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

Deliverable 2.3

GrowBot Specifications and Scenarios of Use

WP 2 – Tutorials and design specifications

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Contents

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Executive Summary

Background	**Goals**
• GrowBot aims at developing growing robots able to build their bodies by additive manufacturing process and capable of anchoring, climbing and negotiating voids. • **WP2** aims at creating a common language between biologists and engineers and proposes a methodology to overcome barriers among disciplines. • **Task 2.3** aims at releasing a report on the application scenarios and the GrowBot requirements and specifications.	• Reporting on selected scenarios of use with basic expected functionalities. • Defining the specifications for each developed platform to reach the expected working conditions. • Establishing the basic constraints for the development of the different enabling technology, in terms of dimensions, power consumption, and data exchange, to ensure a smooth integration phase in **WP8**.
Approach and course of action	
• Analysis of the state of the art among different backgrounds of the partners. • New findings from the biological partners that provide inputs for further development of the technologies. • Definition of the possible applicative scenarios. • Integrated design of the three developed platforms with specifications of the developed subsystems.	

Findings and results	
• In this **Deliverable 2.3**, three macro scenarios have been identified: exploration, environmental monitoring, and structural consolidation. • Based on the high level scenarios, a set of low level functionalities have been identified: morphological adaptation, perception and behaviour, support identification, anchoring strategies, adhesive mechanisms, and energy requirements. • In order to achieve the expected low level functionalities, basic requirements have been defined.	
Impact	**Planned dissemination and exploitation**
• Released requirements and specifications will impact on the development of the GrowBot prototypes and related enabling technologies. • Scenario definitions will impact on the definition of the validation activities.	• Results of the activity reported in this deliverable will be shared at public level (Dissemination Level PU).

1 Introduction

The objective of this document is to provide a description of the specifications for the study and development of different enabling technologies for GrowBot. In order to properly define the robot specifications, the authors provide a description of the possible scenario of use and tasks that the robot will accomplish in its final version. The document is the result of the activities performed in the first six months of the projects. These activities involve two tutorials (**D2.1** and **D2.2**) that served to mutually

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share knowledge, to define a common language and terminology, and to propose methodologies to overcome barriers among disciplines. This allowed to share and discuss fundamental information and to define the first step for the definition of the integrated design for the GrowBot artefacts.

The biological knowledge on climbing plants, relevant for the design and development of innovative GrowBot technologies, is grounded on data available in the literature, as well as on the discussions emerged with the GrowBot experts on plant biology at the kick-off meeting and tutorial (**D2.1**). Aspects related to the growth toward support, circumnutations and tropisms, the sensing mechanisms at the base of the detection of the support, and the mechanisms of attachment are the main climbing plant features under investigation. The biological data will serve as a guideline for the design of the GrowBots, as discussed later in this deliverable. Specific scientific questions have been already addressed (see box), and will be updated during the project, as planned in **WP3**, to provide new inputs to the technological partners, and tune the implementation and functionalities of the final prototypes.

Q1: How do the environmental conditions affect the localization of the support?

Q2: How do tactile feedbacks and other sensory feedbacks interact and affect the localization of a support?

Q3: How do climbing plants adapt anchoring behaviour and morphology according to different supports?

Q4: How is this adaptation related to the tactile stimulation?

Q5: Which is the role of other sensory perception in the anchoring adaptation?

The expected technological final results will include multifunctional materials and multiple fabrication techniques enabling growth in robots, new plant-inspired robot sensory-motor architectures, anchoring structures, attachment solutions, and bio-hybrid systems for energy harvesting from plants. Specifically, a set of materials endowed with tactile, humidity, and chemical perception will be developed to sense and interact with the environment. These will be compatible with microfabricated additive manufacturing technologies, as well as novel soft actuation mechanisms with attachment and morphological adaptation capabilities. Energy efficiency will be intrinsic to this approach, thus innovative bio-hybrid solutions for energy harvesting and generation from plants will be also implemented. Perception and behaviour will be based on the adaptive strategies that allow climbing plants to explore the environment through purposive movements, described mathematically after experimental observations. Ultimately, three integrated robots are planned, all with the ability to move by growing, having different functionalities for the negotiation of different needs imposed by a specific scenario of use. Functionalities achieved by the robots should reflect the observed abilities in climbing plants, mixing features coming across different plant models if needed and compatible.

In Section 2 of this document, we will introduce a series of possible macro scenario of use for which we describe the key features observed in climbing plants that might help in addressing specific tasks of each scenario. All the required aspects and behaviours are then summarized in a table to facilitate reading and to better identify the peculiar and shared characteristics of the GrowBot robotic artefacts. In Section 3 we will describe the requirements for GrowBot dictated by the biological models and how we plan to transfer the biological features into the technological solutions. Section 4 of the document contains the proposed design of the three GrowBots. The fundamental artificial strategies that will be followed for achieving the movements, thus including the control, sensing and actuation, as well as electronic subsystems are therