel Aviv University, Israel (M4). These tutorials were at the basis of the scientific and technical discussions among the partners, crucial for defining the GrowBot specifications and scenarios of use, as defined in Deliverable D2.3.

List of deliverables released:

- [TAU, M4] – D2.1 Tutorial on fundamentals of plants biology
- [Linari, M4] – D2.2 Tutorial on GrowBot related technologies
- [IIT-CMBR, M8] – D2.3 GrowBot specifications and scenarios of use

2.2.1 Task 2.1: Biology vs artificial

TASK LEADER	PARTNER INVOLVED	DURATION
TAU	ALU-FR, CNRS	3 months (M1-M3)

This part of the tutorial focused on sharing knowledge on climbing plant features that are relevant for the project, based on the following talks:

- Thomas Speck (ALU_FR) “Plant movements: mechanics and underlying structures”
- Marc Thielen (ALU-FR) “Damping in plants: mechanics and underlying structures”
- Nick Rowe (CNRS) "The nuts and bolts of being a climbing plant: a biological perspective” and "Diversity of climbing strategies: a perspective palette of different functional GrowBot models”
- Yasmine Meroz (TAU) “Plant decision-making: observations and models”

These talks covered a spectrum of aspects, including movements, attachments, mechanics of climbing plants, as well as climbing strategies. Behavioural models were also discussed, including memory phenomena and decision-making involved in plant tropisms, in general.

2.2.2 Task 2.2: Artificial vs biology

TASK LEADER	PARTNER INVOLVED	DURATION
Linari	IIT, HZG, GSSI, SSSA, Bioo	3 months (M1-M3)

This part of the tutorial provided a review of available and future technologies able to create plant-inspired artefacts using additive manufacturing technologies; active and passive control systems to drive the growing module; and sensing elements to provide feedback to control systems. Engineering partners presented growing modules based on polymeric material deposition techniques, such as electrospinning, fused deposition, foldable structures, expansion foam and combination of these solutions for different parts. Miniature MEMS sensors capabilities, dimensions and power consumptions, as well as microprocessors to acquire and process signals were listed as sensing technology. Cameras were excluded from available options to mimic real plant capability and total power consumption of the entire growing robot as to be maintained as low as possible to be partially powered by energy harvesting source. A summary of mechanical specifications is reported below (Table 1).

Table 1: Summary of mechanical specifications.

INDOOR ONLY	
Diameter	40-60 mm
Growing Rate	>2 cm/h
Maximum Power Consumption	10 W (peak)
Minimum Bending Radius	3xD
Minimum Artefact Length	1 m
Wall Thickness	0,5÷2 mm
Wall Porosity	< 90%

2.2.3 Task 2.3: GrowBot specifications and definition of applications

TASK LEADER	PARTNER INVOLVED	DURATION
IIT-CMBR	All	3 months (M4-M6)

The discussions carried out during the first three months of the project and during the tutorials lead the next step of the partners in defining key specifications for the GrowBot artefacts. These include:

- the definition of three macro-scenarios of use;
- the definition of low level functionalities that will be implemented in the GrowBot artefacts, according to the scenario where each artefact should act;
- the definition of basic requirements for the development of the different enabling technology, in terms of dimensions, power consumption, and data exchange;
- preliminary designs or architecture of each of robots identified in the project.

The scenarios of use were defined based on the need to negotiate conditions unknown *a priori* in robots released in outdoor/unstructured environments. Climbing plants can offer many ideal solutions for those conditions and understanding their working principles can enable new technological solutions for robots able to grow and climb. At the same time, robotic systems implementing climbing plants functionalities might help to find answers to biological questions.

In this perspective, we envisioned three macroscopic scenarios: exploration, environmental monitoring, and structural consolidation.

For each scenario, we identified key functionalities of climbing plants that would help accomplishing some specific tasks; also, we defined which functionalities will be implemented in each GrowBots, suggesting the association between scenario and suitable robot.

Several climbers have being explored during the project to identify functional, structural and bio-mechanical properties useful for the GrowBot implementation. A description of climbing plants features relevant in robotics is also reported in a recent publication from IIT-CMBR: Fiorello et al. titled “Taking Inspiration from Climbing Plants: Methodologies and Benchmarks - A Review” accepted in the *Bioinspiration & Biomimetics Journal*.

For instance, we identified five groups of functionalities belonging to climbers: morphological adaptation and plasticity, perception and behaviour, strategies for support identification, anchoring strategies, and adhesive mechanisms. All the partners discussed the aspects enabling these functionalities in climbing plants, to provide guidelines for the design of the robots; and discussed how to deal with the energy sustainability in the solutions proposed in GrowBot.

Deliverable D2.3 “GrowBot specifications and scenarios of use” describes these scenarios and represents a useful starting point to design the robots.

2.3 WP3 Climbing plants observation and modelling

WP LEADER	PARTNER INVOLVED	DURATION
ALU-FR	ALU-FR, IIT, TAU, GSSI, CNRS	24 months (M1-M24)

WP objective - WP3 aims to extract the structural and functional benchmarks required to design the plant-inspired growing robots and attachment solutions. The starting points are based on several scientific questions relevant in robotics and materials science, which include, among many: Why are climbing plants increasing in ecological importance? What functional traits underlie their adaptability and success? What are the mechanics, physics and chemistry behind attachment mechanisms? What evolutionary patterns underlie this diversity, success and range of climbing strategies? What methods and tools (database technologies, ecological approaches, study plots, experimentation) do we need to develop and improve? What properties of vines and tendrils are useful for biomimetics research?

List of milestones achieved:

- [TAU, M9] – MS1 Equipment setup and image analysis software
- [CNRS, M12] – MS2 Provide list of functionally diverse climbing plant behaviours as potential starting points for GrowBot “life histories” (please, refer to Annex 3.4)

2.3.1 Task 3.1: Macro-characterisation of biomechanical properties

TASK LEADER	PARTNER INVOLVED	DURATION
ALU-FR	CNRS, IIT-CMBR	24 months (M1-M24)

The objective of Task 3.1 is to gain an overview of the overall organisation and development, searcher deployment and attachment structures of climbing plants and to explore their functional strategies and especially their mechanical architecture.

CNRS experts are focusing on a broad scale approach on climbing plants in natural habitats from tropical, sub-tropical and temperate regions. The research focuses on large scale processes, strategies and adaptive functions.

ALU-FR researchers are concentrating on cultivated plants that are already established in the botanical garden of the University of Freiburg and that are under cultivation in green houses and in controlled conditions. The research focuses on fine scale processes and adaptations of climbing plants.

IIT-CMBR researchers are carrying out cross-activities aimed to establish the required conceptual infrastructure to bridge the biological knowledge into artefacts specifications.

Our overall goal aim is to gather essential information on climbing plants from their organisation, behaviour and ecology in their natural habitats right down to fine scale measurements of biophysical and chemical characteristics under controlled conditions. Together with IIT-CMBR, concepts of how the functional principles can be transferred into GrowBots are being discussed and evaluated.

CNRS Research – From a broad scale

CNRS has set up research sites, identified habitats and stations where are located species of interest in South America, West and Central Africa and Europe. This sampling across different Tropical zones will provide a vast range of liana growth models for present and future research (Figure 1).

i) Located sites for liana "searcher" ecology -, searcher diversity, habitat diversity types in **South America**: Lowland tropical rainforest (French Guyana) and dry coastal "Restinga" Atlantic Forest, Brazil; **Central Africa**: Tropical Rainforest **Europe**: Mediterranean mixed woodland, Southern France.

ii) Developed methods (a) with technical staff and students for measuring searcher properties and characteristics in field conditions – reach, length, tapering, mechanical properties (bending rigidity and stiffness), stem density, estimated "cost" per length of reach. (b) Developed approaches for measuring attachment structures in terms of initial contact, strength of attachment and effect on matrix (**T. Hattermann Ph. D.**).

Figure 1: There is a vast diversity of liana growth, behaviour and attachment in the natural world that remains unknown and undescribed. CNRS studies in collaboration with GrowBot partners will measure the "Reach": distance and "searching range" of climbing plant stems across voids and between supports. Our preliminary notion of "Reach" includes (a) "length" of the stem that can increase by growth and (b) active stem movement. This is one of our stations in French Guiana (*Doliocarpus* sp., Dilleniaceae). Time lapse analysis at specific stations will also measure the timing of searching as well as recording the events before, during and after

attachment. In this example a *Doliocarpus* stem has grown (and searched) a linear length of approximately 1.5 metres and has searched for supports laterally across a space of approximately 1 metre during a period of 24 hours.

iii) Located sites in French Guyana for measuring “obstacle course” behaviour of climbing plants across different 3D terrains and surface substrates with two potential model plant species: *Condylocarpon guianense* (Apocynaceae) and *Bauhinia guianense* (Fabaceae).

iv) Collected 76 species of liana searcher for large-scale comparison of anatomical architectures in climbing plant searcher to compare with leaders of trees.

v) Identified potential functional traits of a succulent climbing cactus for functional transfer (collaboration with HZG).

Selected results (CNRS)

i) Succulent “climbing cactus” *Hylocereus setaceus* (Cactaceae) reveals a “low biomass” highly adaptable stem geometry, mostly comprised of soft tissue that can optimize rigidity necessary for traversing voids via star-shaped cross-sectional geometries rather than by increasing material stiffness with biomass. The species also deploys a “two-step” attachment mechanism via 1- spine grappling and 2- root attachment that is effective across a wide range of unstructured three-dimensional environments (Figure 2). This work has been submitted to *Frontiers in Robotics and Artificial intelligence* in collaboration with P. Soffiatti (Department of Botany, Federal University Parana State, Brazil).

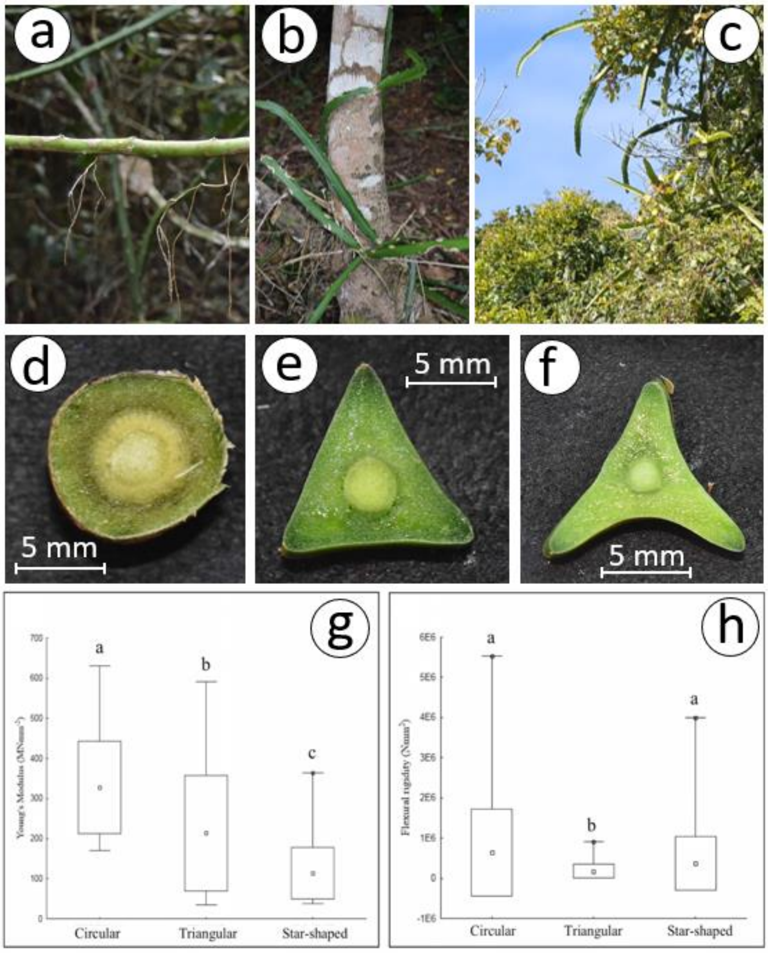

Figure 2: Different growth stages of *Hylocereus setaceous* (Cactaceae). (a) Creeping stems in understory with circular cross sections (d); (b) Climbing stems with spines and attachment roots with triangular cross-sections and “root searchers” (e); (c) Searcher axes emerging from tree canopy with strongly winged cross sections (f).

Mechanical properties of different stages vary depending on presence of wood and geometry. Circular stems have the highest modulus in bending due to a cylinder of wood (g). However, searcher stems produce similar levels of flexural rigidity via a highly optimized star-shaped geometry (h) (different letters indicate statistical significance).

ii) Searcher diversity – initial observations of our growing data set indicate that different searchers of different species have different reaches which are linked to different anatomical and mechanical organisations and these have different costs (**Summer School Undergrad project**). Attachment type likely varies across this spectrum of searcher types. (**Ongoing – a wide-scale analysis of this spectrum** will be of interest to the GrowBot project and to the ecology community.

iii) *Doliocarpus* sp. results.

The mechanical architecture of different stems of *Doliocarpus* sp. shows a variety of strategies. Sun branches, climbing stems, creeping stems and self-supporting stems have anatomical differences (especially regarding vessel diameter and fibre wall thickness) and also in terms of mechanics. Sun branches have lower values of rigidity due to the lower values of second moment of area while creeping stems have the lowest values of Young's modulus. These data indicate that some lianas can modulate their mechanical properties according to whether they are creeping on the ground or climbing or self-supporting (in collaboration with P. Soffiatti, Department of Botany, Federal University Parana State, Brazil).

ALU-FR: Towards a fine scale

ALU-FR concentrated on a) self-stiffening, intertwining searcher shoots and b) on twining stems, coiling tendrils and related attachment structures. Searcher structures serve climbing plants to find new substrates (e.g. host plants), on which they can then climb along. For this purpose, it is necessary to span gaps between host plants, for which a high stiffness allowing for a wide reach is of enormous advantage. A survey in the botanical garden revealed that many plant species feature "searcher braids" consisting of a varying number of intertwined individual searches, providing mutual support (Figure 3). Mechanical tests (2- and 3-point-bending tests) were and are currently being performed on *Dipladenia* sp. as they typically feature relatively straight "searcher braids" (Figure 3d-e). First results (Table 2) show the drastic increase in bending stiffness from the apex towards the base of the "searcher braid" and prove that this testing protocol is suitable for further investigations, also on other plant species. These tests will allow to assess the contribution that friction between individual searchers on the one hand, and axial second moment of area on the other hand, have on the overall bending stiffness of searcher braids (Manuscript in preparation for: *Frontiers in Robotics and Artificial intelligence*). The work on the mathematical aspects of this topic will be supported by GSSI and TAU.

Table 2: Bending stiffness of a *Dipladenia* sp. searcher braid.

Section of the searcher braid (i.e. number of intertwined searchers)	Bending stiffness [Nmm^2]
1	7.88
2	77
3	130-570
4	1696-1636

The macro-characterisation of the mechanical properties of tendrils and searchers is strongly overlapping with anatomical (e.g. histological) analyses performed as part of Task 3.3. In order to perform functional-anatomical analyses (i.e. histology, light microscopy and scanning electron microscopy), different tendrils (*Cobaea scandens, Bryonia alba, Cyclanthera brachystachya, Luffa aegyptiaca*) and twining stems (*Apios americana, Humulus lupulus, Thunbergia alate, Ipomoea tricolor, Aristolochia macrophylla*) from various plant species have been collected and fixated in a mixture of formalin, acetic acid and alcohol (FAA) and in methanol (50 %).

Coiling tendrils are of special interest for GrowBot as they are able to provide a strong hold to plants while still being flexible enough to absorb energy and thus to prevent premature failure. The genus *Passiflora* turned out to cover the perfect model plants in this regard as the attachment structures are very diverse in terms of size and functional principle. From an evolutionary point of view this is quite interesting because they all feature coiling tendrils, whereas only some (evolutionary basal) species, as e.g. *P. discophora*, have adhesive pads while most (evolutionary more derived) species do not. *Passiflora caerulea, P. x belotii, P. quadrangularis, P. garckei* and *P. amethystina* as well as *P. discophora* were established in the Botanic Garden in Freiburg. Setups have been adapted in order to measure tensile strength, hysteresis and energy dissipation in coiled tendrils. Test series on turgescent and senescent tendrils of *P. discophora* have been performed so far. To this end, ten different methods for attaching the individual very small, delicate and desiccation-prone tendrils to the force measuring setup (Figure 4a-c) have been evaluated. Typical force-displacement curves resulting from tensile tests showed three distinct phases (Figure 4d). The interpretation of the results from this first test series suggest that during phase I overwinding of the perversion and stretching of the helically coiled tendril takes place. During phase II the coiled tendril is further stretched, and unwinding takes place, and eventually, during phase III, the fully unwound tendril is being stretched. For turgescent tendrils the maximum forces before rupturing force ranged between 0.12 N and 1 N. For senescent tendrils these forces were considerably higher (between 0.7 N and 2.3 N). Hysteresis tests are currently being completed and evaluated in order to assess the damping capacity (energy dissipation) of turgescent and senescent tendril of *P. discophora* and subsequently also of tendrils of other *Passiflora* species will be analysed. To this end tendrils were subjected to cyclical loading with incrementally increasing strain (5 %, 10 %, 30 %, 50 %, 70 % and 75 %). Figure 4e-f show a representative force-elongation curve for a sequence of hysteresis-loops at increasing strain amplitudes. Viscoelastic behaviour of the turgescent tendril becomes evident but also that plastic deformation is increasing with strain (Manuscript in preparation).

The spring-like coils in plant tendrils normally develop after their distal end made contact and adhere to a substrate. During this process the tendril is tautened, and the stem is pulled towards the substrate. As the tendrils emerge alternately on one side and the other of the plant stem, the stem is thus stabilized while at the same time it retains a certain freedom of movement due to the flexibility of the coiled tendrils. In parallel to the ongoing tensile tests described above, a setup is currently being developed that allows measuring the force development during the coiling process of tendrils *in vivo*. For this purpose, a highly sensitive 3-axis force sensor is attached to the back of a substrate wall that is divided into individual segments, to which the adhesive pads of the tendrils are supposed to adhere.

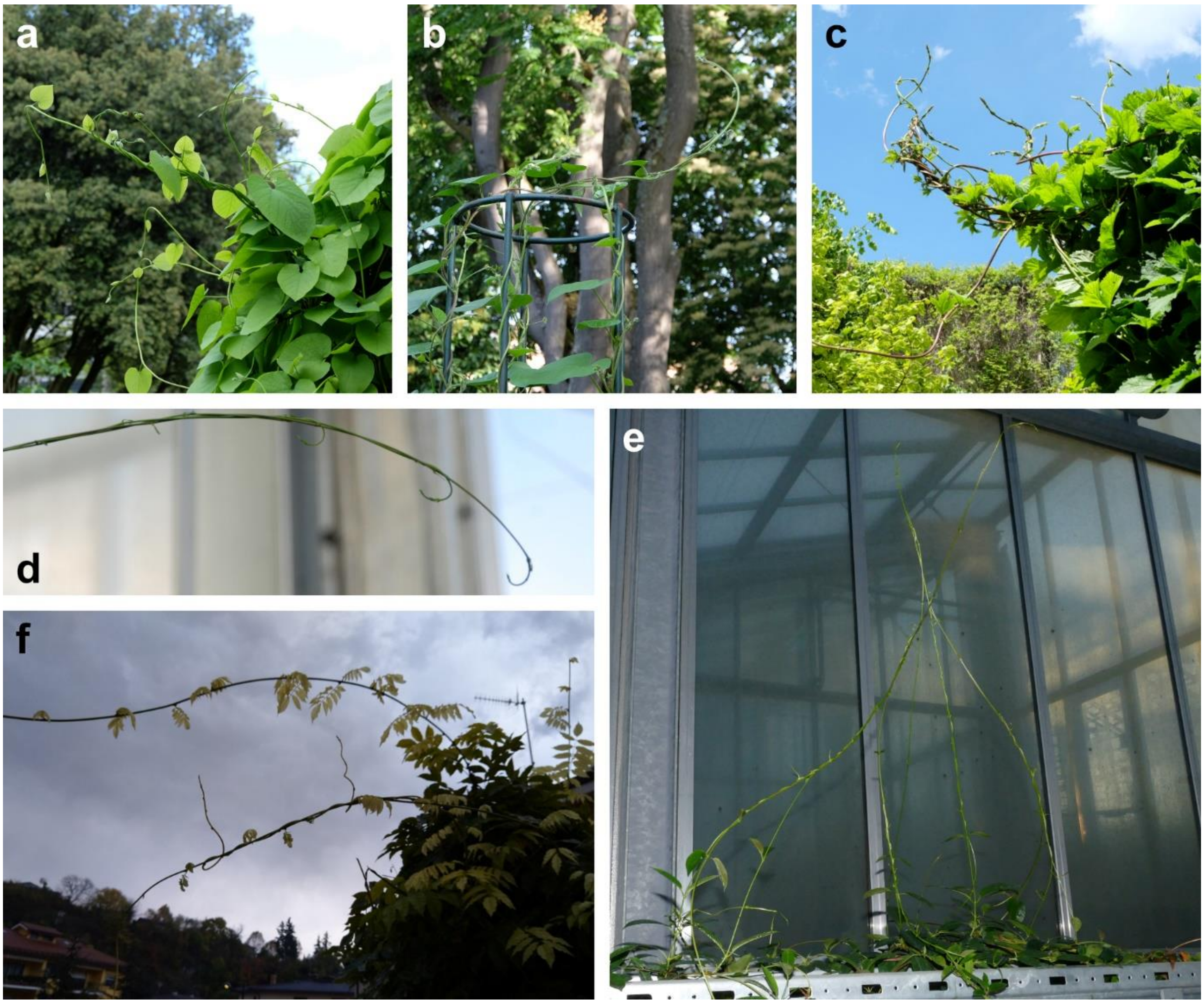

Figure 3: Plants with searcher shoots that are intertwining and providing mutual support. *Aristolochia macrophylla* (a), *Ipomoea tricolor* (b), *Humulus lupulus* (c), *Dipladenia* sp. (d-e), and *Wisteria* sp. (f).

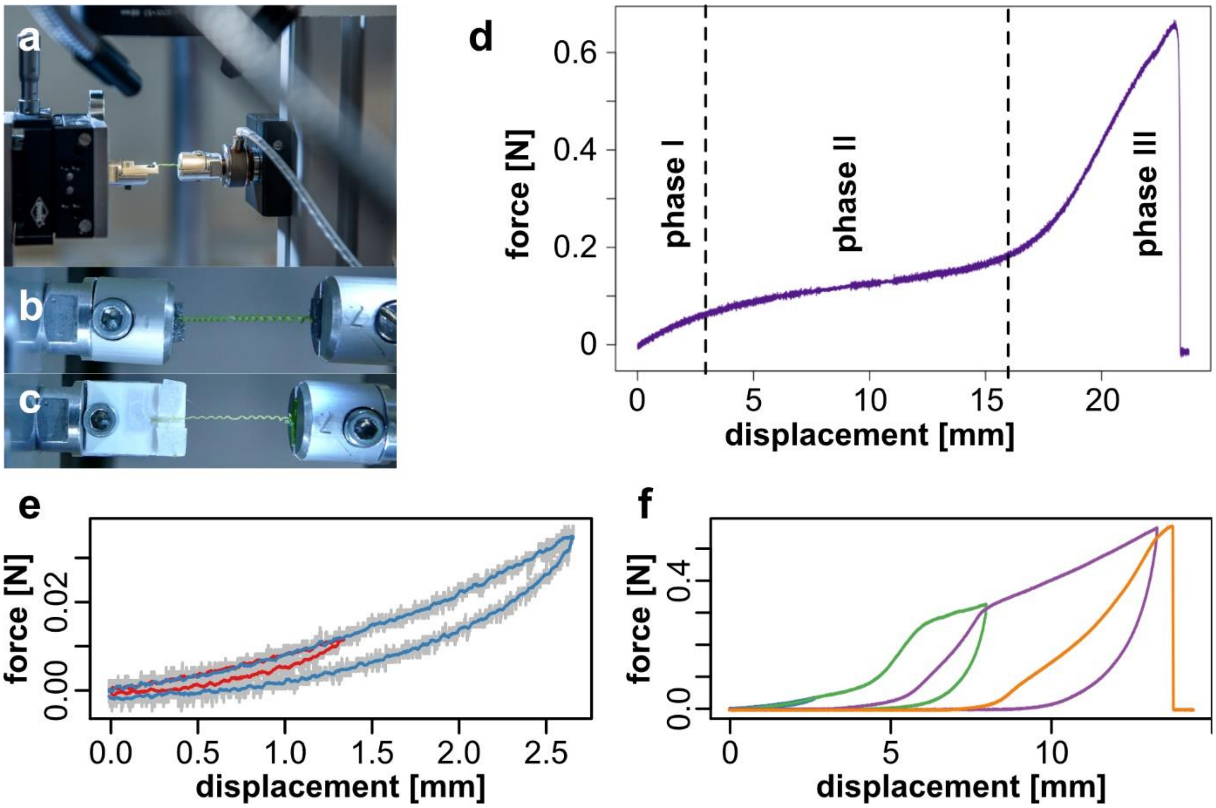

Figure 4: Custom build testing setup for testing mechanics of coiled tendrils (a). Close-up of the testing setup showing different attachment methods of the coiled tendril (b & c). Typical force-displacement curve from a tensile test on a turgescent *P. discophora* tendril showing 3 distinct phases (d). Incremental hysteresis test on a turgescent tendril of *P. discophora* (e-f). Force and displacement during elongation up to 5% (red), 10% (blue), 30% (green), 50% (purple) strain and until failure (orange) is shown. Original data is shown in grey, smoothed data using a moving average in colour.

IIT-CMBR: Biology/Robotics Bridge

IIT-CMBR carried out biological investigations on selected hook-climbers, such as *Gallium aparine* L. and *Rosa arvensis*[12] in order to identify the biological requirements needed to define the artefacts specifications.

The cleaver *G. aparine* L. was investigated for its ability to produce a unique mechanical parasitic adhesive mechanism to climb over the host plants using specialized different types of microhooks[3]. Scanning electron microscope investigations were performed on fixed natural abaxial and adaxial leaf hooks samples (Figure 5) to extract the main morphological parameters for designing bioinspired artificial hooks model. Abaxial and adaxial hook have different shape, size and mechanical properties (Figure 5c-d).

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[1] I. Fiorello, O. Tricinci, A. K. Mishra, F. Tramacere, C. Filippeschi, and B. Mazzolai, "Artificial system inspired by climbing mechanism of galium aparine fabricated via 3D laser lithography," in *Conference on Biomimetic and Biohybrid Systems*, 2018: Springer, pp. 168-178.

[2] I. Fiorello, F. Meder, O. Tricinci, C. Filippeschi, and B. Mazzolai, "Rose-Inspired Micro-device with Variable Stiffness for Remotely Controlled Release of Objects in Robotics," in Conference on Biomimetic and Biohybrid Systems, 2019: Springer, pp. 122-133.

[3] G. Bauer, M. C. Klein, S. N. Gorb, T. Speck, D. Voigt, and F. Gallenmüller, "Always on the bright side: the climbing mechanism of *Galium aparine*," (in eng), Proc Biol Sci, vol. 278, no. 1715, pp. 2233-9, Jul 2011, doi: 10.1098/rspb.2010.2038.

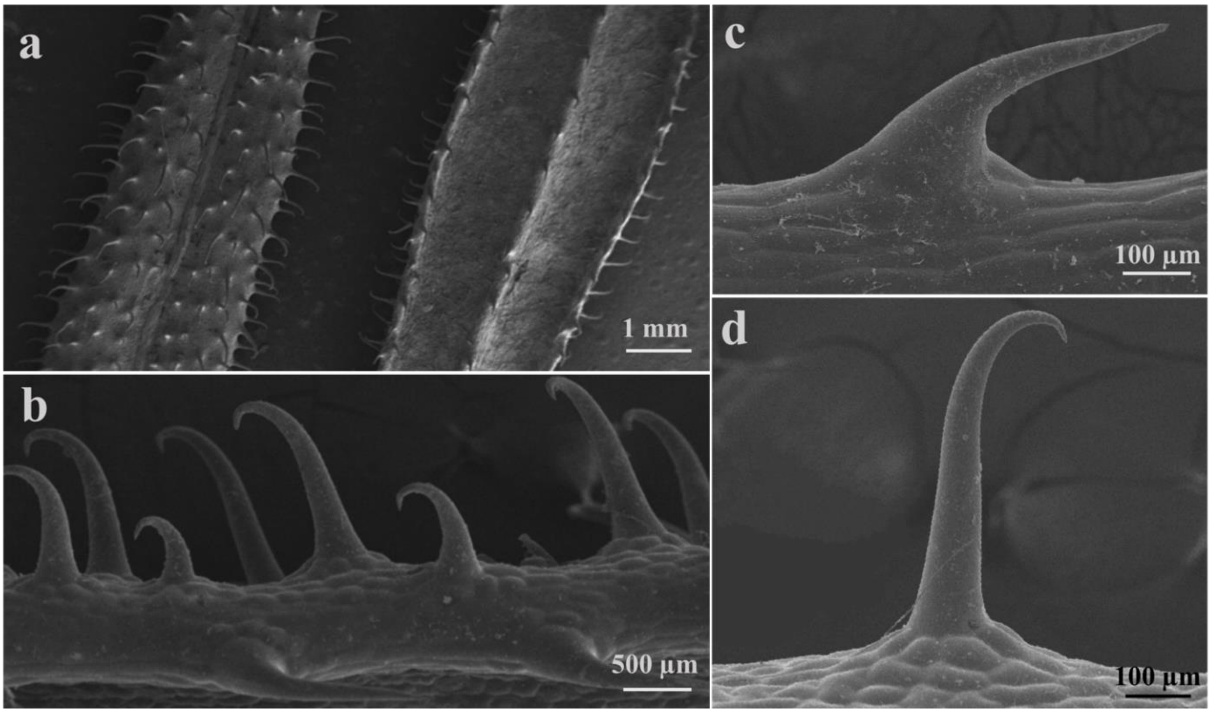

Figure 5: *G.aparine* L. leaf hooks. a) SEM micrographs of abaxial (right) and adaxial (left) side of *G.aparine* natural leaf. b) SEM micrograph of lateral view of G.aparine leaf. c, d) Abaxial (c) and adaxial (d) hooks.

Optical microscope investigations were performed on prickles-like hooks of the climbing *R. arvensis* in order to identify the proper biological investigations and protocols for defining the artificial specifications, as described in Fiorello et al., 2019[2].

Moreover, a review paper was written to gather the main methodologies and approaches used by scientists to investigate and extract the features of climbing plants, in terms of adaptation, movement, and behaviour, which are relevant for developing climbing plant-inspired artificial solutions[4].

2.3.2 Task 3.2: Circumnutations and tropisms in climbing plants relevant for the robot control

TASK LEADER	PARTNER INVOLVED	DURATION
TAU	CNRS, ALU-FR, GSSI	24 months (M1-M24)

The objectives of Task 3.2 are generally divided into (i) mathematical modelling of plant growth-driven responses, including circumnutations and tropisms, and (ii) experimental investigation of decision-making of climbing plants.

In this framework, the milestone MS1 “Equipment setup and image analysis software” was achieved; in the following list the details:

- Experimental setup: TAU developed a first working setup for decision-making between two light sources for seedlings.
  TAU is in the final stages of the more relevant setup for climbing plants, focusing on their decision to twine on a support. The setup is based on the measurement of forces exerted by a climbing plant on a support. TAU expects to complete this more complex setup within a couple of months.

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[4] I. Fiorello, E. Del Dottore, F. Tramacere, and B. Mazzolai, Taking inspiration from climbing plants: methodologies and benchmarks-A review. *Bioinspiration & Biomimetics* (accepted).

- Image analysis: TAU developed written code and experimental setup appropriate for 2D tracking. In order to get tracking on plants, including the growth zone etc., the researchers added fluorescent markers on the plant shoot. This method was validated and will be published as part of a research paper in future.
  For 3D tracking, the researchers are currently working on stereo cameras in order to get 3D information.

3D model of growing and interacting organs

TAU has developed a mathematical model which describes the growth-driven dynamics of a plant shoot, such as a climbing plant, as a response to an external stimulus, or as a result of internal cues. The model is three-dimensional (see Figure 6), and includes an active growing part (an elongation zone) as well as a static part which no longer grows. External cues include well known tropic responses to distant signals (such as phototropism or gravitropism), as well as tropic responses to point-like signals such as a nearby chemical cue - this is mathematically distinct from a distant signal (see Figure 6b). Furthermore, twining can be achieved by assuming a rod-like signal (Figure 6c). Internal cues allow reproducing the well-known oscillatory movement of circumnutations (Figure 6d). We are collaborating with GSSI on showing how control theory can lead to the equations of motion in the case of accretive growth (where material is added at the tip, and there is no elongation zone).

This work will be submitted to the collection on "Generation GrowBots: Materials, Mechanisms, and Biomimetic Design for Growing Robots" in "Frontiers in Robotics and AI" (under peer review).

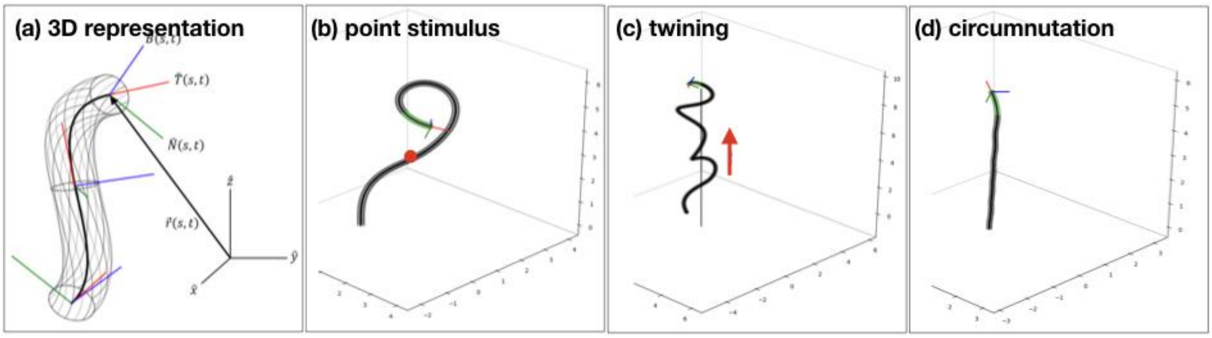

Figure 6: 3D simulations of growth-driven organs. (a) 3D representation of a rod-like cylinder, at the basis of the model (b) tropic response to a point stimulus (red dot). In green is the growth zone, which responds to stimuli by changing its morphology. In black is the part of the organ which cannot grow and therefore is fixed. (c) Twining can be achieved by allowing a line stimulus (grey line) together with gravitropism (red arrow represents direction of gravity). (d) Circumnutations – internal driver leading to oscillatory motion.

We have recently initiated a collaboration with Prof. Mattia Gazzola at University of Illinois at Urbana-Champaign, with the aim to include elasticity and mechanics – this is required in order to consider physical interactions of the plant organ with obstacles in the environment.

A mathematical framework for interacting organs and collective dynamics

We have developed a mathematical framework that allows considering the general question of interacting growing organs. We assume that each organ (each GrowBot) can emit a signal that other organs can sense, and which causes them to grow towards or away from it. Such local interactions are at the basis of well-known collective dynamics such as schools of fish and flocks of birds, and we expect that this framework will allow for a robust description of the inherently different collective dynamics of a group of GrowBots, giving rise to emergent structures which to do not require a growth plan.

This work has been published in (Bastien R, 2019) "Towards a framework for collective behavior in growth-driven systems, based on plant-inspired allotropic pairwise interactions", R Bastien, A Porat and Y Meroz (2019) Bioinspir. Biomim. 14 055004.

Decision-making of twining attachment in climbing plants

We have recently started to design an experimental setup with the goal of investigating decision-making and memory phenomena in the attachment strategy of climbing plants. We initially focus on twiners, using the common bean (*Phaseolus vulgaris*) as a model system. We have developed a method which allows tracking the movement of the shoot via image analysis, by adding fluorescent markers. We now focus on the attachment strategy of the twiner to a pole. A shoot circumnutates in searching a structure. Upon contact with a pole we have identified 3 main types of scenario: (i) the shoot touches the pole but quickly brushes against it and continues on it circumnutating trajectory (Figure 7a) (ii) the shoot touches, gets stuck for a several minutes without starting a twining response (as if pushing at the pole) but eventually continues (Figure 7b) (iii) the shoot attempts to twine around the pole, actively bending in order to wrap around, bending and turning up and down, and sometimes misses the pole entirely (Figure 7c). We plan to investigate the underlying mechanism which leads to these different scenarios, by measuring the contact point along the shoot, and the force the pole exerts on the shoot. We plan to make force measurements in collaboration with ALU-FR using their planned experimental setup.

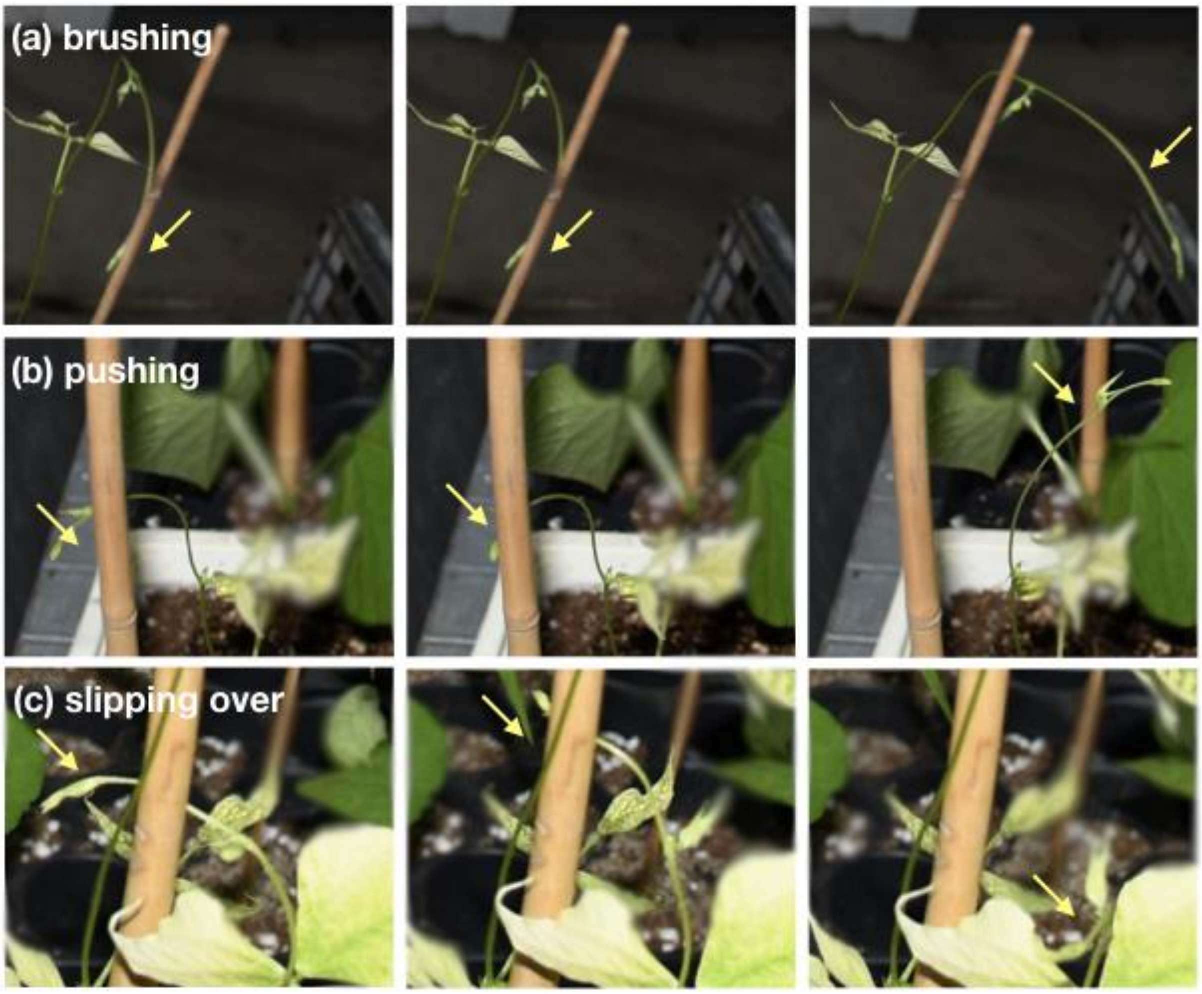

Figure 7: Three main scenarios of twining shoots upon contact with a pole: (a) the shoot touches the pole but quickly brushes against it and continues on it circumnutating trajectory (b) the shoot touches and cannot continue its course, but does not start a twining response (stays straight), eventually manages to "push" past and continue (c) the shoot attempts to twine around the pole, actively bending in order to wrap around, turning up and down, and sometimes misses pole entirely.

Furthermore, we have identified that when a twiner climbs along a diagonal pole, we see that it reverts between a twining mode and a searching mode (see Figure 8): (i) twining along the pole, and (ii) untwining and searching for a new attachment. This switching behaviour seems to be related to the relative angle of the climber and the gravity vector (the angle of the pole). We therefore plan to study the role of gravitropism in the decision-making process between twining and searching modes.

In future we plan to compare the resulting decision making model to plant behaviour in the field (CNRS) and in the greenhouse (ALU-FR).

Figure 8: A twiner growing along a diagonal pole switches between a twining mode (a, c) and a searching mode (b). We will study the role of gravitropism in the decision-making process.

2.3.3 Task 3.3: Attachment structures, climbing mechanisms and searcher-attachment diversity

TASK LEADER	PARTNER INVOLVED	DURATION
CNRS	CNRS, ALU-FR	24 months (M1-M24)

ALU-FR

In order to perform functional and anatomical analyses, different tendrils and twining stems from various plant species have been collected and fixated in mixture of formalin, acetic acid and alcohol (FAA). This allowed preserving them until they were embedded into resin (Technovit) prior to making the sections. Staining, segmentation, abstraction, and parametrization of underlying tissues (Figure 9) allows to asses a (or several) basic functional structures and principles providing the driving force for the coiling processes in tendrils of different plant species. This work is ongoing. Results of these studies will be transferred into artificial tendrils by HZG. Parallel to the *in vivo* force measurement experiments (cf. Task 3.1) the ontogenetic development of *Passiflora* sp. tendrils' anatomical features will be analysed by performing thin sections at different tendril parts (at several positions from the basis to the apex) and a different developmental stages: un-coiled vs. coiled (turgescent state) vs. coiled (mature, fully lignified state).

Extraction of so-called G-fibres ribbons (or cylinders), which constitute the active layer – at least in most of the tendrils – using specific enzymes (the fungal carbohydrolase "Driselase") could not yet be done due to temporary commercial unavailability of the enzyme. This would allow to, at least indirectly, assess the mechanical properties of this individual tissue. An alternative maceration protocol is at the moment being sought.

Parallel to these studies on the functional morphology/anatomy and biomechanics of selected liana stems and tendrils in collaboration with Nicola Tirelli (IIT Genova) we started to analyse the chemical composition of the glue secreted by the adhesive pads of *P. discophora*.

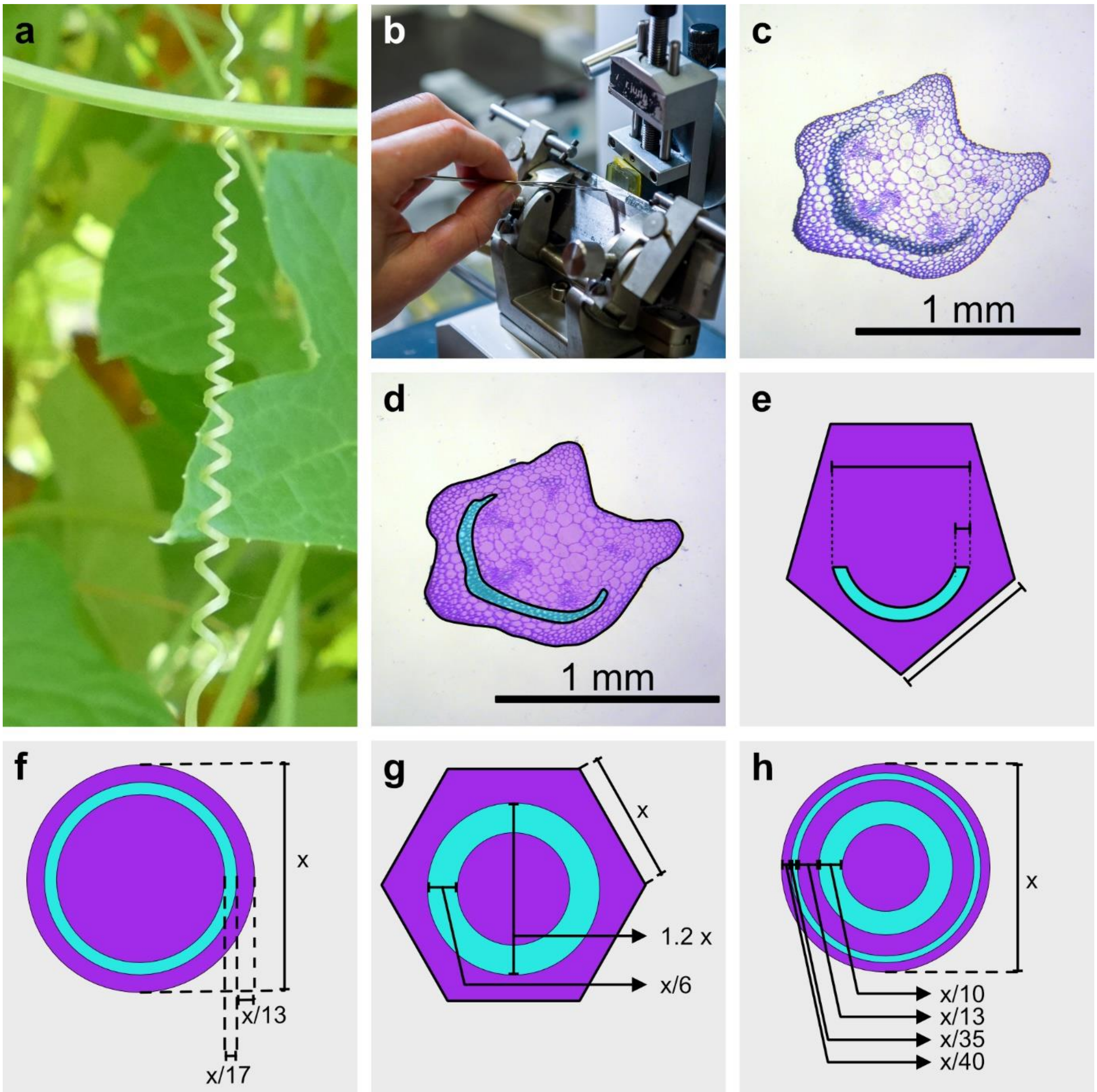

Figure 9: Tendril of *Cyclanthera brachystachya* (a). Preparation of cross-sections from resin embedded plant material (i.e. tendrils) using a microtome (b). Cross-section of *C. brachystachya*, stained with toluidine blue (c). Segmentation of the cross-section according to the different tissues (d). Qualitative abstraction and parameterization of the functional anatomy for later transfer into technical materials and artificial tendrils (e). Quantitative abstraction and parameterization of functional anatomy of *Ipomoea tricolor* (f), *Humulus lupulus* (g), and *Apios americana* (h). (d-e) light blue: lignified / G-fibre regions.

CNRS

CNRS has developed the following for the study of attachment and their deployment

i) Development of techniques for rapid preparation of macro-anatomy of searcher stems (Emilien Fort Master 2 thesis) for potential use in lab and field studies.

ii) Development of techniques and data processing for field testing of macro-hook, adhesive pad, micro-hook and tendril connections under field conditions.

iii) Location of stations for setting up time-lapse observations of (a) circumnutation and (b) attachment structures (Figure 10) and their development in natural conditions.

Figure 10: Field stations in S. America and Africa will document attachment mechanisms of wide ranging functional and phylogenetic groups of climbing plants. South American species of *Bignoniaceae* (a-d) can develop highly active, adhesive pads that can not only attach the plant to the substrate but likely consolidate the support matrix as well. (A) Forest of French Guiana (Paracou research station) -Searching, creeping axes scout the irregular three-dimensional surface of the rough flaky bark surface of a tree trunk. Our pilot time-lapse studies suggest an almost "human rock-climbing" organisation with "arms" searching laterally for holds from a vertically aligned "body"! After initial adhesion (b) adhesive pads then grow via crescent -shaped tissue growth that explores laterally (c) and vertically (d) forming an irreversible attachment and likely consolidating the flaky matrix at the same time. Consolidation of the host substrate is probably a widespread feature in climbing plants because host plants (trees) renew outer surfaces with an outer boundary tissue (bark) that is temporary and sloughes away over time.

i) Completion of measurements on the anatomy and biomechanics of trellis-forming stems of *Condylocarpon guianense* (Master thesis Emilien Fort, 2019). Indicates stem development from stiff to soft wood is adaptive (Figure 11) and the switch occurs when a plant connects with a support. In this species the transition from stiff to compliant is "hard-wired" and always occurs at a stem diameter of 6 mm whether the stem encounters a support or not. This indicates "specialization" of stem mechanics to niches with closely spaced supports. (manuscript in preparation).

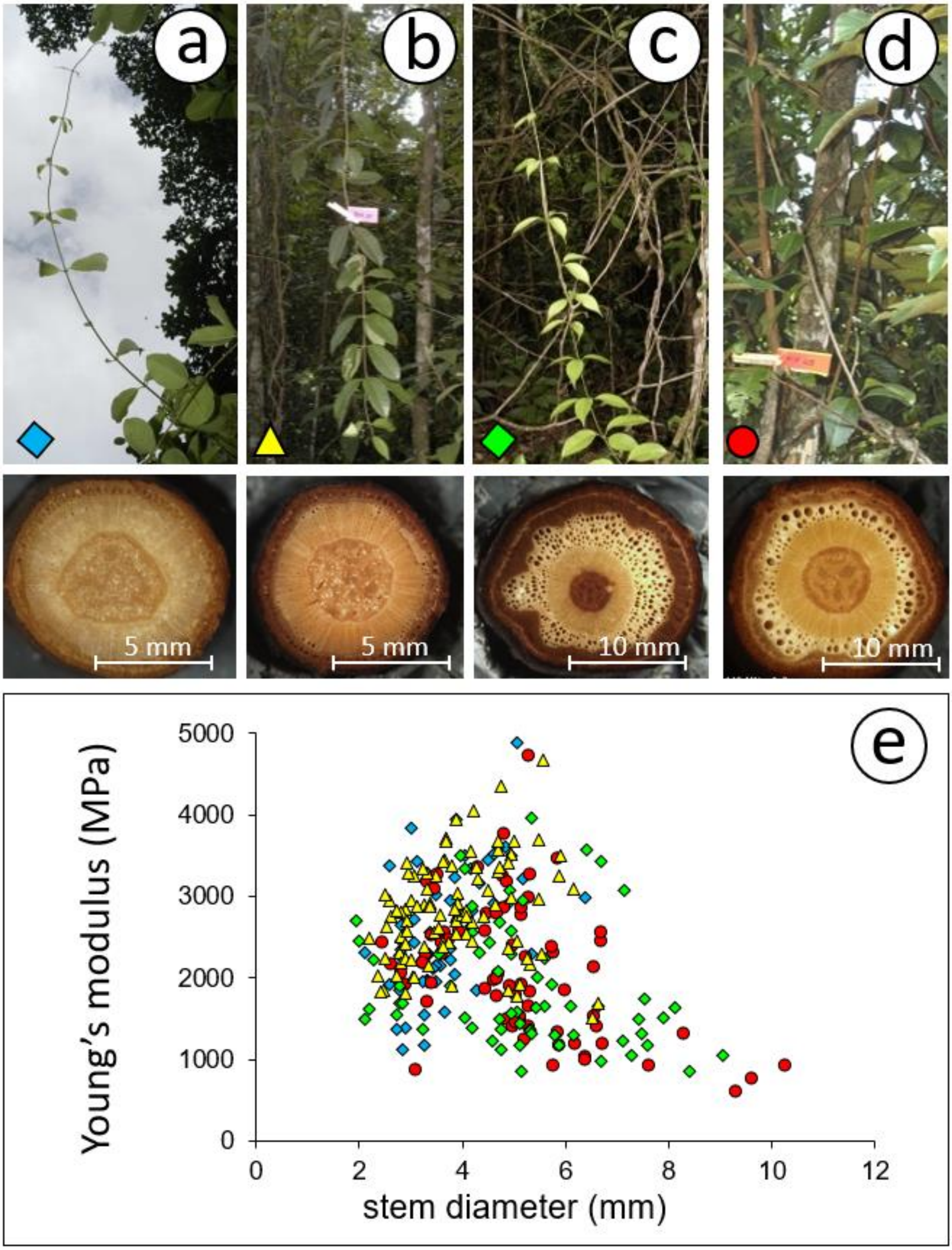

Figure 11: Anatomy and biomechanics of trellis-forming stems of *Condylocarpon guianense* (*Apocynaceae*). Self-supporting searcher stems (a) produce a cylinder of stiff wood only up to a stem diameter of 6 mm. Stems that do not find a support stop growth in diameter after approximately 6 mm. Stems that find a support and climb(c) and become fixed (d) produce a clearly defined second compliant wood. The species therefore develops a wide range of mechanical properties in forming a trellis and this variation (e).

ii) Hook attachment in lianas (*Strychnos* sp. and *Bauhinia guianense*) can involve "smart" partially closed hooks like mountaineer's carabiners that clip on and can clip off supports. These are probably adaptations for highly unstructured environments that are also "moving" – apical branches of trees and lianas in a wind-blown canopy. "Smart" hook thickening and strengthening is highly adaptive and occurs only in attached and stably attached hooks. (Manuscript in preparation).

iii) Micro hook attachment in vines and lianas provide high attachment forces for stabilizing young stems on surrounding supports. Micro hook form, geometry, structural organisation, composition and biomechanics are extremely diverse and include biomineralized spine tips for sharpness. Our study shows that no two species produce the same kind of micro hook and friction properties and that there is a great diversity of these structures that is likely linked to a great diversity of attachment strategies. (Manuscript in preparation).

2.3.4 Task 3.4: Mathematical modelling of growth in climbing plants

TASK LEADER	PARTNER INVOLVED	DURATION
GSSI	-	24 months (M1-M24)

In order to describe the growth of climbing plants, it is fundamental to understand both the mechanical interactions between plants and external obstacles and the metabolic interactions arising intra-plant. As a first step toward a complete understanding of climbing plant development, we have preliminarily designed a model in ("Plant Efficiency: a comprehensive and quantitative definition through a physiological approach", Tedone et al., 2019, submitted) describing the plants' internal interactions of starch, sucrose, nitrogen and phosphorus during its vegetative phase. In particular, we have considered such a research question from a new perspective, based on the concept of plant efficiency (namely the ability to acquire resources and survive in either the presence of competition or stressful environments). This modelling philosophy will be further developed based on the specific features of climbing plants. Indeed, one of the main differences between climbing plants and self-supporting ones is the different biomass allocation among the aboveground and the belowground. As outlined in ("Biomass and Nitrogen distribution ratios reveal a reduced root investment in temperate lianas vs self-supporting plants", Wyka et al., Annals of Botany, 2019), these differences are the key factor for the fast growth of climbing plants like lianas. To better investigate the evolutionary adaptation of climbing plants is crucial to take into account plants' metabolic needs and behaviour ("Biomass and Nitrogen distribution ratios reveal a reduced root investment in temperate lianas vs self-supporting plants", Wyka et al., Annals of Botany, 2019).
On a side note, to study the mechanical stresses due to the interaction of climbing plants and environmental obstacles, we have also formulated a new framework ("Hamilton-Jacobi-Bellman Equation for Control Systems with Friction", Tedone, Palladino, https://arxiv.org/abs/1909.08380), describing the forces and tropisms (tasks 3.2 and 6.2) acting on a growing tip. As a final goal, we aim to connect the previous models to develop insights to design climbing robots able to exploit the environmental obstacles while growing most efficiently.

2.4 WP4 - Smart materials for growing process and attachment solutions

WP LEADER	PARTNER INVOLVED	DURATION
HZG	IIT-POLBIOM, Linari	18 months (M7-M24)

WP objective – WP4 focuses on the design and development of innovative materials and smart soft actuators required for and compatible with the growing mechanisms developed in WP5. Specifically, the following activities will be performed: 1) production of polymeric materials with stimuli-responsive behaviour, compatible with the growing mechanism described in Task 5.1; 2) in situ fabrication of soft actuators as structural materials for the growing parts integrable with the mechanism described in Task 5.4; 3) bioinspired attachment structures.

2.4.1 Task 4.1: Structural materials responsive to (bio)chemical stimuli

TASK LEADER	PARTNER INVOLVED	DURATION
IIT-POLBIOM	HZG	18 months (M7-M24)

Planned activities and expected results

To develop materials that change their shape/volume/optical appearance in response to soft stimuli and that report the process remotely, by translating the response in the form of (di)electric signals. Two different 'translation' approaches are explored: A) through changes in dielectric properties (impedance). The stimulus is oxidation, with the materials (polysulfides) responding either directly to oxidants, or to compounds such as glucose or oxalate through the use of oxidizing enzymes. When oxidized, polysulfides massively increase their dielectric constant, which allows detection, and swell, inducing a curvature in the robot body, while also possibly changing its transparency. B) Through changes in conductivity. We will produce hybrids containing both PEDOT-PSS and polysulfides, where swelling of the latter will be detected via a different conductivity of the former.

Expected results: Spinnable/sprayable (bio)responsive materials with two different detection methods.

Technical activities report

A) Unexpectedly, in early 2019 Sigma Aldrich has withdrawn the main precursor of polysulfides, a chemical known as propylene sulfide (PS), from the market. Our first task was to set up a large-scale synthesis (>100 g) for PS, which was optimized in late summer 2019.

B) Based on the availability of PS, we developed procedures for the preparation of acrylate-terminated polysulfides; these terminal groups allow the conversion of linear polymers in cross-linked networks through a thermal or a photochemical treatment, as depicted in the first stage of Figure 12.

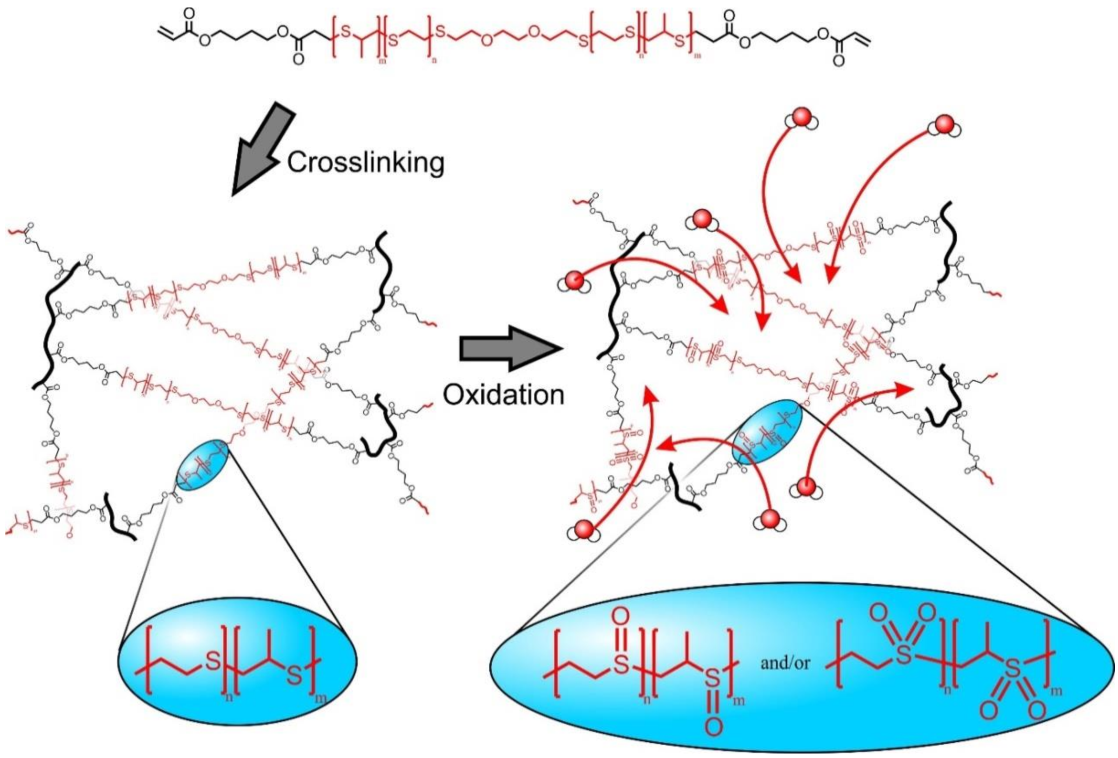

Figure 12: Structure of acrylate-terminated two-armed poly(sulfides), of their networks after cross-linking (either photochemically or thermally induced), depicting the water uptake (swelling) that occurs upon oxidation of the latter.

The network structure determines the overall stability of the material and its general shape, which is important to then allow its fine tuning through oxidation (swelling, bending), as much as through thermal treatments (e.g. for shape-memory applications, materials provided to Task 4.2). The latter will be possible, because some of the polysulfides, in addition to the chemical cross-links, will be kept together by a thermally reversible crystallinity, whose level can be adjusted through the appropriate choice of monomers (PS-only polymers are amorphous, but become semicrystalline with ethylene sulfide) and by controlling their sequential order in the polysulfide chains. Additionally, crystallinity and cross-linking can make the materials processable through techniques such as electrospinning or micro-extrusion (materials to be provided to Tasks 5.1 and 5.3, respectively).

Results

The preparation of acrylate-terminated, two-armed polysulfides is described in Figure 13.

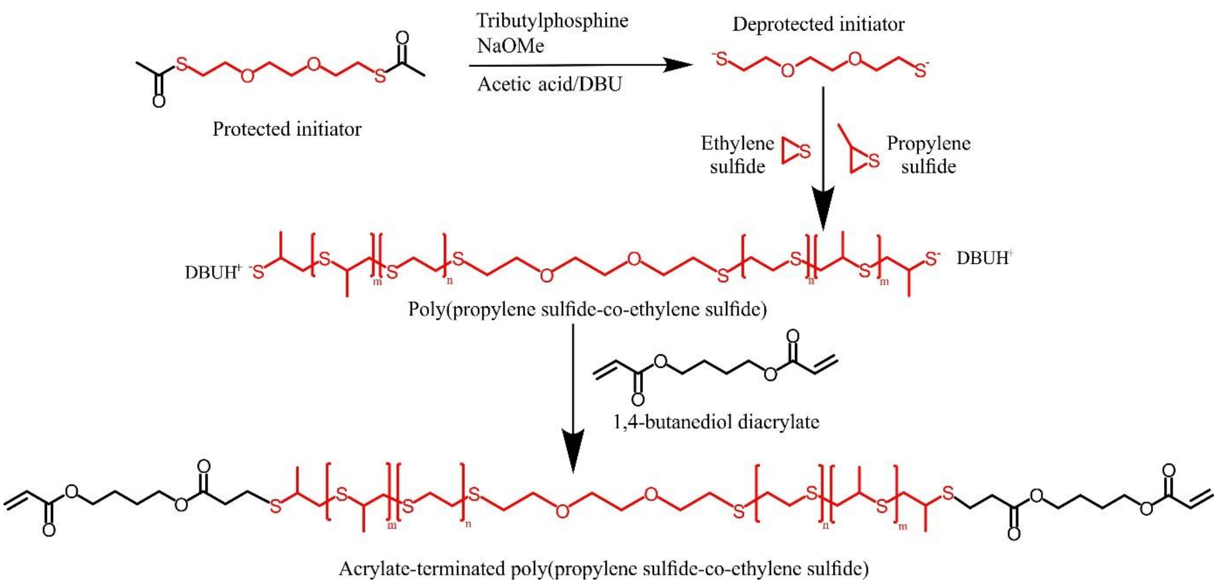

Figure 13: Synthesis of acrylate-terminated, two-armed poly(propylene sulfide-co-ethylene sulfide) (PPSES).

A bifunctional initiator was used to polymerize ethylene sulfide (ES) with PS, using different methods of addition to produce different sequences (random or semi-blocky) of the two monomers. The resulting polymers were end-capped using a Michael-type addition onto a diacrylate, where the excess of the latter allows avoiding its double reaction with two polymer ends. To date, three different polysulfides were prepared (Table 3) and provided to HZG for use in soft actuators (**provision of materials to Task 4.2**). In the meantime, the formation of networks/gels from these polymers and the effect of their oxidation is being investigated. Their combination with PEDOT, investigating their viability as sensors for moisture, will be performed in 2020.

Table 3: Acrylate-terminated polysulfides produced in Task 4.1

Polymer name	Intended $\overline{M_n}$ (g/mol)	$\overline{M_n}$ obtained[a] (g/mol)	Intended ES content (mol%)	ES content obtained[a] (mol%)	Degree of end-capping (%)
Poly(propylene sulfide)	4600	4000	0	0	91
PPSES Seq[b]	4300	4600	40	38	89
PPSES Si[c]	4300	4400	40	39	90

[a]by NMR spectroscopy, gel permeation chromatography (GPC) yielded similar results in terms of molar masses.
[b]Slow, sequential additions of monomers (random sequence). *[c]Single addition of monomers (semi-blocky sequence).*

2.4.2 Task 4.2: Structural materials based on soft actuators responsive to physical stimuli

TASK LEADER	PARTNER INVOLVED	DURATION
HZG	IIT-POLBIOM	18 months (M7-M24)

Planned activities and expected results

This task aims at developing an innovative material technology for in-situ fabrication of controllable soft actuator elements as structural material for the growing parts of the GrowBot. The desired technology of soft actuators requires an integrated approach combining material synthesis or modification, a controlled deposition process (Task 5.3) and encoding (programming) the actuation information in an almost simultaneous fashion. The sensitivity of the actuating components to relevant environmental stimuli such as light or humidity will be achieved by incorporating photo-sensitive (e.g. gold nanoparticles) or humidity-sensitive (e.g. hydroxyethyl cellulose or hydrogels) micro- or nanofillers. Three different material concepts will be explored for printable actuators: i) highly deformable, crystallisable thermoplastics and ii) crosslinked crystallizable thermoplastics and blends thereof as thermo-reversible actuators that preferably switch in the temperature interval between 10 °C and 60 °C, as well as iii) temperature- and photo-sensitive hydrogel actuator systems. In a second step, the best-suited material system will be adjusted regarding the growth rate and energy consumption.

Expected Results: Development of a material technology for in-situ fabrication of controllable soft actuator elements as integral structural parts of the growing robot body.

Technical activities report

The state of art in shape-memory polymer research has been critically reviewed and the potential as actuators for plant inspired movements elucidated. The technology platform of deformable crystallisable thermoplastic materials has been screened towards potential candidate materials as actuator materials. Initial attempts to structure these materials by 3D printing have been conducted. A concept of 3D printable crosslinked actuators has been developed. Its applicability is going to be investigated.

Various hydrogel systems based on different molecular architectures and capable of thermal actuation have been prepared and their reversible actuation has been characterized with respect to their molecular architecture. The influence of changing environmental conditions like temperature, type of solvent or pH as well as the combination thereof was investigated in order to gain insights into the parameter – actuation function relationship.

Based on the discussions in the initial workshops, sensitivity towards oxidation was identified as another promising stimulus to control actuation and could provide the potential of electrical conductivity. Accordingly these systems have been regarded of higher priority than systems sensitive towards light.

Also based on the discussions of the initial workshops a cooperation with in Task 3.1 has been initiated to create actuators capable of tendril like movements. Initial concepts to realize tendril like movements have been identified and are going to be explored. Key parameters of these systems to be investigated will be the spatial arrangement of a fibre component from a mulitblock copolymer within a soft elastic matrix. Fibres from different kind of multiblock copolymers have been prepared by extrusion as well as by electrospinning. Electrospun fibre meshes were selected to realize fibre diameters comparable to plant tissue. As matrix component, two systems have been identified, one soft and non-hydrophilic and the other a hydrogel matrix.

Results

First highly deformable crystallisable, thermoplastic materials, which can be processed by 3D printing have been identified. In this context precursor materials for 3D printable crosslinked actuators have been synthesized.

Thermally-induced hydrogel actuators capable of reversible movements have been created and their movements could be controlled by the change of environmental conditions like type of solvent or pH.

First precursor materials for the synthesis of oxidation sensitive hydrogel matrices have been provided from task 3.1 at the end of M12. Synthesis of the oxidation sensitive hydrogels will be explored from now on.

Initial tendril like multimaterial systems have been designed and synthesized. Three different tendril systems with circular or twisted fibres have been created. Silicone networks and hydrogel networks providing covalent and coordinative bonds have been synthesized. In initial experiments a reversible actuation could be realized with the non-swollen systems. From those experiments it was found that the number of turns of the tendril depends on the relative elasticity between the matrix and fibre and the volume ratio between matrix and fibre.

2.4.3 Task 4.3: Design and development of attachment mechanisms

TASK LEADER	PARTNER INVOLVED	DURATION
IIT-POLBIOM	Linari	18 months (M7-M24)

Planned activities and expected results

The main aim is to obtain attachment to a solid substrate in a selective, on-demand and bio-inspired fashion. The selectivity aspect is tackled by developing polymers with lubricious silicone segments, in order to better differentiate areas of adhesion from those of non-adhesion (which should therefore slide better). Further, an on-demand, bio-inspired adhesive will be developed, following two biological mechanisms: the adhesion of plants such as ivy (production of attachment structures), and of animals such as mussels (dopamine-like glues). This part of the activity will see the development of formulations containing tyrosine (phenol)-rich compounds combined with oxididative enzymes to generate catechols (at the basis of polydopamine mussel adhesion). Besides, polysaccharides are added to the formulation to provide mechanical interlocking during calcium-induced crosslinking (as in ivy) and to render the formulation spinnable/sprayable by machinery developed in WP5.1.

Expected Results: Development of selective and on-demand attachment structures.

Technical activities report

A triblock-copolymer of poly(ε-caprolactone) (PCL) and poly(dimethylsiloxane) (PDMS) was developed as lubricious component for better discrimination between adhering and non-adhering surfaces. This block copolymer contains PCL blocks to integrate materials used for task 5.2 (such as PCL) and should therefore show similar bulk (thermal) properties. On the contrary, PDMS will dictate its surface properties due to segregation of the two polymer blocks and the low surface tension of the PDMS block. The resulting lubricious surface should readily slide past most surfaces, whereas the localized addition of an adhesive formulation will allow a topologically controlled ‘sticking’.

A biologically inspired adhesive was designed to rely on contemporaneous oxidation of phenols and calcium-mediated cross-linking (described in Figure 14). In this adhesive, eugenol (naturally present in a plethora of plants and a precursor to lignin) is oxidized by laccase to form catechols and eventually yield a lignin-like, naturally adhesive product. Ascorbic acid is added to this formulation to fine tune the oxidation kinetics. As a second element in the same mixture, pectin is mixed with calcium carbonate (a powder), glucose and glucose oxidase. The latter two elements generate an acidic environment with a predetermined kinetics, liberating calcium ions from the powder to crosslink pectin (similar to ivy adhesion). Combining the two, enzyme-dependent reactions delivers a gel-like glue with cohesive properties based on two strategies from the plant (and animal) world.

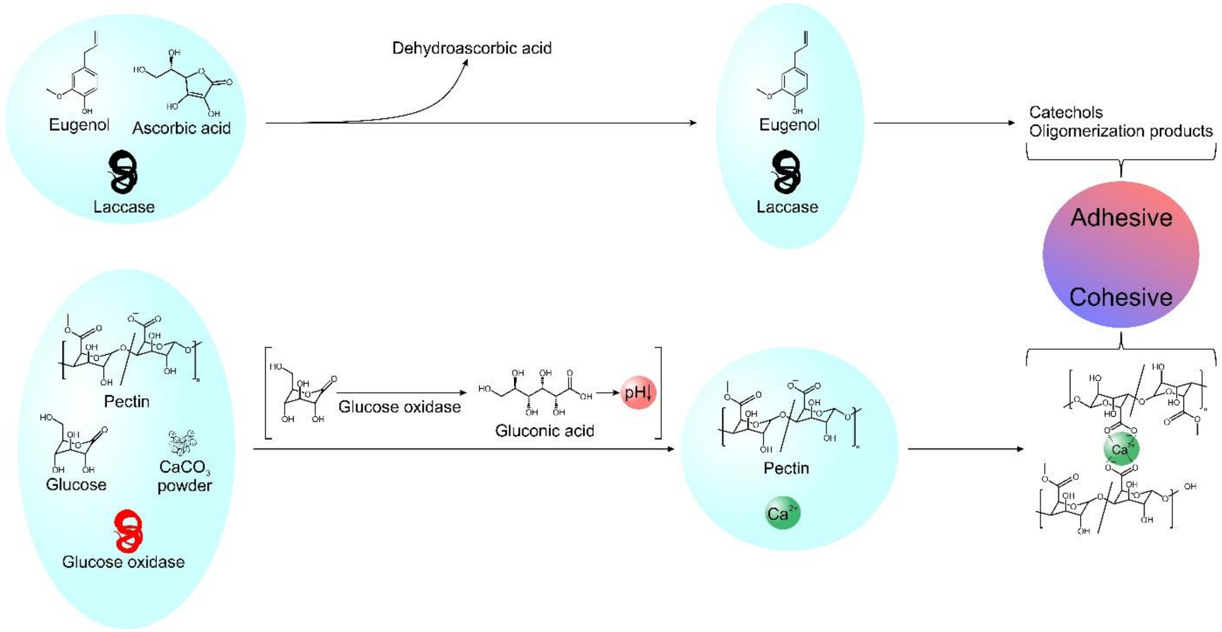

Figure 14: Formation of a biologically inspired adhesive, based on phenol conversion to catechols and calcium-mediated crosslinking of pectin.

Results

The synthesis of a lubricious triblock copolymer was performed by ring-opening polymerization of ε-caprolactone initiated by hydroxy-terminated PDMS (shown in Figure 15).

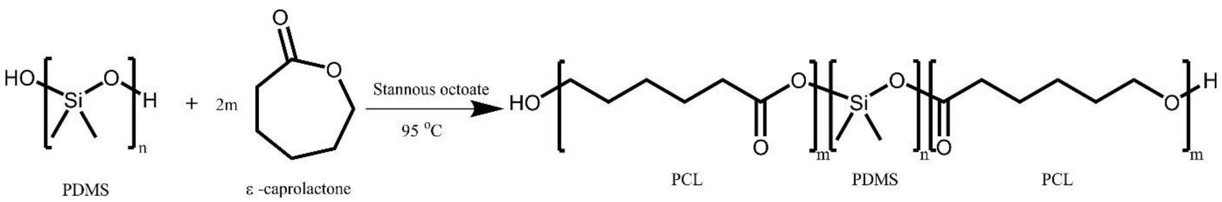

Figure 15: Synthesis of a lubricious triblock copolymer, PCL-PDMS-PCL.

Thermal analysis of PCL-PDMS-PCL corroborated its properties to be in range of pristine PCL (Table 4), confirming the possibility to integrate commercially available PCL. Samples of this block-copolymer have thus been provided to IIT-CMBR for filament deposition experiments (provision of materials to task 5.2) and surface properties are being investigated.

Table 4: Comparison of the thermal properties of PCL (literature values) with PCL-PDMS-PCL (experimental).

	Pristine PCL (literature values[1-3])	PCL-PDMS-PCL
$\overline{M_n}$ (kg/mol)[a]	-	30
PDMS content (% w/w)[a]	-	37
T_g (°C)[b]	-55 to -60	-50
T_m (°C)[b]	55 to 65	60
T_d (°C)[c]	230 to 380	270
Table references		

[1] Ali S.F., Materials Science and Engineering, 137, 2016, 012035
[2] Kim H.-S. et al., Advanced Composite Materials, 17, 2008, 157
[3] Persenaire O. et al., Biomacromolecules, 2, 2001, 288

[a]by NMR spectroscopy. [b]By differential scanning calorimetry. [c]Decomposition temperature determined by thermogravimetric analysis

Concerning the biologically inspired adhesive, the effect of eugenol, laccase and ascorbic acid concentration on the kinetics of eugenol conversion in water was investigated by monitoring absorption during the reaction. Figure 16A and Figure 16B respectively show the effect of eugenol and laccase concentration on the conversion of the eugenol. Both eugenol and laccase concentration increase conversion rate as either is enhanced. Especially laccase concentration was found to have a profound effect, with nearly no eugenol conversions at very low concentrations of the enzyme. Also addition of ascorbic acid was able to adjust the conversion rate of eugenol as is depicted in Figure 16C. At considerable ascorbic acid contents (10 mM ascorbic acid versus 50 mM eugenol), the conversion of eugenol is clearly delayed.

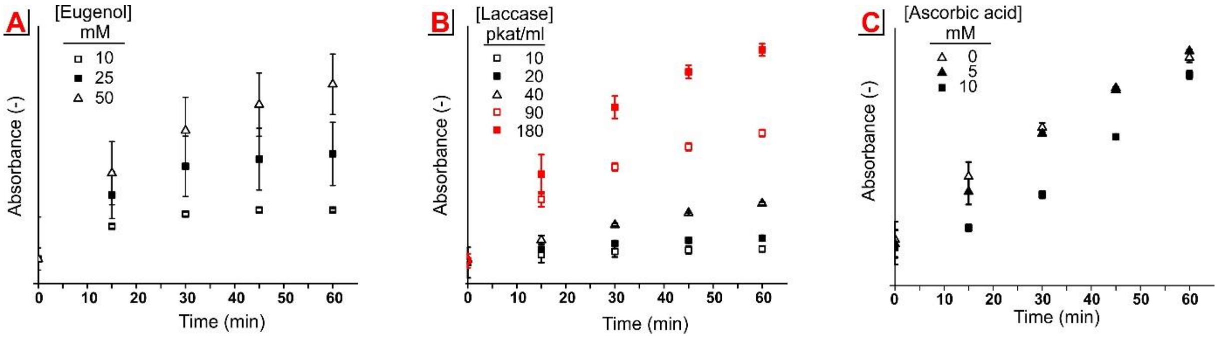

Figure 16: Conversion of eugenol by laccase monitored through absorbance, showing the effect of eugenol concentration (A, at 40 pkat/ml laccase), laccase concentration (B, at 50 mM eugenol) and the presence of ascorbic acid (C, at 40 pkat/ml laccase and 50 mM eugenol).

The adhesive strength of the proposed formulation is now under investigation and formation of cross-linked pectin using the proposed, calcium-mediated method is now studied along with a mode of application of this material by means of electro-spinning or –spraying.

2.5 WP5 - Embodied additive manufacturing mechanisms for growing robots

WP LEADER	PARTNER INVOLVED	DURATION
IIT-CMBR	HZG, SSSA, Linari	18 months (M7-M24)

WP objective – WP5 focuses on developing a set of additive manufacturing sub-robotics mechanisms aimed to build the robot structure. Three mechanisms for growing robots will be developed compatible with different materials such as liquid, gel, or filament (developed in WP4 or commercially available).

2.5.1 Task 5.1: Microfabricated spinner

TASK LEADER	PARTNER INVOLVED	DURATION
Linari	-	18 months (M7-M24)

Spinneret for electrospinning able to produce micro/nanofibers to create a mechanical structure of the robot body and anchoring system to substrates were analysed in two different setups using PVA material to spin nanofibers around 300 nm in diameters. First results will be used to design specific micro-fabricated spinneret and related auxiliary system.

1) To test anchoring capability with *in-situ* nanofiber production a circular PLA frame 50 mm in diameter created with a 6 mm triangular matrix was 3D printed, as shown in Figure 17 and Figure 18 from top and lateral views, respectively. As starting point, we use a single emitter for nanofibers even to fine tune material composition able to operate with very small distance from collector (less than 50 mm) instead of the usually reported in literature over 150 mm.

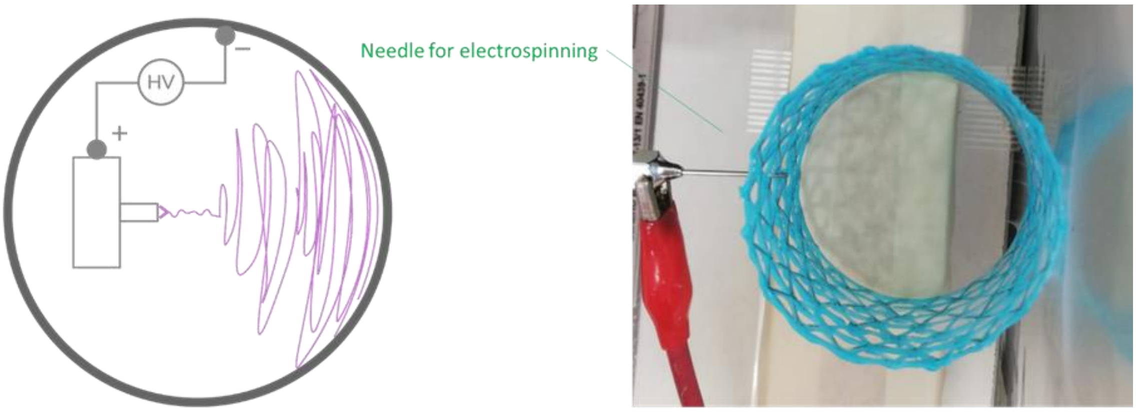

Figure 17: Testing condition for anchoring setup – Top view.

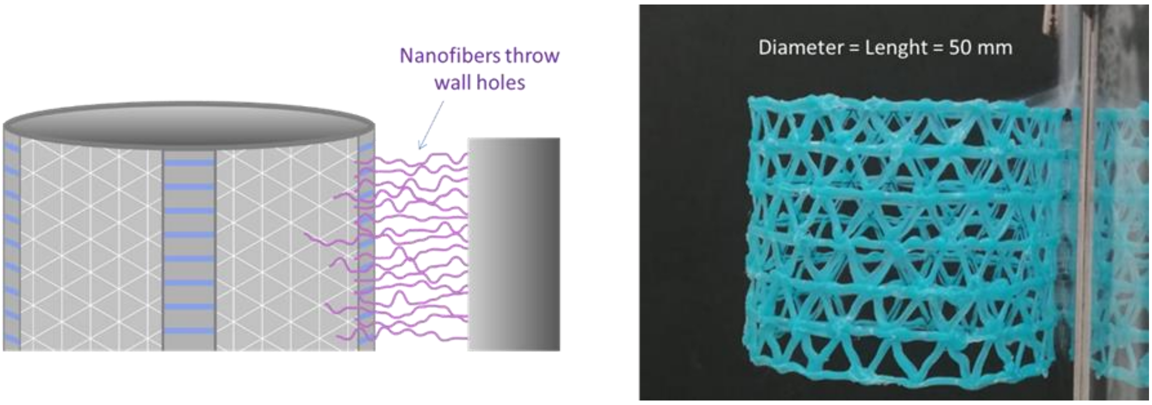

Figure 18: Testing condition for anchoring setup – Lateral view.

Results demonstrate the ability to create a stable mechanical link using nanofiber with a reasonable time with expected growing speed of the artefact: 20 min to fix 50 mm long pipe using a single spinneret.

Mechanical test to measure the maximum force to detach the frame from the wall with an orthogonal force is plotted in Figure 19 with breached structure. Longer time over 20 min did not provide significant mechanical strength increase.

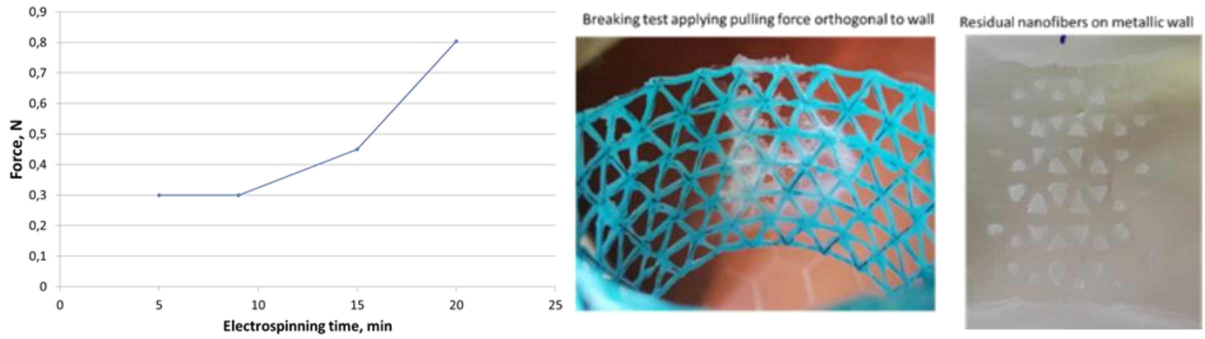

Figure 19: Pulling force test results, pictures and maximum load.

2) A different vertical electrospinning setup was created to study a growing principle of the entire circular robot body, as shown in Figure 20. Even in this case a single needle is used to produce PVA nanofibers. The Teflon disk wounded with copper wire act as collector for nanofibers to create a circular structure for the artefact and moving the disk up will create a tubular structure in the lower part, as shown in Figure 21, after 2 mm vertical movement.
From this test appears a very interesting possibility to create a "growing cone" with nanofibers from the central Teflon screw. This "growing cone" can be used efficiently to collect a lot of nanofibers from a multiple emitter array over a wide surface to reduce the artefact growing time.

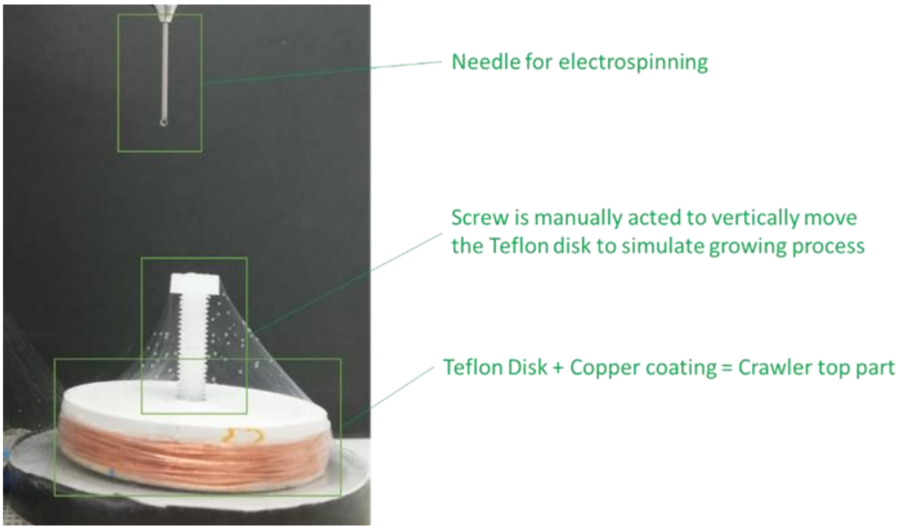

Figure 20: Simple vertical setup for electrospinning growing module – Initial position.

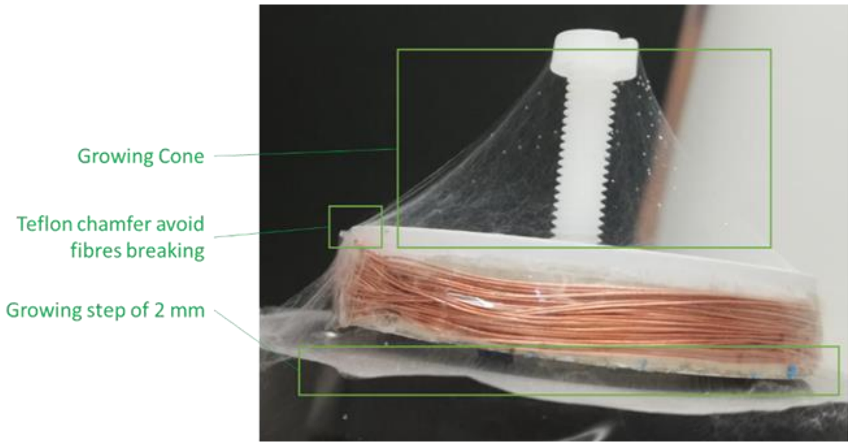

Figure 21: Growing system after 2 mm growth.

Next version of the spinner will include a miniature HV generator able to be installed inside the body itself and a well-shaped Teflon disk integrated with a smooth upper profile to promote the formation of a "growing cone" without sharp edges.

2.5.2 Task 5.2: Multi-filament deposition mechanism

TASK LEADER	PARTNER INVOLVED	DURATION
IIT-CMBR	-	18 months (M7-M24)

This task started together with the WP at month 7. Within the first six months, the activities mainly concerned the study of materials suitable for the deposition by 3D additive manufacturing processes (via FDM technique) and in designing and prototyping a new growing mechanism, compliant with the GrowBot specifications (Deliverable 2.3). More in detail:

- The state of the art self-growing robot based on additive manufacturing technologies was used to test different thermoplastic filaments beside PLA. In particular, we found the commercial PCL promising for its property to melt at low temperature with benefit for energy consumption, system life time, and structural properties, with respect to the previously adopted PLA. We focused the interest in finding the optimal deposition parameters. We also exploited these tests to understand how to change the design for the growing mechanism in order to reach a more reliable and efficient deposition process.
- Novel custom filaments were realized and tested to add functionalities to the robot's body structure. In particular we developed a PCL/Alginate composite able to remediate polluted environment from heavy metals, and a PVDF-HFP (Polyvinylidene fluoride-co-hexafluoropropylene) filament with piezoelectric properties to potentially monitor the stress along the built structure (Figure 22).

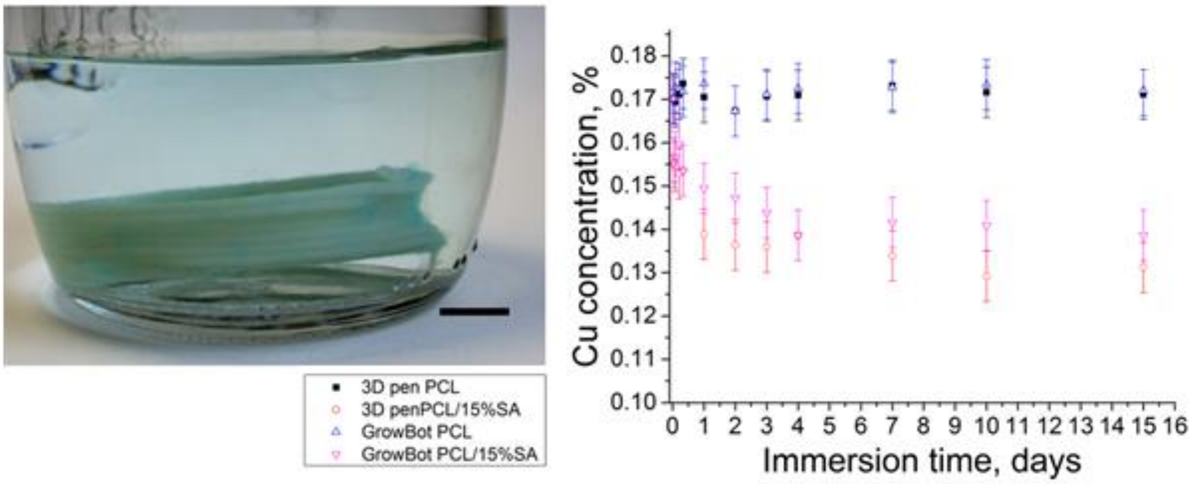

Figure 22: A piece of body structured obtained with the growing robot immersed in 0.17% w/w Cu2SO4 water solution (on the left) (scale bar = 1cm). Kinetics (on the right) over time (2 weeks) of Cu % concentration of structures 3D printed with both a 3D FDM pen and the growing robot, with simple PCL material and with the PCL/Alginate composite.

- Based on these experiments and on the specifications defined in WP2, a new growing mechanism has been designed, having a reduced dimension (with respect to the state of the art version) with consequently lighter weight and a smaller curvature radius for better manoeuvrability in complex environments, as defined in the scenario of use, with confined spaces and to implement coiling behaviour (Figure 23).

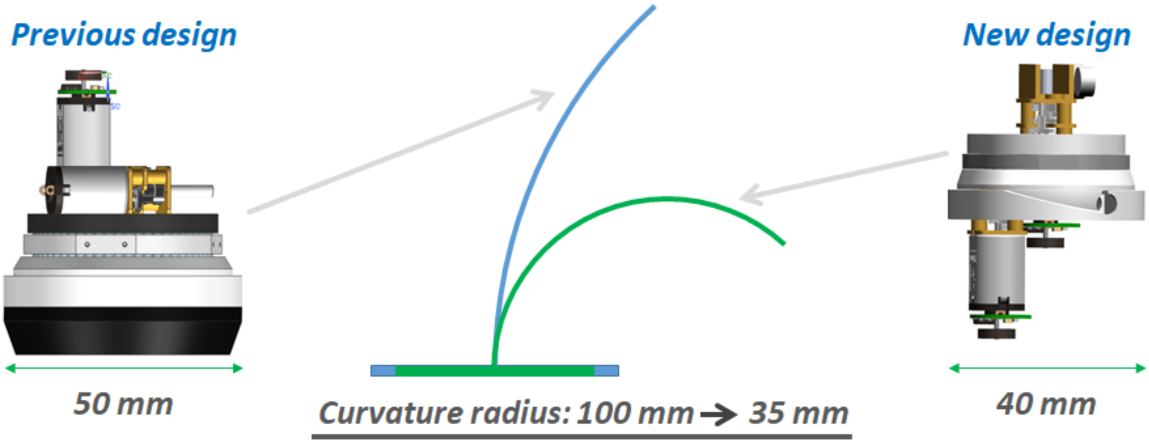

Figure 23: CAD models of the growing mechanism unit. Current and new designs are compared with the expected curvature radius.

- The tip of the robot has been studied to embed sensors suitable to environment exploration and navigation. Sensors for humidity, temperature, light and colour have been added to extract environmental parameters during the exploration to drive the growth. An internal IMU and proximity sensors are also integrated to permit navigation, self-localization and obstacle detection. A Bluetooth communication is expected to decrease the number of wires inside the tubular grown structure.
- We defined a strategy for multi-filament deposition based on a cut-and-merge approach. A dedicated machine, fixed at the base, will be able to combine different types of filaments by segmenting two incoming filaments and merging them into a single multi-type filament, which will be provided to the tip of the GrowBot and extruded by the robot. This way, the body will be composed by a multifilament structure which might combine different properties.
- Other solutions are also analysed to enable multi-filament deposition, including alternative designs for the growing mechanism. In particular, a double extruder mechanism will be developed in the second year of the project.
- With the aim to control and localize the robot during environment exploration, we analysed the kinematics of robots able to growth at the tip as well as the geometrical key parameters imposing constraints on growing robots' workspace, in light of different possible application scenarios. Growing robots are able to move in any 3D direction and can be kinematically considered as non-holonomic mobile systems. We also defined a strategy for finding sub-optimal trajectories toward target poses and by the proposed solution we analysed the affordable workspace of such systems. Finally, we analysed the geometrical key parameters imposing constraints on growing robots' workspace, in light of different possible application scenarios, for better guiding the design of the growing system. The proposed kinematics was applied to a plant-inspired growing robot moving in a 3D environment in simulation, obtaining ~2 cm error after 1 m of displacement (Figure 24). The model will be integrated with the dynamics and tested on the new growing robot in the next months of the task.

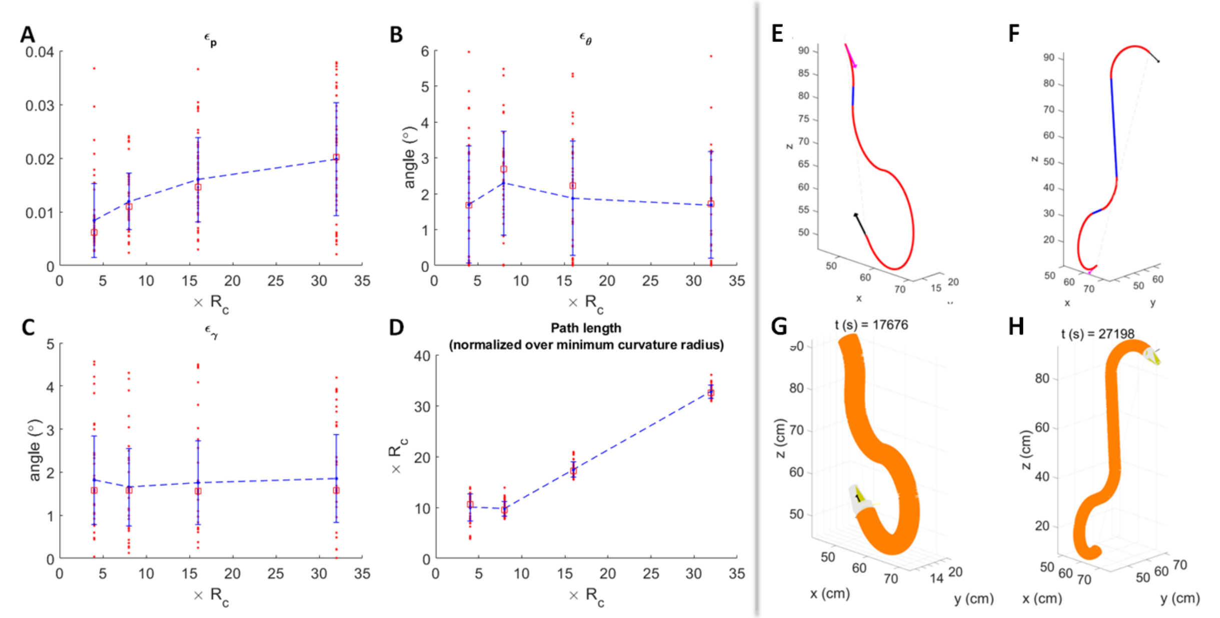

Figure 24: Performance achieved with the plant-inspired growing robot in simulation with representative paths extracted from two groups of simulations. (A) positional error over four groups of simulation 50 repetitions each, having random starting and target position with Euclidean distance 4Rc, 8Rc, 16Rc, and 32Rc; (B,C) orientation errors, heading and pitch, respectively; (D) final path length of the random paths that have been performed, normalized over the minimum curvature radius. In each graph, the red dots are the single simulation and red squares are median values. Mean values are connected by the dashed blue lines. (E, F) Dubins' paths obtained by the proposed path planner, having starting and target position with Euclidean distance of 4 times the curvature radius (E) and 8 times the curvature radius (F). In the Dubin's paths, blue segments are straight lines and red segments are curvilinear paths; the starting tip position and orientation is described by magenta arrow, and target position and orientation is described by the black arrow. (G, H) The output of the simulation is described in the figure by the final robot body (orange) and tip (white and yellow) configuration.

Currently the first new design of the robot is ready and has been manufactured. The growing mechanism has a radius of 40 mm and a minimum curvature radius of 50 mm that permits to wrap around structures with a diameter of 60 mm or greater. The electronic part is under development as well as the tip with integrated sensors. New materials have been investigated, realized and tested in the first 6 months of the project. Particularly the PCL/Alginate composite has been realized and tested in the robot and the results have been collected in the paper Liakos et al. "*Toward self-growing biomimetic robot for heavy metal adsorption by 3D printing polycaprolactone / sodium alginate composites*" submitted to *Materials Chemistry Frontiers RSC*. The kinematic model for the control and localization of the growing robot has also been developed and published in Del Dottore et al. "*Characterization of the Growing from the Tip as Robot Locomotion Strategy*" *Frontiers in Robotics and AI*, 6, 45, 2019.

2.5.3 Task 5.3: Micro-extrusion approach for deposition of viscous polymers

TASK LEADER	PARTNER INVOLVED	DURATION
HZG	-	18 months (M7-M24)

Planned activities and expected results

A controllable circular micro-extrusion approach will be developed and applied for depositing polymer melts or highly viscous polymer solutions or gels developed in Task 4.2. A key component of the custom-made circular micro-extrusion setup will be a temperature and pressure controllable specifically designed multi-lumen die mounted on a 360° rotating extrusion head. This way, the controlled deposition of single or multiple polymeric materials can be achieved in well-defined circular geometries (e.g. layers or core-shell morphology). By alteration of processing parameters, like the feeding pressure and temperature, extrusion head speed and the spatial distribution of the different polymeric materials the creation of numerous GrowBot body architectures will be realized. On demand, addressable UV curing supply positioned at the extrusion head enables a controllable chemical modification of the deposited material, in particular the introduction of covalent crosslinks. Spatial control of the applied extrusion shear stress will be utilized for orienting the macromolecules within the deposition process required for local encoding the actuating capability in the newly formed robot tissue elements. By incorporation of fillers such as silver, carbon black, carbon nanotubes or graphite into the polymer feed conductive material systems will be realized, which are required for interfacing the actuator components with the GrowBot controlling unit and the activation of the thermo-reversible movements.

Expected results: the technology of printable polymeric actuators will be optimized in terms of reduction/minimization of the weight and thereby lowering the overall energy consumption.

Technical activities report

An outcome of the two workshop meetings has been that micro-extrusion requires high energy, which either needs to be stored in GrowBots or needs to be generated by itself. The layout of GrowBots with sufficient energy storage capacities would contribute substantially to the weight of those systems. Accordingly a technology has been looked for, capable to provide high speed of material transport and ideally to have the energy storage system already implemented in the material. Reactive foaming of diisocyantes with oligodiols has been suspected to be such an enabling technology. Furthermore, it could be demonstrated that water blown polyurethane foams from semicrystalline oligodiols could be equipped with a reversible actuation capability. In this context, five commercially available polyurethane foaming kits have been characterised with respect to the pore morphology and thermal transitions suitable for actuation. The expansion capability was explored in model systems providing a confined reaction and foaming area. Here it was explored whether the increase in volume is a function of the diameter of the confining system. Furthermore, in these experiments it was also explored whether these systems are capable to sustain their own weight when expansion occurred in non-confined conditions.

In the strive to gain a better understanding of the mechanics of plants, model systems mimicking the geometry, the arrangement and the function of the single components within a plant have been created. Inspired by the physiology of *Hylocereus setaceus*, whose appearance changes from the base (round shaped) over the middle part (triangular shaped) to the apex (star shaped) 3D printed star shaped soft elastic components were created. These soft components are supposed to provide a similar elasticity as the core part of the cactus. From these components, multimaterial constructs will be synthesized, which are supposed to mimic the plant mechanics. In combination with a directed swelling also directed actuation could occur, in this way these systems are also bridging the research activities with WP 4.2.

Results

It could be shown that commercially available PU foams differed in their reaction kinetics, but pore sizes were quite similar and were around 200 µm. So far, these commercially available systems could not be equipped with an actuation capability as they are lacking a melting transition.

From the experiments of PU foaming, it became apparent that the reaction of PU foaming needs to be optimized towards faster reaction kinetics to gain sufficient solidification and by directed volume expansion.

Concerning the cactus inspired plant model approach 3D printed components were created. Here is could be shown that the printing direction matters and needs to be considered when printing these components. Various star shaped 3D components varying in diameter and width of branch were created and are analysed with respect to their elastic properties. Furthermore, these 3D printed components act as inner core for multimaterial constructs. A current challenge is the synthesis of the multimaterial constructs from these components as the monomers for the hydrogel matrix are absorbed by the printed construct.

2.5.4 Task 5.4: Soft "searcher-like" robot

TASK LEADER	PARTNER INVOLVED	DURATION
IIT-CMBR	SSSA	18 months (M7-M24)

This task has the main aim to develop a robotic device that mimics the apical region of the climbing plant (i.e. the "Searcher"). Among the expected functionalities, the searcher-like robot should perform circumnutation movements and explore the environment by tactile feedbacks.

To better understand the structural properties of the searchers, we performed a series of analysis on the apical part of climbing plants. We applied an image-based approach to reconstruct the shapes of coiled and uncoiled tendrils in order to identify the requirements, and the parameters for the development of a first version of the searcher-like robot.

The prototype is a cable driven robot based on a modular design approach that simplifies both the manufactory and the assembly of the different components (Figure 25).

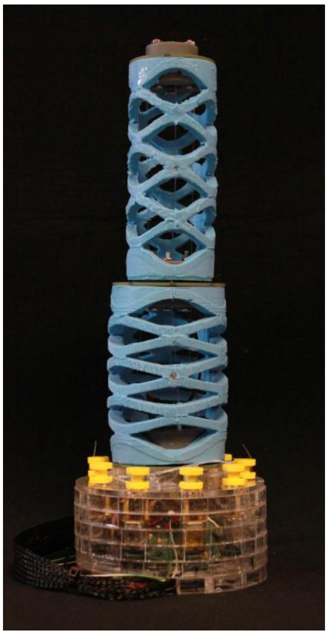

Figure 25: The searcher (with two modules) assembled on the test platform. The actuation unit is encapsulated in the base, while the manipulator consists in the two soft modules connected in series. The full system is cable driven and uses three cables to control each module.

The design of each module is inspired to the wave spring washers commonly used in traditional mechanical applications. The modules – made of a commercially available silicone rubber Smooth-Sil^{TM} 950 (Smooth-on) – can be connected in series by means of 3D-printed disks, provided with holes to allow the passage of cables. The actuation unit consists in a single module containing all the motors (one for each cable), and the dedicated electronics used to actuate the searcher-like robot. The motors (Pololu 986.41:1 micro metal gear motor; Pololu Inc.) are controlled in position by a microcontroller (PIC32MX150F128B, Microchip Inc.) connected to three motor drivers (LV8548MC, ON Semiconductor). Using this configuration, by sequentially pulling the single tendons, it is possible to perform circumnutation movements and, by adding modules at the tip level, to perform coiling and twisting motion. The main drawback of the current prototype is the total weight (around 500g, considering all the necessary electronics and two modules) which is dictated by the presence of a high number of motors to properly control the modules, and the high density (1.24 g/cm^3) of the material used to cast the modules. While we are considering different actuation mechanism (e.g. pneumatic) that might reduce the weight of the structure at the expense of a larger and heavier base unit, so far, we could not find any good alternatives to the material used for the modules. In fact, although the design of the structure helps in reducing the total weight of the material, by choosing a softer and lighter material, we may compromise the structural stability of the robot, which might collapse under its own weight. On the contrary, by reducing the dimensions (i.e. thickness of the wall, and the ratio between the diameter and the length of the modules) and by choosing a stiffer material – to compensate the self-weight –the deformability of the structure may turn out to be unsuitable for the scope.

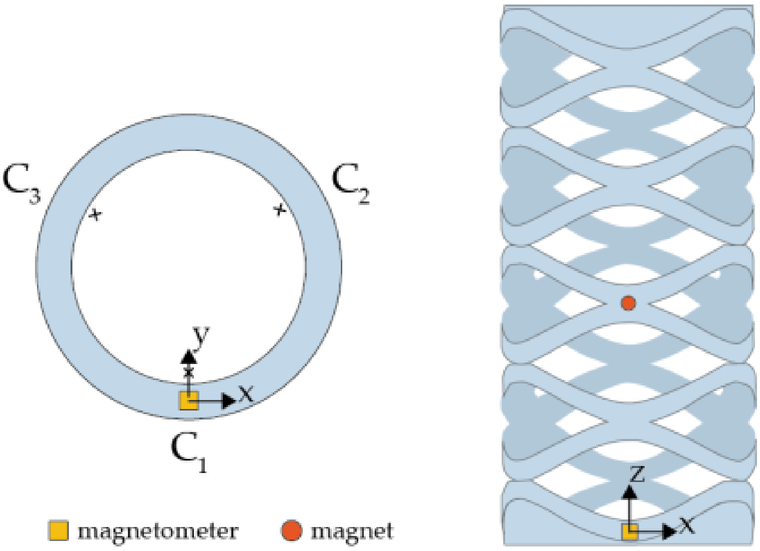

Figure 26: Schematic representation of a module and the integrated sensing. (left) Top view of the module and its cable configuration, and (right) frontal view with the location of the magnet.

Regarding the mapping of the surrounding environment, we did not use any direct exteroceptive sensors (e.g., time of flight, capacitive/resistive touch) that would add the complexity of the data processing and increase the wire routing inside the structure that will affect its deformability. Instead, following a simplification approach, we evaluated the disparity between the position of a reference point – consisting in a magnet embedded in the soft structure – measured by using a magnetometer and the expected position of the same point computed by a mathematical model (Figure 26). The approach is simple and effective since it only requires solving linear algebraic equations and comparing the result with the value returned by the sensor. However, due to the use of a magnetometer, the accuracy of the method is jeopardized by the presence of metallic structures in the surroundings. For this reason, we are considering to implement a different sensing method that can overcome such issue while keeping simple its processing.

The results obtained between M7 and M10 have been accepted as two conference papers[5,6] (one related to the framework used for the image processing, and another of the mapping capability using proprioception) to IEEE 2020 RoboSoft conference.

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[5] Francesco Visentin, Giovanna A. Naselli, Barbara Mazzolai, “A New Exploration Strategy for Soft Robots Based on Proprioception,” 3rd IEEE International Conference on Soft Robotics (RoboSoft), 2020, in Press.

[6] Jie FAN, Emanuela Del Dottore, Francesco Visentin, Barbara Mazzolai, "Image-based Approach to Reconstruct Curling in Continuum Structures,” 3rd IEEE International Conference on Soft Robotics (RoboSoft), 2020, in Press.

The data integration and processing performed in this task serve as input for Task 6.1 as starting point for the definition of the data signal processing framework. The initial prototype, instead, serves as a proof of concept for the behaviour developed within Task 6.2 for which an early integration will be performed during M13 and M14.

2.6 WP6 - Robot sensory-motor architectures

WP LEADER	PARTNER INVOLVED	DURATION
SSSA	IIT-CMBR, TAU, GSSI	18 months (M7-M24)

WP objective – WP6 aims at developing control strategies and sensory-motor behaviours of self-creating robots. Main strategies are based on CNs and thigmotropic responses in climbing plants. The corresponding reactive control algorithms will be implemented on the embedded control unit to properly direct the growing of the robot in real time. In addition to such reactive, local, behaviours, sensory-motor architectures will be defined for implementing plant-level strategies and mechanisms for overall movement and coordination of climbing parts, as studied in WP3.

2.6.1 Task 6.1 – Data signal processing

TASK LEADER	PARTNER INVOLVED	DURATION
IIT-CMBR	SSSA	12 months (M7-M18)

Within the first six months of this task, focus of the activities has been to understand how climbing plants perceive the environment and how to translate their perception in the robots. In particular, we needed to define which kind of perception to embed on each robot, how the sensing elements of the robots can be read and to plan a common middleware control layer between perception and high-level behavioural control in the robotic artefacts. More in detail:

- Commercially available sensors have been investigated for robots navigation and environment mapping. As result, we selected a set which includes: inertial sensors, time of flight, humidity, wavelength and temperature. These sensors are discrete with standard digital or analogic signals. They will be embedded at the tip level and some of them might be integrated in the growing mechanism module. They will be acquired and processed with standard data signal processing techniques (e.g., averaged filter, thresholding).
- Since tactile feedbacks are fundamental all over the tissue of the searchers of climbing plants for perceiving the environment, we investigated different possible approaches for embedding continuous or continuous-like mechano-sensing in the searcher-like robot (see Task 5.4). Two possible alternatives have been analysed: continuum sensing, obtained by using Electrical Impedance Tomography, and the use of discretized sensing elements, by using capacitive-based sensing. Result of this activity is a deep analysis of pro and cons of these alternatives which, in the next months, will help guiding in the selection of the technique to implement in the current and new design of the searcher-like robot. The proper technique for data signal processing will be then adopted.
- In parallel, we investigated on the relation between tactile stimuli and visible responsive behaviour in climbing plants by analysing electrical signals produced by the searcher structures. Preliminary studies have been carried out to evaluate the state of the art, the feasibility of acquiring the signals from the plant and on how to process those data. Key results of these preliminary investigations are the definition of model plants (*Passiflora* and *Phaseolus vulgaris*), the feasibility of the experiments and the experimental protocol. In the next months, the protocol will be refined and multiple experiments will be carried out. The acquired signals will be characterized in terms of frequency, amplitude, decay, and shape and the transduction of such signal will be related to the observable responsive behaviour of the

plant. Such analysis will characterize the data signal processing in plants and will inspire data signal processing for the robotic counterpart in future.

IIT-CMBR and SSSA are currently discussing and collaborating for a first integration and test of the sensory-motor architecture on the searcher-like robot. This step will help defining and testing the middleware, as well as generalize it across the robotic platforms.

2.6.2 Task 6.2 – Robot behaviour based on CNs and tropisms

TASK LEADER	PARTNER INVOLVED	DURATION
SSSA	TAU, IIT-CMBR, GSSI	12 months (M7-M18)

For task 6.2, current efforts have been put towards addressing the first two objectives: (i) identification of the principles underlying plant tropisms and circumnutations; (ii) translating these principles into a plant-inspired behaviour-based control architecture. The major achievement has been implementing the control framework on a simulated modular soft manipulator for reaching in 3D Cartesian space through directional bending.

Work in this regard initiated in month 7 by analysing the state-of-art. Tropisms are the directional growth of a plant in response to an external stimulus. Due to lack of a nervous system, these movements operate on a severely elapsed timescale of perception-action loops. Although, this results in a plant's sessile nature, but it is this very characteristic that facilitates their ability to process environmental signals and with greater sensitivity and discrimination than the roaming animal. A detailed study by Trewavas[7] provides a computational insight to how movements are generated (Figure 27a). Specifically, he states that information processing capabilities in plants comprises of two key-aspects: *(i) closed-loop between perception and action* – the plant receives a wide array of signals arriving from the surrounding local environment. The biomechanics of signal reception, explained in detail at the tutorial meeting in Tel Aviv, relies on the temporal integration of perceived data. This can then be distinguished and prioritized in order to accurately occupy local space, change its phenotype as it grows, forage accurately for resources, and ultimately achieve optimal growth; *(ii) inter/intra-plant synchronization* – the plant receives information at different levels of hierarchy including cell, tissues, etc. As the strength of the connection between the hierarchical levels weakens, the plant becomes more plastic to its surrounding environment. Discussions on hierarchical morphological levels of attachment systems in the project meeting in L'Aquila demonstrated how information flow at different levels of hierarchy would result in a specific behaviour, a principle applied subsequently.

The control architecture is formulated by translating the above-mentioned principles: each actuator of the soft robotic system (which must also be equipped with sensing capabilities) is considered a reactive agent that closes the loop between perception and action without any planning. The relation between perception and action operating spaces is constrained to a linear equation, in line with the Bunsen-Roscoe reciprocity law[8] obeyed conservatively by phototropic motions. This is possible: (i) because the arrangement of the actuators is generally such that every activation pattern which results in a bend has a characteristic radius of curvature, i.e., *one-to-one* mapping; (ii) by operating the activation limits from either max to min or vice versa, i.e., *monotonic* function. Consequently, the overall artificial system is equivalent to a distributed architecture of multiple reactive modules (Figure 27b). Its behaviour is given by the summation of weighted linear equations, where, the weight for each module can take a binary value. The novelty of this architecture lies in exploiting the notion of information flow, such that, the activation of a reactive module at a time instance also activates

[7] Trewavas, A., 2009. What is plant behaviour?. Plant, cell & environment, 32(6), pp.606-616.
[8] Blaauw, A.H., 1909. Die perzeption des lichtes. Recueil des travaux botaniques néerlandais, 5(2/4), pp.209-372.

neighbouring modules. This way the system is able to generate coordinated unique behaviour in a quick and synchronized manner. Consequently, the modulation of a single parameter (information flow) within the system can provide a wide array of behaviour useful both for local and global manipulation of the environment. Note that biologically, the magnitude of activation for neighbouring modules is less than the initiating module.

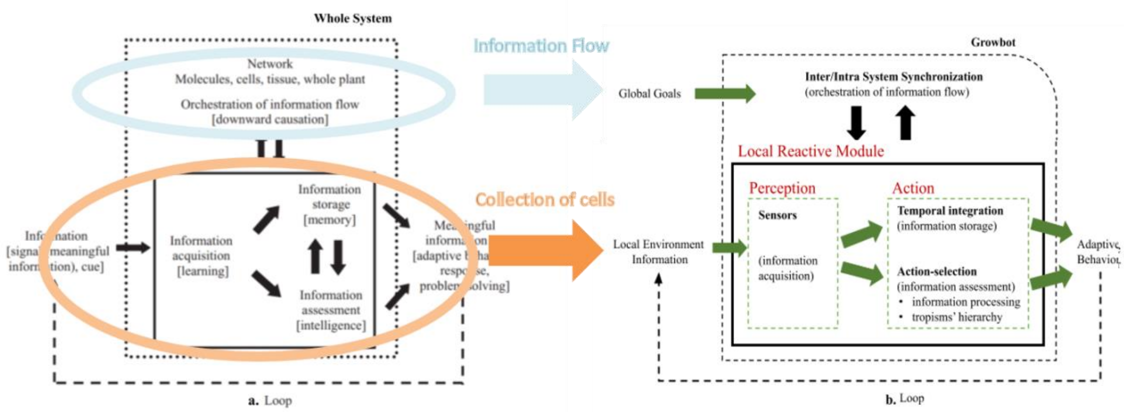

Figure 27: a) A schematic representation of information processing capabilities in plants inpsired from Trewavas[1] b) The proposed architecture.

Initial testing of the proposed architecture was conducted on an open-source[9] simulation of a six-module soft robotic manipulator (Figure 28a) for reaching in 3D with plant-like movements. The simulator models the kinematics of a soft modular manipulator through constant-curvature approximation from the length of the actuator to the 3D cartesian coordinates. If the actuator variables and their corresponding end-effector variables are represented by vector $\boldsymbol{x}$ and $\boldsymbol{q}$, respectively, then according to the proposed architecture, the overall system behaviour is,

$$q_i = \sum_n \alpha_i * J\big((x - \delta x)_i\big) * w_i \quad (1)$$

where, n corresponds to the total number of actuators; q_i is the end-effector position of the i^{th} actuator; α_i is a scaling factor whose values can be assumed from the range of 0 to 1, such that, 1 implies an initiating agent and lesser values correspond to neighboring agents. The value is decreased in proportion to the distance with-respect-to the initiating agent; w_i is the Boolean weight associated with each actuator that is activated to 1 if and only if the distance of the i^{th} actuator is within a certain distance to the external stimulus.

The algorithm runs on a loop that constantly monitors the presence of an external stimulus within the reachable workspace of the manipulator. When this is true, the index of the actuator closest to the stimulus, i, is calculated and is activated along with neighboring actuators in the vertically higher direction. In response, the system starts to bend towards the stimulus. The direction and number of neighboring actuators that are activated controls the type of bending exhibited by the system. For example, Figure 28b shows that by selecting a single neighbour in the vertically higher direction, the manipulator reaches the external stimulus through a whole arm grasp. Figure 29 demonstrates that: (i) the curvature of the grasp can be increased by increasing the number of neighbours activated in the vertically higher position. In this figure, two extra neighbours are activated; (ii) the direction of bending is dependent upon the direction of the stimulus, similar to the biological phenomenon.

[9] Rolf, M. and Steil, J.J., 2012, October. Constant curvature continuum kinematics as fast approximate model for the Bionic Handling Assistant. In 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems (pp. 3440-3446). IEEE.

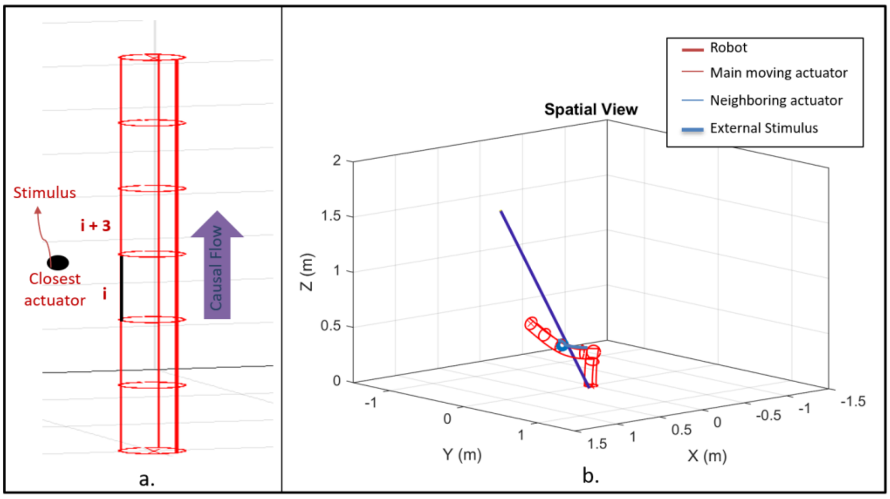

Figure 28: A modular soft robotic manipulator reaching an external stimulus in 3D Cartesian space through directional bending inspired by plant-like movements.

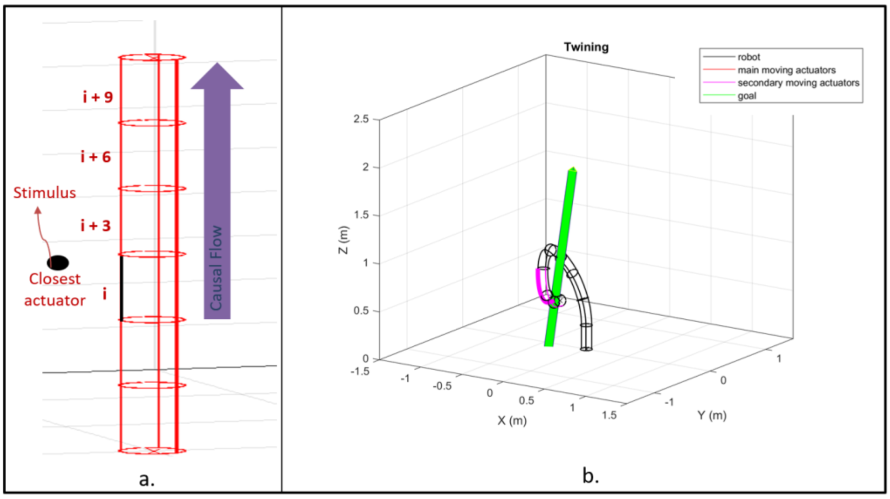

Figure 29: A modular soft robotic manipulator reaching an external stimulus in 3D cartesian space through directional bending inspired by plant-like movements. In contrast to the previous result, the radius of curvature is increased due to the activation of additional two actuators. Also, the direction of bending is dependent upon the direction of the stimulus.

2.6.3 Task 6.3 – Robot sensory-motor architecture

TASK LEADER	PARTNER INVOLVED	DURATION
SSSA	IIT-CMBR	18 months (M7-M24)

For task 6.3, current efforts have been put towards addressing the following objective: building upon the algorithm introduced in task 6.2 to integrate a decision-making component that allows the system to switch between different behaviours to achieve a task. In particular, keeping the same problem presented in Task 6.2, the major achievement has been to allow the artificial system to explore the environment through directional bending until a support is found. Thereafter, it starts to wrap around the support through circumnutation.

Circumnutation is a hallmark plant movement used to interact with complex natural environments. As thoroughly discussed in the introductory meeting for the project, this refers to oscillatory movements in plants causing it to rotate around its central axis induced by unequal growing rates on opposite sides of the plant. Interestingly though, it is not clearly defined in either category of plants movement, i.e., tropisms or nastic motions. In one school of thought, it is postulated that this motion is controlled only by internal factors and backed by experimental investigations that demonstrated ion flux oscillations in the elongation zone of the root. In another school of thought, mathematical formulations and subsequent experimental studies demonstrate this motion to be the result of gravitropism overshoots. Currently, the most accepted theory considers circumnutations induced by both an internal oscillator and gravitropism[10], and also in line with our findings.

Work in this regard began in month 7 after the development of the control framework developed in Task 6.2. In order to exhibit circumnutation, the artificial system must first find a support, which is implemented through the approach discussed in task 6.2. Specifically, the algorithm runs on a loop that constantly monitors the presence of an external stimulus within the reachable workspace of the manipulator. When this is true, the index of the actuator closest to the stimulus, *i*, is calculated and is activated along with neighbouring actuators in the vertically higher direction. In response, the system starts to bend towards the stimulus. If the manipulator is able to touch the stimulus, it considers it as a support. Then the task is to wrap itself around this support. Interestingly, the algorithmic implementation requires only the addition of a simple if-statement to the developed linear control framework, through which the closest neighbour in the horizontal vicinity is also activated. This results in an increased information flow throughout the system, leading to reduced plasticity to the environment and is exhibited as the circumnutation movement, as highlighted in Figure 30.

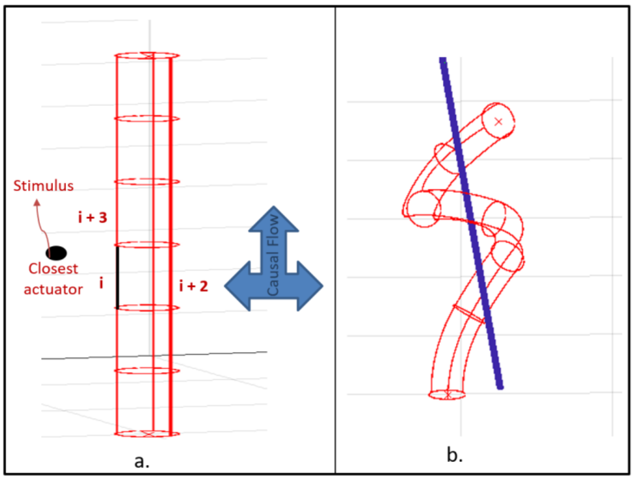

Figure 30: A modular soft robotic manipulator reaching and wrapping around an external stimulus in 3D Cartesian space through directional bending and circumnutation, inspired by plant-like movements.

2.7 WP7 - Plant-robot interfaces for bio-hybrid energy generation

WP LEADER	PARTNER INVOLVED	DURATION
BIOO	IIT-CMBR	18 months (M7-M24)

WP objective – WP7 aims at i) implementing an energy functionality by using real plants and MFCs used to recharge GrowBots; and; ii) developing interfaces between real plants and GrowBots to convert environmental mechanical energy (wind & rain) into electrical energy harvested, creating a “plant-robot, bio-hybrid symbiosis”.

2.7.1 Task 7.1 Microbial fuel cells (MFCs) for topsoil energy harvesting

TASK LEADER	PARTNER INVOLVED	DURATION
Bioo	-	18 months (M7-M24)

[10] A. H. Brown, "Circumnutations: From Darwin to Space Flights," Plant Physiology, vol. 101, pp. 345-348, 1993.

To harvest energy from the underground structure of the plants, microbial fuel cell (MFC) technology will be used. MFC are bio-electrochemical systems that drive an electrical current by using specific bacteria properties contained in the fuel cell, therefore permitting bio-electricity production. Such specific bacteria colonies, which can be naturally found in the soil, metabolize organic carbon-based substances, while releasing electrons during such oxidation reaction.

Combining MFC technology with a soil matrix leads to soil-MFC technology, where the organic compounds found in the nutrients that the soil contains are used to power the biological fuel cell. In order to simplify the system and control the effects resulting of the soil, before the introduction of the plant in this system, this has been the focus of the efforts during M7-M12.

Combining MFC technology with plants leads to PMFC technology (Plant-MFC), where the continuous source of organic compounds dissolved in the medium are not externally dosed as in standard MFCs, but comes from the proteins and sugars generated during the photosynthesis and after excreted by plant's roots, in a process called rhizodeposition. This section will be studied in M12-M24.

Our preliminary results during M7-M12 have been focused on studying the electricity generated on soil-MFC, in order to understand and control all the variables, before the introduction of the plant on the soil, which due to the plant's rhizodeposition will provide to the biological cells a continuous source of nutrients to the electricity-generating bacteria, which will lengthen the durability of the biological cells.

Experimental design and Methodology

The preliminary tests have been carried out in PET cylindrical tubes of 1 cm of radius, a height of 15 cm which corresponds to 47 cm^3 (Figure 31). The anode has been constructed with 10 cm^2 of graphite plate (2 cm x 5 cm) and the cathode with 4 cm^2 of carbon felt (1 cm x 4 cm). The soil selected to perform these preliminary experiments have been universal potting soil, compost ratio 1:1. The characterization has been performed using a Potentiostat Dropsens® µSTAT 4000P. The method Linear Sweep Voltametry have been used in order to plot PxVxI curves to characterise the different arrangements of the biological cells (Figure 32).

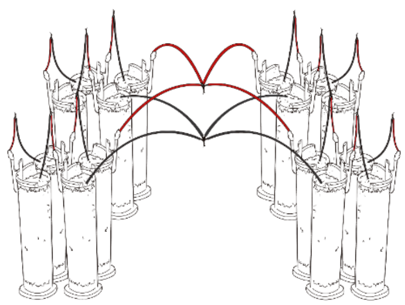

Figure 31: Array of 16 biological cells. It consists in 4 sets of 4 biological cells. The 4 cells compromising each set are connected to each other in a series array. The 4 sets are connected to each other in a parallel array. This system will be described from now onwards as 16 cells (4S = P).

Preliminary Results obtained

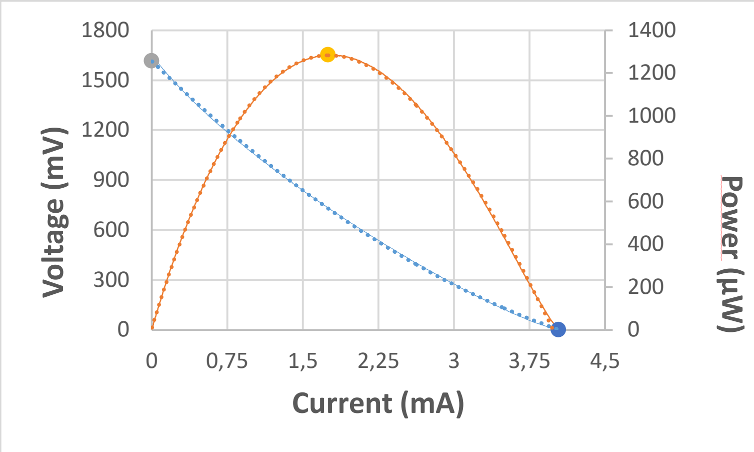

Figure 32: PxVxI curves of the array of 16 cells (4S = P) at day 7.

Table 5. Summary table containing the results obtained from Figure 32. The results are given as per anodic surface.

	OCV (mV/cm^2)	PMAX ($\mu W/cm^2$)	IMAX (mA/cm^2)	VMAX (mV/cm^2)	ISC (mA/cm^2)
16 cells (4S=P)	10,09	8,03	$1{,}09\cdot10^{-2}$	4,59	$2{,}53\cdot10^{-2}$

Where:

OCV = Open circuit voltage (Voltage when intensity is 0)

Pmax = Highest power obtained by the system.

Imax = Intensity at highest power obtained by the system.

Vmax = Voltage at highest power obtained by the system.

Isc = Intensity at short circuit (Intensity when voltage is 0)

With the results electrical results obtained which are summarized in Table 5, it has been possible to lit low-power LED prototypes. After further examination and implementation of the plant system (M12-M24), the functionalities of GrowBot that can be expected to be powered by this technology can be low-power humidity and temperature sensors, which can provide information of GrowBot surroundings. All of these future findings and a further detailed report regarding the energy application that this system can supply will be reported in D1.5 – Periodic Activity Report II.

2.7.2 Task 7.2 Plant-robot interfaces for energy harvesting

TASK LEADER	PARTNER INVOLVED	DURATION
IIT-CMBR	-	18 months (M7-M24)

Explanation of the work carried out: During the reporting period month 7-12, the work on task 7.2 focussed on the understanding on how to build modules of flexible artificial “leaves” (flexible electrodes to be installed at natural plants that enhance contact electrification of the plant and the overall energy output) and how to assemble them on plants. Therefore, flexible electrodes have been produced in IIT based on a triple layer of polyethylene terephthalate (PET), indium-tin-oxide (ITO)

and silicone rubber based on a material analysis in our preliminary results published in Advanced Functional Materials, 28(51), 1806689. The materials were laser-cut into defined shapes and equipped with an attachment system that allows assembling the electrodes at the petioles of the leaves of a plant. By constraining the electrodes to the petioles, mechanical motion for example such as due to fluttering in the wind produces mechanical contacts between plant leaves and the artificial leaf electrodes that are converted by the plant and the artificial leaves into electricity. IIT developed a circuit that enables to charge eight individual capacitors by the current produced by up to eight leaves. This circuit was characterized in terms of functionality and impact on the system and used to evaluate energy generation of plants at different wind speeds. IIT conducted experiments together with ALU-FR at the botanical garden at ALU-FR where a phytochamber with controlled ventilation system provided the opportunity to investigate energy harvesting of the plants as function of wind speed and enabled investigation of impact of other outdoor relevant parameters like humidity and temperature. The results showed that the power output scales with the wind speed and wind direction. In addition, the power output multiplies with the number of leaves indicating that it is possible to upscale energy output by using multiple leaves of a tree. The achieved power outputs were found in the range of up to 350 nW for eight leaves. The joint results of IIT and ALU-FR are currently (status of the 31st of January 2020) submitted as a full article for consideration in “Energy & Environmental Science” (Figure 33).
In addition, the electrode that penetrates the plant tissue to several electrode types for harvesting has been varied and several electrode types in particular thin film surface electrodes, standard Ag/AgCl electrodes and various invasive (tissue penetrating) metal electrodes have been investigated in terms of their influence on the voltage generation. Yet, highest output was obtained from electrodes penetrating the tissue and no adverse effects on the plants have been detected so far, the analysis is in progress. Materials (a silicone rubber-based electrode and a basic circuit for harvesting energy from plants using the triboelectric effect) have been exchanged with WP partner Bioo for a potential combination of both plant-based energy harvesting technologies that has potential to improve the overall power output as both techniques are complementary while using different approaches.

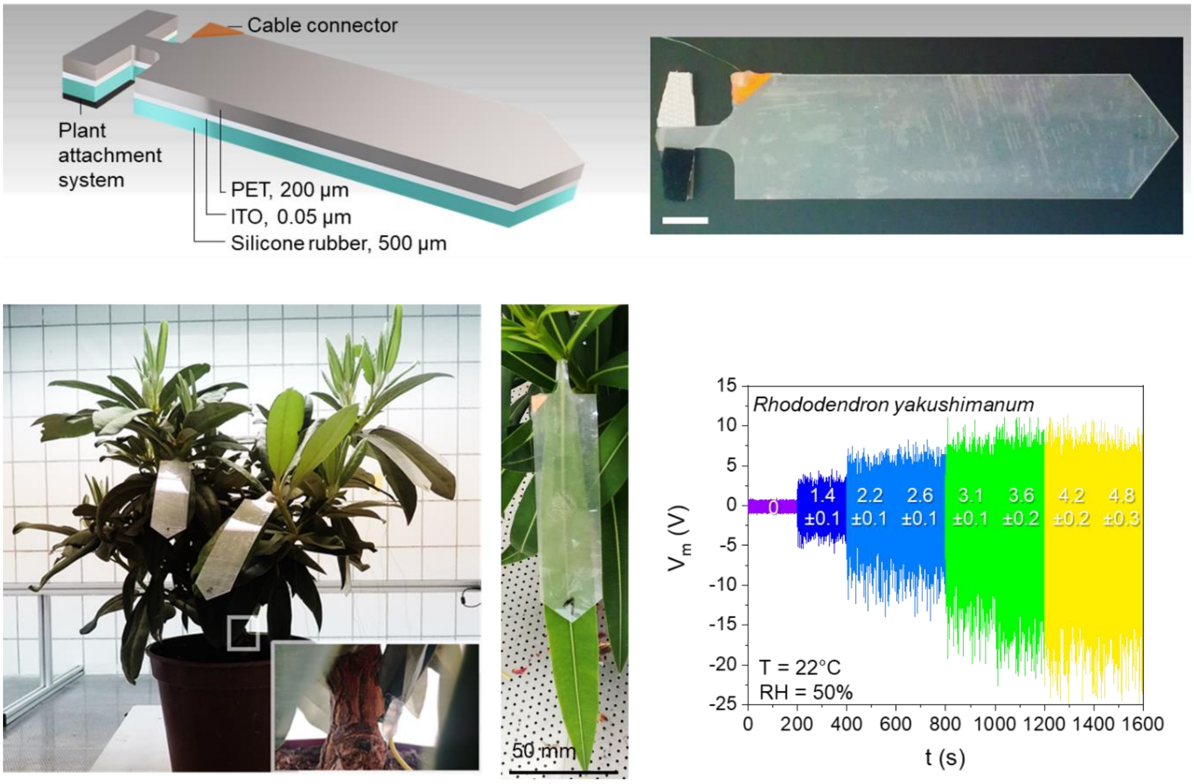

Figure 33: The upper illustration and image shows the structure and dimensions of the artificial silicone rubber, PET, and indium tin oxide-based leaves that are used to enhance the overall plant energy output. The lower left

images show the installation of the leaves on a *Rhododendron yakushimanum* (the inset shows the tissue electrode that is used to harvest energy generated by the plant). The graph on the right shows as example for the plant energy conversion, the voltage signals measured at the tissue electrode as function of wind speed confirming that higher wind speeds lead to higher voltage amplitudes and hence the energy that can be harvested.

Overview of the progress towards the objectives of the action: The results and data obtained are a clear confirmation of the possibility to harvest energy by plants using the described approach. In addition, they show that wind energy can be translated into electricity. From the data it can be expected that the power output can be further improved by tailoring parameters of the system which is necessary to provide sufficient energy for powering compartments of the GrowBots. Although this requires substantial fundamental investigation, which cannot be fully performed within this project period, the results allow an initial redesign of the materials installed at the plants to improve output generated (e.g., by reducing the electrode weight and increasing vibrational motion). In addition, the data provides information on how to layout the electronic harvesting circuit that accumulates energy over a certain period and then powers a sensor (e.g., a resistive thermometer). The electronic design including a sensing task will be a key focus in the next project period.

Summary: Artificial silicone rubber-based leaves have been designed and produced and installed at plants for energy generation. An electrical circuit has been developed for data acquisition of energy generation of up to eight leaves. First tests of energy harvesting plants have been carried out as function of wind speed in joint experiments between IIT and ALU-FR. The results that were send for publication indicate the general feasibility to convert wind energy by plants and to store the generated electricity. The data will be used to design an energy harvesting circuit that accumulates energy for a sensing task of GrowBots. For directly powering sensors, the power output requires further improvements that need in depth fundamental investigation of the plant-hybrid energy conversion phenomena.

2.8 WP8 - Integration

WP LEADER	PARTNER INVOLVED	DURATION
IIT-CMBR	All	12 months (M25-M36)

WP objective – WP aims at releasing the final prototypes of GrowBots (TRL 4). Three different growing robots will be integrated with different functionalities and for different aims. The integration process will be held at the IIT facilities, where the final prototypes will be located. Periodic integration meetings involving all the partners will be organized at the IIT laboratories during this working period to guarantee a smooth coordination and integration phase.

Activities will be started on M25 (1st January 2021).

2.9 WP9 – Experimental validation

WP LEADER	PARTNER INVOLVED	DURATION
CNRS	All	19 months (M30-M48)

WP objective –WP aims at carrying out continuous and later validations towards final GrowBot prototypes at two overall levels: i) biological validations (9.1&9.2), where developed platforms will be used to implement climbing plant control strategies and verify capabilities that imitate plant behaviour; and later ii) application-oriented validations (9.3&9.4), where the three GrowBots will be tested in simulated lab scenarios to verify their capabilities to move and explore in highly unstructured environments under different tasks.

Activities will be started on M30 (1st June 2021).

2.10 WP10 – Community building

WP LEADER	PARTNER INVOLVED	DURATION
CNRS	All	48 months (M1-M48)

WP objective –WP aims at consolidating a ground-breaking and disruptive community on plant-inspired robotics technologies, strongly grounded on an inter-disciplinary character. GrowBot will lay the foundational activities to make this community active within, outside and beyond the project and within and among specialists in biology and technology.

Our activities will address diverse communities from connecting with kids, schools, young scientists and the general public to meetings and workshops at established scientific institutions along with published theme submissions and collected papers. The innovatory results now emerging from the GrowBot project will not only serve to contribute to new technologies but will also stimulate new ideas, methods and lines of research for energizing biological research – what we call "reverse biomimetics". For these reasons both the technological and biological communities will benefit from our community building activities linked to the project. Finally, collaborative research and our activities with scientist colleagues along with their community building activities in tropical countries e.g. (Brazil, French Guiana, Cameroun, D R Congo) where climbing plants are a common but probably undervalued resource, will foster the realisation and importance of plant diversity as an important and potentially "useful" resource.

List of deliverables released:

- [IIT-CMBR, M7] - D10.1 GrowBot Platform
- [IIT-CMBR, M12] - D10.2 Prizes
- [CNRS, M12] - D10.3 Workshops, Working Groups, Editorial Initiatives

2.10.1 Task 10.1 GrowBot on-line platform with open access

TASK LEADER	PARTNER INVOLVED	DURATION
IIT-CMBR	All	48 months (M1-M48)

This task aims at setting up a platform to link different communities that work on plants from different perspectives and aims.
There is, in fact, a growing scientific community that addresses and studies plants for pursuing innovation in different fields. This includes several actors, such as, among many, biologists, especially interested in plant environment interaction and stimulus-signal transduction and interpretation; engineers and material scientists, who intend to imitate plant functionalities, energy efficiency, geometries, strategy of movements, etc.; architects and designers, who exploit plants' beauty and aim to integrate green energy production in their work. GrowBot aims at sharing this vision and changing the way to see plants in the future. This process requires a merging of different disciplines (including biology, materials science, engineering and robotics), which goes beyond the typical boundaries of a traditional robotic manufacturing approach
In this scenario, the GrowBot Platform plays a strategic role in representing a reference tool for this growing community.

The platform includes a collection of experimental protocols and set-ups, a list of tools for analysis of plant features, links to other related projects, tutorials, video, news, and a list of upcoming events related to plants (Figure 34). The contents are continuously updated.

The GrowBot platform is hosted on the project website (www.growbot.eu) under the "Community" section.

GrowBot Platform, as the entire project website, will be updated and maintained within and beyond GrowBot project, managed by IIT.

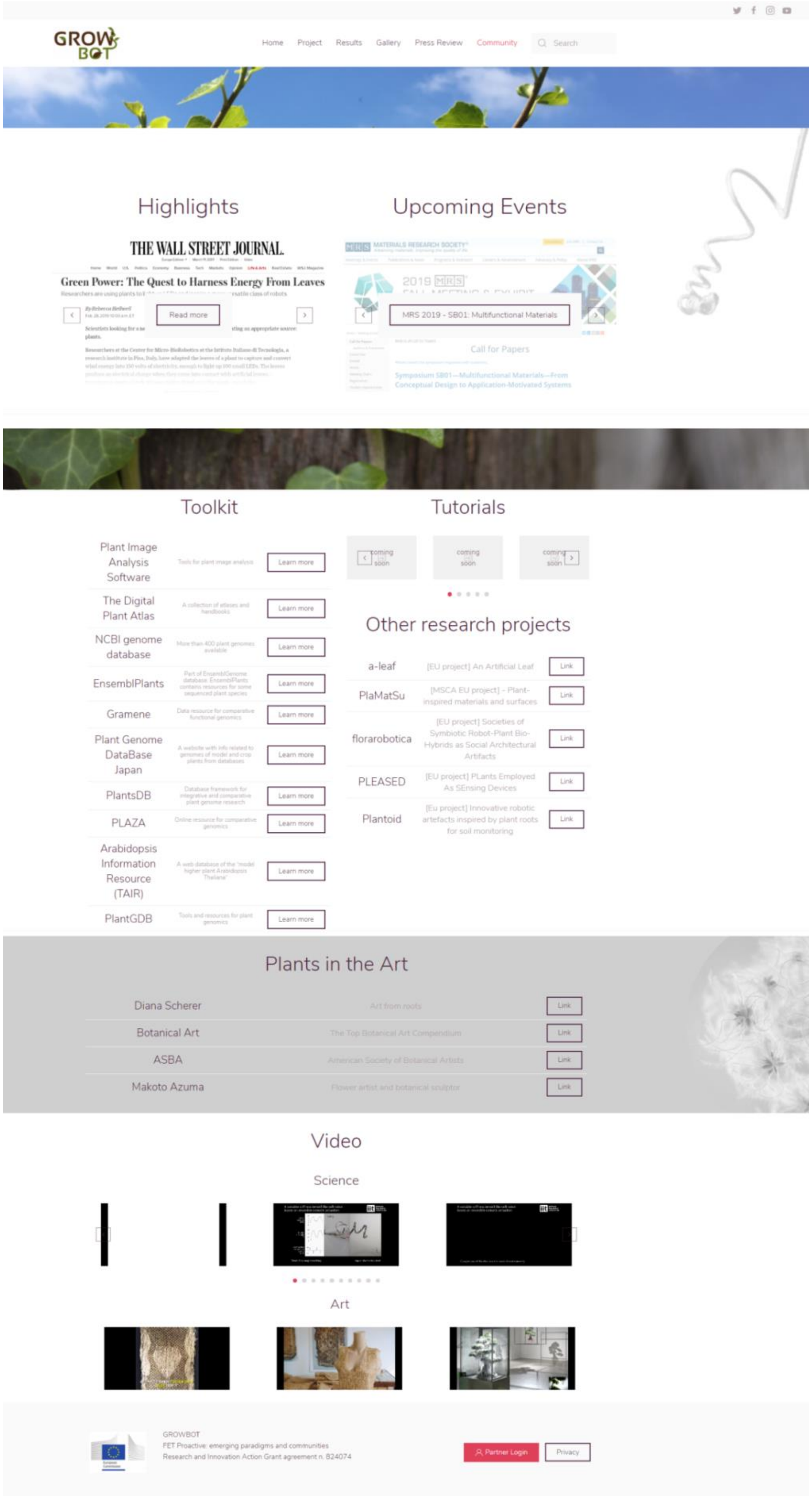

Figure 34: Screenshot of the Community page on the GrowBot project website.

IIT-CMBR released, at month 7, the relative deliverable “D10.1 GrowBot Platform”.

2.10.2 Task 10.2 Prizes

TASK LEADER	PARTNER INVOLVED	DURATION
IIT-CMBR	All	35 months (M2-M36)

This task aims at promoting initiatives to enlarge the scientific and technological community around plants science, bioinspired materials, and robotics by launching two calls for ideas in the form of prizes for performing selected activities at European level.

The calls are planned to be launched twice during the project on topics that not represent the core activities of the partners, more specifically: i) the first call (prize I – 30 k€) focuses on biological issues relevant to GrowBot; ii) the second call (prize II – 30 k€) aims at proposing technological solutions for specific and assigned application domains.

The calls for ideas are dedicated to young researchers, especially PhD students and young PostDocs (max 35 years old), to support career promotion and enlarge to topics not covered within GrowBot but relevant to the project aims.

The first call for ideas was launched at month 5 (Figure 35). The topic of the call was deeply discussed (especially with partners involved in the biological activities, CNRS and ALU-FR) and defined in the occasion of the kick-off meeting, held in Pisa on 30-31 January 2019.

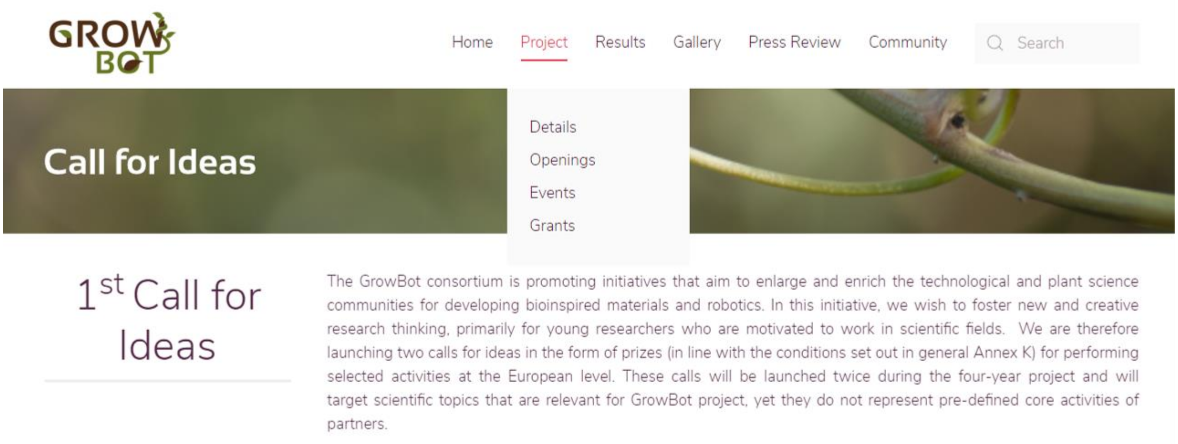

Figure 35: Screenshot of the introduction section of "First call for ideas" page.

The selected topic was: *In situ* growth dynamics of vines and lianas in the forest canopy.

(Abstract - The core element of the GrowBot project is to understand how climbing plants move and translate this principle into a new generation of climbing artefacts. However, a very few studies document how vines and lianas behave in the forest canopy. This topic addresses issues relating to the development of new tools and methodologies for the observation of the growth dynamics of lianas in the forest canopy. Currently, the traditional approaches include pictures or movies taken from ground or air. The main drawbacks are related to the difficulty of access, resolution of features, visualizing amid stem and leaf clutter, limited ranges of studied canopies and expense of observing more than a few locations using canopy rafts, cranes or climbers.)

Candidates were invited to address the topic by considering all potential options and methods. Improvements over current approaches were strongly encouraged and suggestions for new or unconventional approaches were more than welcome.

The proposals were evaluated by a commission composed of the GrowBot members of the Scientific and Management Board (SMB), the Innovation Management Board (IMB), and the Advisory Board on the base of novelty, feasibility, proposed CV and coherence with the GrowBot objectives.

The winner of the first call for ideas was: Mrs Begüm Kacamak with MOLIDRO (Monitoring tropical lianas with high resolution drone Systems).
Mrs Begüm Kacamak, selected the Agricultural Research Centre for International Development (cirad) of the Centre National de la Recherche Scientifique (CNRS) in Montpellier as host institution.

Unfortunately, due to bureaucratic issues, the activities started with a delay of three months (1st November 2019) respect to the scheduling. The research activity is planned to be completed at month 19 (July 2019).

A video contribution of the winner proposal is available online on the Project website:
https://www.growbot.eu/project/grants/21-first-call-for-ideas

IIT-CMBR released, at month 12, the relative deliverable "D10.2 Prizes I".

2.10.3 Task 10.3 Scientific events and editorial initiatives

TASK LEADER	PARTNER INVOLVED	DURATION
CNRS	All	37 months (M12-M48)

We outline the main community building events since the start of the GrowBot project for biological and technological communities, both in academic and non-academic spheres. We focus on communication among peers as well as understanding and visibility to future researchers at undergraduate and post graduate levels. Finally, we are also planning a range of prospective events and initiatives for understanding among non-academic communities.

This tasks has been started on month 12 (December 2019) and during the first month, CNRS has presented and discussed with GrowBot partners the actions for 2020 and beyond.

In the following, the list:

1) Following the special Frontiers volume based on the RSS Workshop in Freiburg in 2019. A multidisciplinary edited volume for a "biological audience" in a biological interdisciplinary review such as American Journal of Botany, Royal Society Interface, New Phytologist, Current Biology. All these journals have supported and published works on climbing plants recently.

We will target one Journal for a special volume that will explore how climbing plant research during our project has led to the development of new technological artefacts, following a work shop conference at a "biological venue – possibly the Linnean Society of London and or Kew Gardens.

Secondly, we will also plan cross- and multi-partner "opinion point" papers in the major Journals, when our collaborations make break-through findings.

2) June-July 2020, Field Summer School and Field Laboratory in the Tropical Rain Forest

CNRS will hold a summer School for undergraduate and post graduate students in French Guyana for 3 to 4 weeks. The event will include data gathering and field measurements and will provide a working experience in the tropics and hands-on experience in scientific field craft, identification and field measurements. Students will also be encouraged to produce their own blogs, links to social media and visual documentaries of their experience. The event will train students how to work on scientific projects in the tropics and boost their CV credentials for applying for masters and thesis subjects for this and related fields.

3) March 2020 GrowBot lectures and Tutorials for students of the German Academic Scholarship Foundation. Staff ALU-FR and Invited GrowBot partner speakers will provide lectures with the aim of creating a workshop for students from this Foundation to consider GrowBot forms and functions. The event will mirror the field summer school in French Guiana and providing a rich source of interaction between students and GrowBot partners.

4) July 28-31 GrowBot will be event sponsor for Living Machines 2020, Freiburg, Germany – July 28-31, 2020.

The main conference will take the form of a three-day single-track oral and poster presentation programme, 28^{th} to 31^{st} July 2020, hosted at the Botanical Garden of Freiburg, Germany

The conference programme will include five plenary lectures from leading international researchers in biomimetic and biohybrid systems, and the demonstrations of state-of-the-art living machine technologies. The full conference will be preceded by up to two days of Satellite Events hosted at the University of Freiburg, Germany.

5) March 2021, GrowBot meeting and Field excursion hosted in French Guyana.

CNRS is planning a meeting and Field excursion in French Guiana. It will last for one week and involve two days of meeting, talks and workshops in scientific Institutes in French Guiana. Biologists and technology researchers will meet researchers based in French Guyana and visit Tropical rain forest sites and observe the biological diversity of vines and lianas at first hand. Visits and overnight stays will be planned at sites including the forestry research station at Paracou and the more remote field camp at the Piste de St Elie.

6) Following the success of GrowBot partner interactions with the general public (See also WP 11), particularly for kids and young persons, we are planning an ambitious project for artist and illustrator colleagues to write a "Bande Désigné" book on the GrowBot project – from the observations of the plants in the tropical rain forest to brainstorming ideas of scientists to integration of ideas, construction and validation of the final artefact.

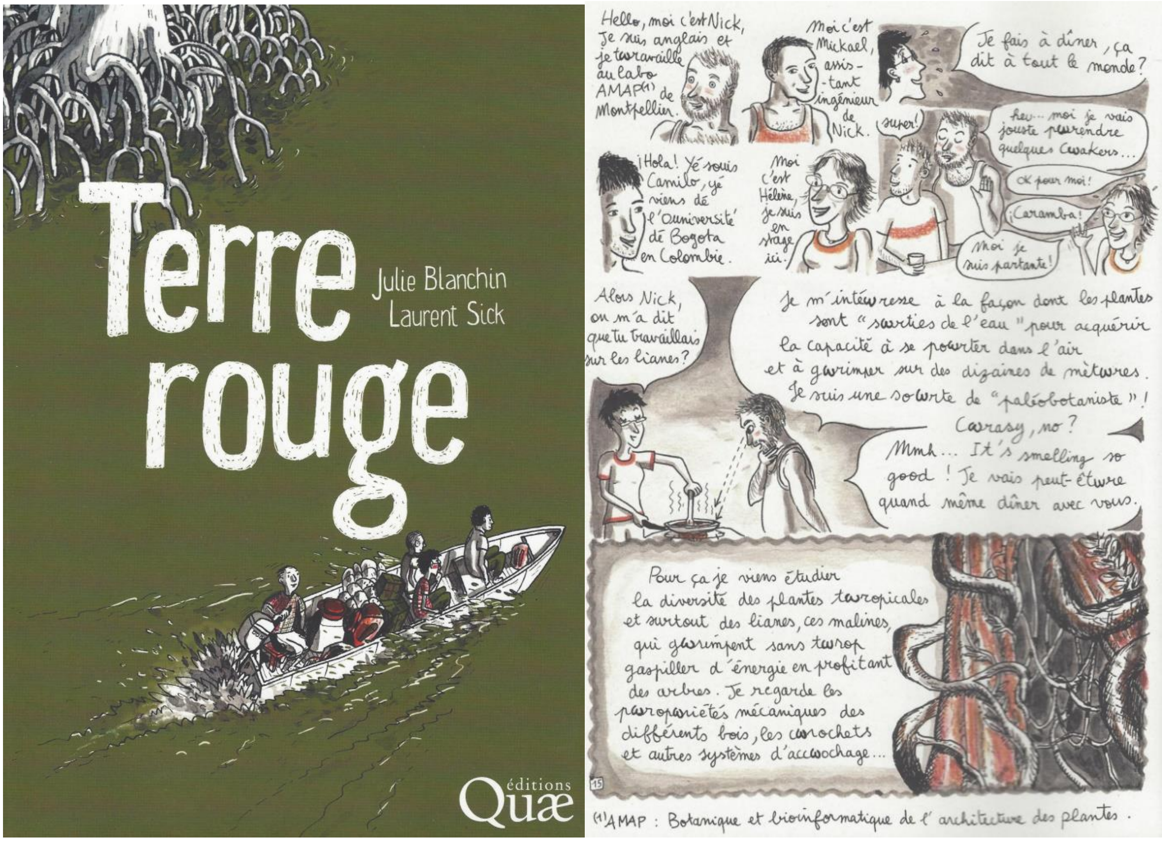

Figure 36: "Terre Rouge" documented the research activities of field workers in tropical rainforest in French Guiana.

We have experience of this kind of outreach publication in recent years and we aim to model the new production on the production and feedback we have learnt from the production of "Terre Rouge" in 2006, which documented the research activities of field workers in tropical rainforest in French Guiana (Figure 36).

2.10.4 Task 10.4 Demo days

TASK LEADER	PARTNER INVOLVED	DURATION
Linari	All	25 months (M24-M48)

To be started on M24 (1^{st} December 2020).

2.11 WP11 – Dissemination, Communication, and Exploitation

WP LEADER	PARTNER INVOLVED	DURATION
Linari	All	48 months (M1-M48)

WP objective – WP aims at managing external dissemination and communication, as well as at exploitation of the project results.

List of deliverables released:

- [IIT-CMBR, M3] - D11.1 Project website and dissemination materials
- [IIT-CMBR, M3] - D11.2 Communication, Dissemination and Exploitation Plan (CoDE)
- [IIT-CMBR, M12] - D11.3 GrowBot Workshops

2.11.1 Task 11.1 GrowBot dissemination activities

TASK LEADER	PARTNER INVOLVED	DURATION
IIT-CMBR	All	48 months (M1-M48)

Task 11.1 is dedicated to the activities for the dissemination of project results toward the scientific community, industrial representatives, and general public. Related to these activities, at month 3, IIT-CMBR released the deliverable D11.2 "Communication, Dissemination and Exploitation Plan (CoDE)" that consists of a detailed plan dealing with the guidelines to be followed by the consortium in dissemination activities.
The CoDE plan is continuously and periodically reviewed and updated according to the progress and results emerging from the project, considering, inputs from the Advisory Board, work context, and potential use of results during the project lifetime.

The current version of the CoDE plan includes the following issues:

- GrowBot website;
- scientific publication in peer-reviewed journals and international conferences;
- dissemination material (i.e., logo, flyers, posters, standard presentation, etc.);
- workshops to present results and technologies.

The earliest task (M1) was the development of an identity for the project. IIT-CMBR designed the logo, the brochure, and the roll-up of the project in order to promote project identity since the beginning (Figure 37 and Figure 38).

GROWBOT

Figure 37: GrowBot logo.

Figure 38: Current version of GrowBot tri-fold brochure.

The brochure is public and available for download from the project website and social media channels. All partners were strongly encouraged to distribute the brochure through their institutes, mailing lists, social networks, and at the relevant events they attend.

The project website (www.growbot.eu) was published at month 1 (Figure 39). The website consists of a public area that gathers all the information related to the project and links to social media channels and a private area that works as a repository platform for allowing consortium to share information about the project. The repository is continuously updated with the documents, information, and details in accordance with the progress of the project.

Figure 39: GrowBot homepage.

At month 3, IIT-CMBR released the deliverable D11.1 "Project website and dissemination materials" with a detailed description of the activities related to project website and dissemination materials.

During the first year of the project, four public events were organized by GrowBot consortium: two scientific events and two events for kids.

Scientific events

"Focus on lianas"	
Event type	Conference
Location	AMAP, (CNRS) Montpellier, France
Date	6th June 2019
Organiser	Nick Rowe (CNRS)
Details	(see Annex **Error! Reference source not found.**)

Event abstract:
Lianas are an iconic growth form in many tropical ecosystems where they play important roles in community composition, vegetation dynamics and likely responses to climatic change. This informal meeting focuses on some of the diverse approaches and projects centred on lianas at AMAP and will kick off with a key note lecture by our guest speaker Stefan Schnitzer. We will be covering a diverse range of subjects from overarching studies on the ecology and evolution of lianas to new approaches of studying lianas in the field, detailed functional traits, biomechanics, modelling at the community level and finally using lianas as models for bio-inspired new technologies.

The conference dealt with different approach and projects centred on lianas.

The meeting included 8 speakers:
- Stefan Schnitzer (Marquette University, Milwaukee, Wisconsin, USA) [invited]
- Patricia Soffiatti (Department of Botany, Federal University Parana State, Brazil) [invited]
- Thomas Couvreur (IRD, DIADE)
- Begum Kacamak (Forestry Club de France)
- Sebastien Levionnois (EcoFog & AMAP)
- Fiston Nininahazwe (AMAP)
- Isabelle Maréchaux (INRA – AMAP)
- Nick Rowe (CNRS - AMAP)

The meeting was attended by approximately 55 attendees with undergraduates, local faculty and staff.

One speaker, Begum Kacamak is our first GrowBot prize laureate working on the ecology of lianas in Central Africa. The meeting was successful in attracting collaborators and students to the GrowBot project who are now actively engaged in the project.

"Generation GrowBots: materials, mechanisms and systems design for adaptable and growing robots inspired by plants"	
Event type	Conference Workshop @Robotics Science and Systems (RSS)
Location	University of Freiburg - Freiburg, Germany
Date	22nd June 2019
Organiser	Barbara Mazzolai (IIT-CMBR) and Ian Walker
Agenda	(see Annex 3.6)
Details	https://www.growbot.eu/project/events/2-uncategorised/34-event-rss-2019-workshop https://bsr.iit.it/events/rss-workshop-2019-generation-growbots

Event abstract:
"Generation GrowBots" will take attendees across the science and technologies of the new field of plant-inspired robotics, and explore the new paradigm for robot mobility inspired by the moving-by-growing ability of plants.
Plants show unique capabilities of endurance and movement by growth.
Across sea and land, through air and underground, some species of plants are the oldest and largest organisms that have ever existed. They can resist unpredictable external forces – such as wind, waves, or falling debris - and can adapt and move their structure by growing across a variety of unstructured environments.
Together with plant biologists and materials scientists, engineers are deeply investigating the biomechanics, materials, energy efficiency mechanisms, and behavior of a variety of plant species, to take inspiration from them for the design of multi-functional and adaptable technologies, and for the development of a new class of low-mass, low-volume robots unique in their movement and growth abilities.
The workshop will bring together a cross-disciplinary panel of scientists and engineers, including experts in material science, soft robotics, plant biology, and architecture to present new scientific discoveries on plants relevant to continuum, soft, adaptable, and growing robots.
Trends, frontiers and potential applications for a variety of high-tech sectors will be also discussed, including future urban and architectural innovation, clean-energy forms and sustainable robotics ecosystems.

The workshop dealt with an overview of new scientific discoveries across different disciplines relevant to the new field of plant-inspired robotics.

The meeting included 12 speakers:
- Petra Gruber (University of Akrion)
- Yasmine Meroz (Meroz Lab, Tel Aviv University)
- Nicholas Rowe (Botany and Modelling of Plant Architecture and Vegetation, CNRS)
- Thomas Speck (Plant Biomechanics Group, University of Freiburg)
- Yasmin Ansari (The BioRobotics Institute, Scuola Superiore Sant'Anna)
- Marwa ElDiwiny (Robotics and Mechatronics, University of Twente)
- Mirko Kovac (Aerial Robotics Lab, Imperial College London)
- Virgilio Mattoli (Center for Micro-BioRobotics, Istituto Italiano di Tecnologia)

- Barbara Mazzolai (Center for Micro-BioRobotics, Istituto Italiano di Tecnologia)
- Thrishanta Nanayakkara (Morph Lab, Imperial College London)
- Robert Shepherd (Dept. Mechanical and Aerospace Engineering, Cornell University)
- Ian D. Walker (Dep. of Electrical and Computer Eng., Clemson University)

The event was intended for robotics researchers and scientists who share the vision of bioinspired and soft robotics, particularly young students and researchers who were encouraged to enter this emerging and challenging field of robotics science (Figure 40).

Figure 40: Pictures of the "Generation GrowBots" workshop.

Following the workshop, Barbara Mazzolai, Ian Walker, and Thomas Speck launched a special issue in Frontiers in Robotics and AI for gathering the contributions presented at the 2019 Robotics Science and Systems (RSS) workshop. The workshop hosted in Freiburg was linked to several working group events for the GrowBot partners resulting in increased collaboration between partners as well as links with robotic specialists and partners.

Events for kids

In the first year of the project, IIT-CMBR organized two workshops for young people and kids in the occasion of the Festival della Scienza (Science Festival) in Genova (24th October – 4th November 2019, http://festival2019.festivalscienza.it/site/home.html).

Festival della Scienza in Genova is a yearly international event that represents a great opportunity for schools and families to meet science and researchers.

IIT-CMBR organized two workshops in order to introduce the GrowBot project to kids and young people.

Both the two workshops were hosted at the Aquarium of Genoa (https://www.acquariodigenova.it/en/).

"Biomimetics: Let's inspired by Nature"	
Event type	Workshop for kids and young people of 8-18 years old
Location	Aquarium of Genoa, Genoa, Italy
Date	24th October – 4th November 2019
Organiser	IIT-CMBR
Details	http://festival2019.festivalscienza.it/site/home/programma-2019/biomimetica-ispirati-dalla-natura.html

The researchers of CMBR-IIT took this occasion to present the GrowBot project to young generations.

The event was organized for the entire festival duration (14 days) and participants were mainly school students and families (Figure 41).

Figure 41: A detail of the GrowBot project roll-up.

"Look at that plant"	
Event type	Workshop for kids and young people of 6-13 years old
Location	Aquarium of Genoa, Genoa, Italy
Date	24th October – 4th November 2019
Organiser	IIT-CMBR
Details	http://festival2019.festivalscienza.it/site/home/programma-2019/guarda-che-pianta.html https://www.growbot.eu/project/events/2-uncategorised/30-event-guarda-che-pianta

The workshop aimed at spreading notions related to biology and robotics to 6-13 year-old kids.

Biology and Robotics are the two pillars of the GrowBot project and IIT-CMBR researchers exploited ludic activities to introduce it to the kids.

The workshops consisted of two main activities:

- a team quiz with questions related to plant biology and robotics;
- a coding challenge where kids had to programme simple robots (provided by Clementoni) for writing the GrowBot project name.

The event was organized for the entire festival duration (14 days) and participants were mainly school students and families (Figure 42 and Figure 43).

The workshop was sold out during all the festival dates.

Figure 42: Kids involved in the coding challenge.

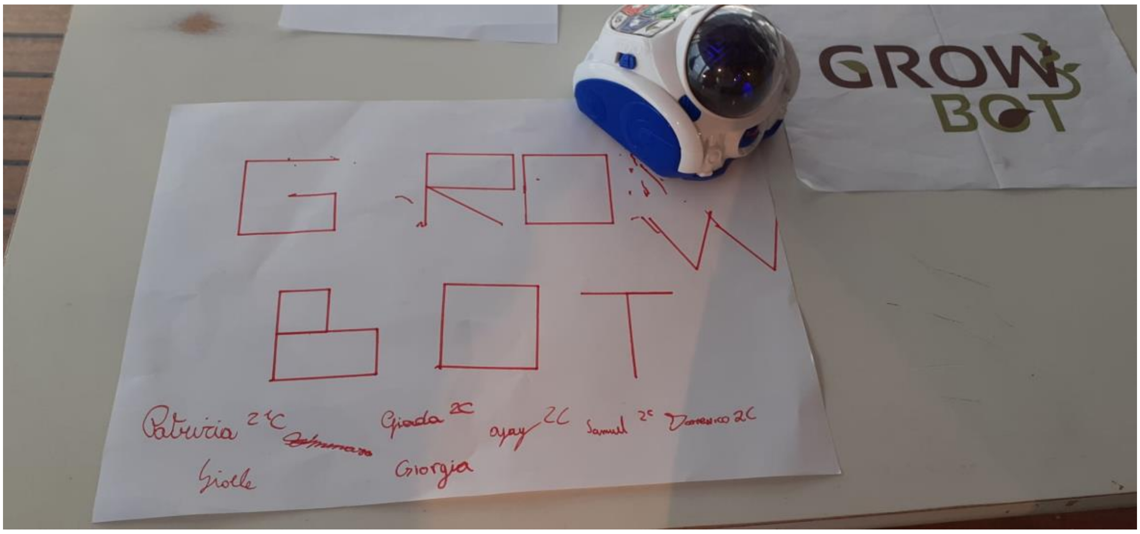

Figure 43: Coding challenge result.

At month 12, IIT-CMBR released the deliverable D11.3 “GrowBot Workshops I” with a detailed description of the activities related to the organization of workshop activities.

2.11.2 Task 11.2 GrowBot communication

TASK LEADER	PARTNER INVOLVED	DURATION
IIT-CMBR	All	48 months (M1-M48)

GrowBot communication activities were carried out since the beginning of the project in order to raise awareness among the general public about the project main goals and the future scenario it may generate in the society, changing paradigms and imaginary in robotics. Activities were coordinated by IIT involving all partners and giving periodically updates on achieved results.

In the first year of activities (M1-M12) the main massages were related to the importance of linking together biological and botanical studies of climbing plants with engineering, material science and computational science, in order to promote a new interdisciplinary approach to bioinspired soft robotics. Environmental issues, such sustainability and energy consumption, were also discussed. An important theme that the project has been promoting is the enrolment of women in scientific and technological fields, having the coordinator and other consortium female members acting as role models and being featured in news and in public events. In this sense, GrowBot project aims to represent an example of innovation both in science and society.

Communication activities were also meant to open the GrowBot scientific community to other communities, such as humanities, art, and culture. Therefore, GrowBot project was presented during public events dedicated to poetry and literature (Book in the City, Monfalcone, October 2019), philosophy (Festival della mente, Sarzana, September 2019), art and fashion (Festival dei due Mondi, Spoleto, August 2019; Pitti Uomo, January 2020), culture and women empowerment (Tempo delle Donne, Milano, September 2019). Besides, specific contributions about GrowBot and bioinspired robotics were held in several science and innovation festivals, such as National Geographic Festival delle Scienze (Rome, April 2019), Food&Science Festival (Mantova, May 2019), Festival della Scienza (Genova, October 2019), Innovative Enterprise Week (Bucharest, June 2019), Wired Festival (Firenze, September 2019) and the European event Future Tech Week (Brussels, September 2019). Events produced also specific media coverage.

In terms of communication to a wider audience, press releases and news were realized at international level, resulting **in more than 170 news,** featuring the project and mentioning the European Union as funding agency.

Press releases dealt with the launching of the project and specific project results. For launching the project IIT circulated among partners a common description of GrowBot that was adapted by different institutions in their own countries as a press release. In Italy the media coverage was promoted by IIT, in coordination with SSSA, GSSI and Linari; in total in Italy there were more than 100 news in the country. A good coverage was also obtained in Germany and in Israel (more than 10 news in one month). The project was also featured by the EU-funded Fet-FX programme, Horizon Magazine and Cordis portal.

The project caught further international attention thanks to first scientific results obtained by Mazzolai's group (published on Advance Functional Material and Nature Communications) and promoted by press releases distributed by IIT at international level (also via Eurekalert! platform). News were covered by Wall Street Journal, BBC News, Euronews and Associated Press.

Social media channels were opened in January 2019, considering different targets. Channels are Twitter (https://twitter.com/GrowBot_project), Facebook (https://www.facebook.com/growbotproject/) and Instagram (https://www.instagram.com/growbot_project/) and they reached more than 18000 people (ref. Twitter Analytics) (Figure 44, Figure 45, and Figure 46).

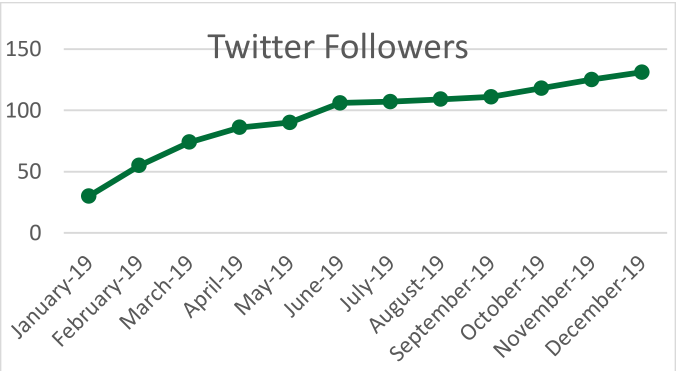

Figure 44: Twitter - 131 followers.

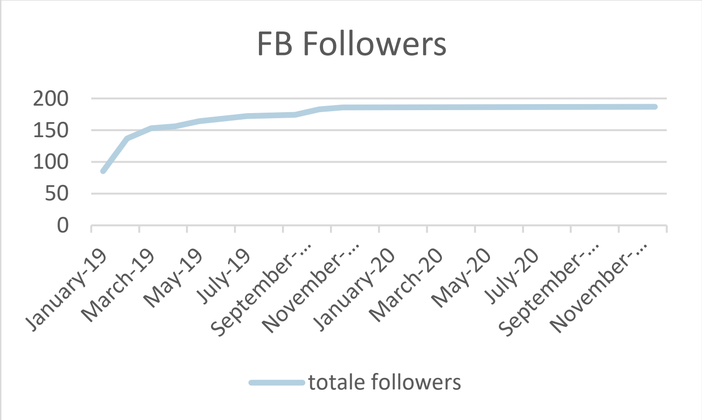

Figure 45: Facebook – 187 followers.

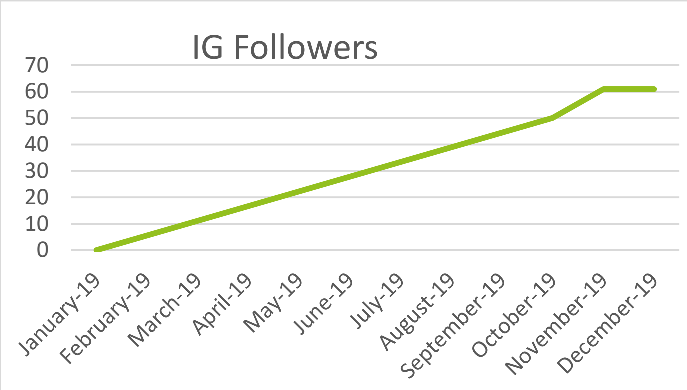

Figure 46: Instagram – 61 followers.

Moreover, project coordinator Barbara Mazzolai published a pop-science book in Italy (La Natura Geniale, Longanesi ed) where GrowBot project is mentioned. The book contributed to enlarging the project audience and its community. Events and news about the book were promoted by the Italian publisher (Longanesi) in coordination with IIT.

2.11.3 Task 11.3 GrowBot Exploitation

TASK LEADER	PARTNER INVOLVED	DURATION
Linari	All	48 months (M1-M48)

During this first initial stage of the project, industrial partners have not been involved yet, since the consortium considered necessary to set up preliminary demos of the GrowBot technology.

First interesting commercial applications are emerging not only from robotic components but even from software tools able to simulate natural plant growing process for agriculture, soil consolidation and even video games.

First contacts with potential industrial users are ongoing and will be consolidated in the future.

3 Annex

3.1 Agenda of the kick-off meeting

30 - 31 January 2019

Domus Comeliana- Pisa (Italy)

Kick-off meeting

GROW BOT

FETPROACT-01-2018

FET Proactive: emerging paradigms and communities

Research and Innovation Action

Grant agreement no. 824074

Towards a new generation of plant-inspired growing artefacts

NOTE

The main objectives of the kick-off meeting focus on:

- sharing partners' expertise and background relevant to GrowBot and the specific role within the project;
- discussing and defining contents and activities related to GrowBot Tutorials, Prizes and joint workshops.

Institution PIs are invited to give a 25' presentation including:

(I) a general overview of the institution, team members, and relevant facilities (5');

(II) a description of scientific background and main expertise (10');

(III) a description of the role in GrowBot, including responsibilities as WP leader or contributing partner, and of specific activities to perform (10').

Each presentation will be followed by 5' for Questions & Answers.

Day 1 (January 30)

Time	Title	Speaker
	"Introductory session"	
9:30 – 9:35	Welcome and short introduction of the meeting	**Barbara Mazzolai** Project Coordinator
9:35 – 10:15	Istituto Italiano di Tecnologia - Bioinspired Soft Robotics (Intro, expertise and role) GrowBot project vision and challenges	**Barbara Mazzolai** IIT
	"Biology"	
10:15 – 10:45	Le Centre National de la Recherche Scientifique (Intro, expertise and role)	**Nicholas Rowe** CNRS
10:45 – 11:15	*Coffee Break*	
11:15 – 11:45	University of Freiburg (Intro, expertise and role)	**Thomas Speck** ALU-FR
11:45 – 12:15	Tel Aviv University (Intro, expertise and role)	**Yasmine Meroz** TAU
	"Materials and Manufacturing"	
12:15 – 12:45	Helmholtz-Zentrum Geesthacht (Intro, expertise and role)	**Andreas Lendlein** HZG
12:45 – 14:30	*Lunch Break*	
14:30 – 15:00	Istituto Italiano di Tecnologia - Polymers and Biomaterials (Intro, expertise and role)	**Nicola Tirelli** IIT
15:00 – 15:30	Alleantia and Linari Engineering (Intro, expertise and role)	**Stefano Linari** Linari
15:30 - 15:40	Project administrative management Guidelines on reporting and budget	**Chiara Andreoli** IIT
15:40 – 15:50	Project dissemination Guidelines on communication and social media	**Valeria delle Cave** IIT
15:50 – 16:10	*Coffee Break*	
16:10 – 17:00	Discussion and plan of activities (Tutorials, Prizes, AB vote and joint workshops)	Moderated by **Barbara Mazzolai**
17:00 – 19:00	*Free time*	
from 20:00	*Social Dinner (in loco)*	

Day 2 (January 31)

Time	Title	Speaker
	"Modelling and Control"	
9:30 – 10:00	Gran Sasso Science Institute (Intro, expertise and role)	**Pierangelo Marcati** GSSI
10:00 – 10:30	Scuola Superiore Sant'Anna (Intro, expertise and role)	**Cecilia Laschi** SSSA
	"Energy"	
10:30 – 11:00	Arkyne Technologies (Intro, expertise and role)	**Marc Segalés** Bioo
11:00 – 11:20	*Coffee Break*	
11:20 – 12:00	Wrap-up meeting with conclusive remarks	Moderated by **Barbara Mazzolai**
12:00	*Farewell light lunch*	
14:00 – 18:00	*TOUR OF IIT LABORATORIES* --- *14:00 Bus from Pisa to Pontedera* *15:00 – 17:45 Labs tour* *18:00 Bus from Pontedera to Pisa*	

3.2 Agenda of the tutorials meeting

GrowBot Tutorial

Plant-Like Robots Are Growing Up

9-10 January 2019 / Tel Aviv University

April 9		
8:30 - 9:00	**gathering + coffee**	
9:00 - 9:30	**Greetings by Tel Aviv University President, Prof. Joseph Klafter**	biology
9:30 - 10:00	T. Speck (ALU-FR) "Plant movements: mechanics and underlying structures"	
10:00 - 10:30	M. Thielen (ALU-FR) "Damping in plants: mechanics and underlying structures"	
10:30 - 11:00	**coffee**	
11:00 - 11:30	N. Rowe (CNRS) "The nuts and bolts of being a climbing plant: a biological perspective"	
11:30 - 12:00	N. Rowe (CNRS) "Diversity of climbing strategies: a perspective palette of different functional GrowBot models"	
12:00 - 12:30	Y. Meroz (TAU) "Plant decision-making: observations and models"	
12:30 - 14:00	**lunch**	behavior & control
14:00 - 14:30	C. Laschi (SSSA) "Sensory-motor behaviour in robots – what can we learn from climbing	
14:30 - 15:00	E. Del Dottore (IIT) "Movements and behavior: from plant roots to plantoids"	
15:00 - 15:30	M. Palladino (GSSI) "On a model for the growth of vines"	
15:30 - 16:00	**coffee**	
16:00 - 16:30	F. Tedone (GSSI) "A mathematical approach for understanding intra-plant communication"	
16:30 - 17:00	F. Meder (IIT) "Living plants as energy converters and for driving electronics and robotics"	

GROW BOT

TEL AVIV UNIVERSITY אוניברסיטת תל אביב

GrowBot Tutorial

Plant-Like Robots Are Growing Up

9-10 January 2019 / Tel Aviv University

April 10		
8:30 - 9:00	**gathering + coffee**	materials & manufacturing
9:00 - 9:30	S. Linari (LINARI) "Growing system and functional blocks"	
9:30 - 10:00	P. Vidarte (BIOO) "Mechanical and Biological conditions for electrical generation from soils"	
10:00 - 10:30	N. Tirelli (IIT) "Environmentally responsive polymers"	
10:30 - 11:00	**coffee**	
11:00 - 11:30	A. Lendlein (HZG) "Polymer actuators"	
11:30 - 12:00	M. Behl (HZG) "Self-healing and degradable materials"	
12:00 - 12:30	**lunch**	
12:30 - 13:30	**dessert + round-table discussion**	
13:30 - 14:15	B. Mazzolai (IIT) // Special Guest Seminar @ Porter Building "Plant-like robots are growing up"	

April 11		
11:00 - 14:00	**Tasting tour at Levinsky Spice Market**	

Questions? Yasmine Meroz / +972-54-7355021 / jazz@tauex.tau.ac.il

GROW BOT

TEL AVIV UNIVERSITY אוניברסיטת תל אביב

3.3 Agenda of the project meeting in L'Aquila

Day 1 (November 11)

Time	Title	Speaker
	Introduction	
9:30 – 9:40	Welcome	Pierangelo Marcati GSSI
9:40 – 9:50	Short introduction of the meeting and agenda	Barbara Mazzolai Project coordinator
	WP2: Tutorials and design specifications	
9:50 – 10:00	WP introduction Report on Task 2.1 (M1-3) - completed	Yasmine Meroz (TAU) WP leader and Task 2.1 leader
10:00 – 10:10	Report on Task 2.2 (M1-3) - completed	Stefano Linari (Linari) Task 2.2 leader
10:10 – 10:20	Report on Task 2.3 (M4-6) - completed	Barbara Mazzolai (IIT-CMBR) Task 2.3 leader
	WP3: Climbing plants observation and modelling	
10:20 – 10:30	WP introduction Report on Task 3.1 (M1-11) – on going	Marc Thielen (ALU-FR) WP leader and Task 3.1 leader
10:30 – 10:40	Report on Task 3.2 (M1-11) – on going	Yasmine Meroz (TAU) Task 3.2 leader
10:40 – 10:50	Report on Task 3.3 (M1-11) – on going	Nicholas Rowe (CNRS) Task 3.3 leader
10:50 – 11:00	Report on Task 3.4 (M1-11) – on going	Pierangelo Marcati (GSSI) Task 3.4 leader
11:00 – 11:15	*Coffee Break*	
	WP4: Smart materials for growing process and attachment solutions	
11:15 – 11:25	WP introduction Report on Task 4.2 (M7-11) – on going	Marc Behl (HZG) WP leader and Task 4.2 leader
11:25 – 11:45	Report on Task 4.1 and 4.3 (M7-11) – on going	Nicola Tirelli (IIT-POLBIOM) Task 4.1 and 4.3 leader
	WP5: Embodied additive manufacturing mechanisms for growing robots	
11:45 – 12:05	WP introduction Report on Task 5.2 (M7-11) – on going Report on Task 5.4 (M7-11) – on going	Barbara Mazzolai (IIT-CMBR) WP leader Task 5.2 and 5.4 leader
12:05 – 12:15	Report on Task 5.1 (M7-11) – on going	Stefano Linari (Linari) Task 5.1 leader
12:15 – 12:25	Report on Task 5.3 (M7-11) – on going	Marc Behl (HZG) Task 5.3 leader
	WP6: Robot sensory-motor architectures	
12:25 – 12:45	WP introduction Report on Task 6.2 (M7-11) – on going Report on Task 6.3 (M7-11) – on going	Cecilia Laschi (SSSA) WP leader Task 6.2 and 6.3 leader
12:45 – 12:55	Report on Task 6.1 (M7-11) – on going	Emanuela Del Dottore (IIT-CMBR) Task 6.1 leader
12:55 – 14:30	*Lunch Break*	
	WP7: Plant-robot interfaces for bio-hybrid energy generation	
14:30 – 14:40	WP introduction Report on Task 7.1 (M7-11) – on going	Marc Segalés (Bioo) WP leader and Task 7.1 leader
14:40 – 14:50	Report on Task 7.2 (M7-11) – on going	Fabian Meder (IIT-CMBR) Task 7.2 leader

	WP10: Community building	
14:50 -15:00	WP introduction Plan for Task 10.3 (to be started at M12)	Nicholas Rowe (CNRS) WP leader and Task 10.3 leader
15:00-15:20	Report on Task 10.1 (M1-11) – on going Report on Task 10.2 (M2-11) – on going	Francesca Tramacere (IIT-CMBR) Task 10.1 and 10.2 leader
	WP11: Dissemination, Communication, and Exploitation	
15:20 – 15:30	WP introduction Report on Task 11.3 (M1-11) – on going	Stefano Linari (Linari) WP leader and Task 11.3 leader
15:30 – 15:40	Report on Task 11.1 (M1-11) – on going	Francesca Tramacere (IIT-CMBR) Task 11.1 leader
15:40 – 15:50	Report on Task 11.2 (M1-11) – on going	Valeria delle Cave (IIT) Task 11.2 leader
15:50 – 16:00	*Coffee Break*	
16:00 – 17:00	Discussion and plan of activities (Plan of review meeting, List of issues to be discussed with the AB, Next deliverables, etc.)	Moderated by Barbara Mazzolai
17:00 – 19:00	*Free time*	
from 20:00	*Social Dinner*	

Day 2 (November 12)

Time	Title	Speaker
9:30 – 9:45	Welcome and short introduction to GrowBot project (for AB members)	Barbara Mazzolai Project coordinator
9:45 – 10:45	Discussion with AB members	Moderated by Barbara Mazzolai
10:45 – 11:00	*Coffee Break*	
11:00	Wrap-up meeting with conclusive remarks	Barbara Mazzolai Project coordinator

3.4 Milestone MS2 - Report

Milestone Title: MS2 Provide list of functionally diverse climbing plant behaviours as potential starting points for GrowBot "life histories"

This milestone provides the selected species and types of behaviour for the tasks related to (i) Ecological scale of observation (CNRS), (ii) the fine-scale observation of structure and function (ALU-FR) (iii) the experimental behavioural observations and modelling (TAU).

3.4.1 Ecological scale (CNRS)

The list is based on recent field work reconnaissance of potential study sites in liana-rich areas of tropical forest for overall life history traits and broad-scale functional traits in (Brazil, French Guiana, Democratic Republic of the Congo, Southern Europe).

The named species represent morphotypic place holders for a certain category of behaviour. Our ongoing list includes additional species for each category that will further cater for a more specific wish list of potential technological innovations.

Our aim is to indicate the interesting and transferable biological traits that might be integrated within the design of GrowBot models in terms of (a) **Capability**: the kind of 3-D terrain and kind of void negotiation (B) **Attachment:** twining, tendril, hook, adhesive pad and so on (C) **Strength** of attachment – brief categorisation weak to strong (D) **Stem construction** – essentially as a guidance for potential additive manufacturing designs – whether the stem system has secondary radial growth i.e. stem expansion by cellular growth (= complex) or whether the construction is just primary growth (= simple); (E) Special attributes: some plants have unique trait combinations or highly specialized structures or behaviours; (F) **Constraints:** we also point out "our perceived" constraints on the plant model – in biology such characteristics likely represent evolutionary selection for economy of design for a specific niche or specialized function. Sacrificing high levels of functionality for a simpler design for a specific function is also a potentially useful that might be considered in the specificity of different GrowBot designs. (G) **Similar models**: we propose further species or groups from which we can observe how some of our model species vary across different plant groups. The list of ecological models is ordered from short to long distance void negotiation.

This list also includes insight gained from different partner's needs and interests expressed during our initial meetings and tutorials Pisa – Tel Aviv – Freiburg – L'Aquila. We have therefore signalled how some model life history traits might be informative or desirable for e.g. kinds of materials, kinds of energy production.

For some selected models we include additional related or similar species showing variant traits of interest.

A more complete version of this list along with key points, images and photographs is being considered as a publication with cross partner input.

3.4.1.1 Sticky root climber - Adelobotrys adscendens (Melastomataceae, French Guiana)

Capability: Negotiating flat to blocky/flaky surfaces (very short-range voids and fissures).

Attachment type: Root hairs and sticky root hairs with suspected hydrogel-like glue exudate.

Attachment strength: Weak-medium strength with some stabilization of substrate.

Stem construction/growth: Wood cylinder – secondary radial additive growth, light construction, creeping searchers close to substrate.

Special attributes: close following topography – many points of light attachment and negotiating tight 3D structures.

Constraints: brittle stems short void capability.

Similar models: Hedera helix (Araliaceae), Araceae, Marcgraviaceae.

3.4.1.2 Spine-root climber - Hylocereus setaceous (Cactaceae, South East Brazil)

Capability: Negotiating flat to blocky surfaces and (short to medium range voids) in high density clutter)

Attachment types: recurved spines and roots

Attachment strength: medium (roots) to strong (spines)

Stem growth: low biomass cost (searchers) and wood cylinder – secondary radial growth.

Special attributes: High rigidity searchers with low cost construction via smart geometry, high level of autonomy with hemi-epiphytic life history. High levels of turgor-driven, hydrogel-like tissue interesting for polymer designs of GrowBot stems.

Constraints: high rigidity but high mass due to water driven turgescence and energy storage**.**

Similar models: *Rhipsalis floccosa*, *Rhipsalis gibberula*, *Rhipsalis neves-armondii*, *Lepismium lumbricoides* (Cactaceae) Showing a range of stem geometries and presence of Hydrogel-like tissue combinations in epiphytes and lithophytes.

3.4.1.3 Sticky pad climber - Tynanthus polyanthus (Bignoniaceae, French Guiana)

Capability: Negotiating irregular blocky surfaces with fissures and short-medium range voids and high density, short range clutter)

Attachment types: short range, sensitive/reactive/high precision, searcher branchlets with large, spreading sticky pads.

Attachment strength: medium to high

Stem growth: Two step: stiff-compliant wood cylinder – secondary radial additive growth.

Special attributes: short range, sensitive/reactive/high precision, searcher branchlets with substrate consolidation

Constraints: High precision, active search-and-attach but relatively short range.

Similar models: *Cissus haematantha, Cissus Sp.* (Vitaceae) showing tendril and pad variants with light structured, low biomass searchers.

3.4.1.4 Stem twiner/winder - Condylocarpon guianense (Apocynaceae, French Guiana)

Capability: Negotiating irregular ground surface, smart climbing decision maker, traverse short-medium range voids (0-1.5 m), “obstacle course” specialist (Medium to high clutter).

Attachment types: short to medium range main stem winder / twiner.

Attachment strength: = failure strength of leading stem in bending / tension / shear, / local buckling)

Stem growth: Two step: stiff-compliant wood cylinder – secondary radial additive growth, rapid shift high to low modulus.

Special attributes: Highly adaptive creeping and negotiating clutter and “smart selection” of suitable vertical supports. Suspect high activity of latex glue-like, sealing, repairing functions in stem.

Constraints: High precision active search and attach but relatively short range.

Similar models: Apocynaceae**,** Connaraceae, Menispermaceae.

3.4.1.5 Micro-spine rover- twiner - Davilla rugosa (Dilleniaceae, French Guiana)

Capability: Negotiating irregular ground surface and host surface and anchoring attachment by micro hook grappling, short to medium voids (0-1.5 m) (medium to high clutter).

Attachment types: main stem winder / twiner and micro-spine friction specialist.

Attachment strength: = failure strength of leading stem in bending / tension / shear, / local buckling) and failure of friction surfaces = slipping.

Stem growth: Two step: stiff-compliant wood cylinder – secondary radial additive growth, rapid shift high to low modulus.

Special attributes: Highly adaptive creeping and negotiating clutter in complex 3-D spaces micro-spines attach to flat, cylindrical, irregular shapes to then permit twining. Smart micro-spine composite (spines + hairs). Friction with moving host branches: potential for frictional energy.

Constraints: High precision attachment by micro spines. Spines are brittle and fracture – perhaps one-shot usage.

Similar models: Dilenniaceae

3.4.1.6 Clip-on hook-tendril climber- Bauhinia guianensis (Fabaceae, French Guiana)

Capability: Negotiating up to medium-large voids (0-3 m) in high clutter and high energy environments (moving tree branches).

Attachment types: Passive*-swaying optimized organisation with clip-on – clip-off sensitive hook-tendrils.

Attachment strength: High strength attachment in tension of lignified hook-tendrils via 2-step secondary growth (inner G-fibre reaction wood and outer dense stiff wood).

Stem growth: Two step: stiff-compliant wood cylinder – secondary radial additive growth, rapid shift high to low modulus – and ribbon-like stems with highly adapted, pre-formed benign fracture strategy.

Special attributes: Highly adapted combination of optimized passive swaying with clip-on - clip-off active points of attachment. Likely leaf /stem clatter** processes linked to optimized passive swaying – potential for frictional energy model technology.

Constraints: Initial point of attachment constrained by diameter of attachment of pre-formed hook.

* Behaviour that uses the elastic instability of long, narrow stiff stems to sway in wind and contact neighbouring plants. The movement is passive, but the stem and attachment system is optimized (mechanically and geometrically) to take advantage and even enhance passive movements in highly unstructured and long distance environments.

** We use the term “clattering” for model species that present leaves and stems in high energy environments and that “clatter together which is consistent and potentially useful for models of energy production.

3.4.1.7 Ultra-light/stiff jointed climber - Ischnosiphon centricifolius (Marantaceae, French Guiana)

Capability: Negotiating large voids (up to 5 m) in forest understory (low to high clutter long distance supports).

Attachment types: flexible nodes (joints) of stem become compliant and form hook-like articulations that secure branches in host vegetation.

Attachment strength: Relatively weak, plant is held in place by a combination of stiff cane-like stems (props) and articulation points around host plants.

Stem growth: One step: high stiffness outer fibres with soft turgor tissue inside. Highly stiff but light unstructured No secondary additive radial growth.

Special attributes: Negotiates large voids via stiff pole-like stems but can re-orientate and attach via flexible dash-pole-like joints.

Constraints: Light architecture depends on turgor pressure to maintain stem organisation supporting highly stiff outer tissues.

(Similar models: *Haumania danckelmaniana*)

3.4.1.8 Whip-lash spine climber - Desmoncus orthacanthos (Arecaceae, French Guiana)

Capability: Negotiating large voids (up to 3 m) in forest understory (low to high clutter long distance supports).

Attachment types: Entirely passive swaying-optimized stems bearing sharp recurved spines on whip-like extensions of leaf rachis – No active attachment mechanism.

Attachment strength: Strong, includes a "smart ratchet" system; the entirely passive but optimized sway organisation is nevertheless highly effective without any twining or tendrils or active growth attachment processes.

Stem growth: Two step: primary growth with soft central stem and outer fibres giving high stiffness. Flexibility in step two caused by senescence and shedding of outer stiff tissue.

Special attributes: Negotiates large voids via stiff pole-like stems held in place by long modified spiny leaf structures. Very efficient in highly unstructured, high energy (windblown- or forest disturbance environments). Technological advantages – no additive secondary growth and no active attachment growth, leaf clattering possible energy interest.

Constraints: attachment depends on ensuring tension between the plant stem and grappling spines via gravity.

(Similar models: *Desmoncus polycanthus*); Calamoideae (Africa S. E. Asia)

3.4.1.9 Long distance clip-on climber - Strychnos sp. - (Loganiaceae, French Guiana)

Capability: Negotiating large voids (up to, possibly over 10 m) in forest gaps (low clutter long distance supports) and high energy high clutter environments and moving tree branches.

Attachment types: Passive-swaying optimized organisation with clip-on – clip-off sensitive hook-tendrils.

Attachment strength: High strength attachment in tension of lignified hook-tendrils via 2-step secondary growth (inner G-fibre reaction wood and outer dense stiff wood).

Stem growth: Two step: stiff-compliant wood cylinder – secondary radial additive growth, rapid shift high to low modulus.

Special attributes: Negotiates some of the longest voids observed, combination of "optimized passive swaying" with clip-on - clip-off active points of attachment. Likely leaf /stem clatter processes linked to optimized passive swaying – potential for frictional energy model technology.

Constraints: Initial point of attachment constrained by diameter of attachment of pre-formed hook.

3.4.2 Fine-scale (ALU-FR)

3.4.2.1 Self-stiffening, self-intertwining searcher shoots

Many twining plant species produce searcher shoots that twine together and it is likely that there is a mechanical innovation to span greater distances. The following species have been selected for study for detailed analysis into their biophysical properties and anatomical and ultrastructural organisation.

Apios americana (Fabaceae)

Aristolochia macrophylla (Aristolochiaceae)

Dipladenia sp. (Apocynaceae)

Humulus lupus (Cannabaceae)

Ipomoea tricolor (Convolvulaceae)

Thurnbergia alata (Acanthaceae)

Wisteria sp. (Fabaceae)

3.4.2.2 Coiling tendrils

These are found in many climbing plants, in many separate groups and show a wide range of diversity in form and likely structure and function. Some of our selected species such as *Passiflora* (here) show interesting evolutionary histories from which we can scrutinize patterns of evolvability, transformation and modifications of structure and function.

Cobaea scandens (Polemoniaceae)

Bryonia alba (Cucurbitaceae)

Cyclanthera brachystachya (Cucurbitaceae)

Luffa aegyptiaca (Cucurbitaceae)

Passiflora discophora (Passifloraceae)

Passiflora caerulea (Passifloraceae)

Passiflora. x belotii (Passifloraceae)

Passiflora quadrangularis (Passifloraceae)

Passiflora garckei (Passifloraceae)

*Passiflora amethystin*a (Passifloraceae)

Passiflora discophora (Passifloraceae)

3.4.3 Circumnutations, tropisms, mathematical models (TAU)

3.4.3.1 Stem twining

One model species, the common bean is currently being used in experimental laboratory work on the behaviour of the twining stem encountering supports.

Phaseolis vulgaris (Fabaceae)

3.4.3.2 Tendril twining

Further experimentation is planned using active tendrils of common pea.

Pisum sativum (Fabaceae)

3.5 Leaflet of “Focus on lianas”Conference

“Focus on lianas”

AMAP 6th June 11:00-17:30

Salle 201, Bâtiment PS2, CIRAD-UMR AMAP, Boulevard de la Lironde

Lianas are an iconic growth form in many tropical ecosystems where they play important roles in community composition, vegetation dynamics and likely responses to climatic change. This informal meeting focuses on some of the diverse approaches and projects centred on lianas at AMAP and will kick off with a key note lecture by our guest speaker Stefan Schnitzer. We will be covering a diverse range of subjects from overarching studies on the ecology and evolution of lianas to new approaches of studying lianas in the field, detailed functional traits, biomechanics, modelling at the community level and finally using lianas as models for bio-inspired new technologies.

Stefan Schnitzer (University Pittsburgh) – *Ecology of Lianas*
Thomas Couvreur (IRD, DIADE) – *Evolution*
Begum Kacamak (Forestry Club de France) – *Liana communities in northern Congo*
Sebastien Levionnois (EcoFog & AMAP) – Anatomical and morphometric approaches
Fiston Nininahazwe (AMAP) – *Imaging spectroscopy for distinguishing lianas in canopy*
Isabelle Maréchaux (INRA – AMAP) – *Functional strategies and modelling*
Patricia Soffiatti (UFPR, Brazil) – *Biomechanics of climbing cacti*
Nick Rowe (CNRS - AMAP) – *Biomimetics*

This meeting has been organised under the aegis of the theme “BIOMIME” at AMAP . For further information please contact Nick Rowe (nrowe@cirad.fr). This as an initiative of the project “GROWBOT” https://growbot.eu/ which has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 824074.

3.6 Agenda of Generation GrowBots

RSS 2019 – Robotics Science and Systems – Workshop

Generation GrowBots:
materials, mechanisms and systems design for adaptable and growing robots inspired by plants

June 22, 2019
Faculty of Engineering, University of Freiburg, Freiburg, Germany
WS1-4, Building 101, Room 01 013

9:00 – 9:15	*Welcome and overview of the event: Barbara Mazzolai and Ian Walker*
9:15 – 9:45	Robert Shepherd, Dept. Mechanical and Aerospace Engineering, Cornell University "Soft robotics: an emerging field"
	Fundamentals of plant biology for new technologies and robotics
9:45 – 10:15	Thomas Speck, Plant Biomechanics Group, University of Freiburg "Plants as role models for (inter-)active mobile technical systems: inspiration for soft-robotics and architecture"
10:15 – 10:45	Nicholas Rowe, Botany and Modelling of Plant Architecture and Vegetation, CNRS "Diversity, performance and developmental strategies of climbing plants in tropical forests"
10:45 – 11:00	***Coffee Break***
11:00 – 11:30	Yasmine Meroz, Meroz Lab, Tel Aviv University "What plant behavioral processes teach us about control strategies for growing robots"
	Plant-inspired technologies, growing robots and bioinspired robotic construction
11:30 – 12:00	Petra Gruber, Biomimicry Research and Innovation Center, University of Akron "A living architecture - how growth in biology informs building design"
12:00 – 12:30	Virgilio Mattoli, Center for Micro-BioRobotics, Istituto Italiano di Tecnologia "Conducting polymers for soft robotics and electronics"
12:30 – 13:00	*Q&A and discussion*
13:00 – 13:45	***Lunch break***
	Plant-inspired technologies, growing robots and bioinspired robotic construction
13:45 – 14:15	Barbara Mazzolai, Center for Micro-BioRobotics, Istituto Italiano di Tecnologia "GrowBots: a new generation of plant-inspired growing robots"
14:15 – 14:45	Ian Walker, Dept. of Electrical and Computer Eng., Clemson University "Plant-inspired continuum robots"
14:45 – 15:15	Marwa ElDiwiny, Robotics and Mechatronics, University of Twente "Modeling, design, and simulation of Knitted and Weaved Ionic Electroactive Polymer for the smart garment"
15:15 – 15:30	***Coffee Break***
15:30 – 16:00	Thrishantha Nanayakkara, Morph Lab, Imperial College London "Conditioning the body to reduce entropy of perception"
16:00 – 16:30	Yasmin Ansari, The BioRobotics Institute, Scuola Superiore Sant'Anna "Control strategies for robots based on soft materials"
16:30 – 17:00	Mirko Kovac, Aerial Robotics Lab, Imperial College London "Construction with robots and what we can learn from biology"
17:00 – 17:30	*Closing discussion: perspectives for growing robots and sustainable architecture*

Organizers: Barbara Mazzolai and Ian Walker
Contact email: barbara.mazzolai@iit.it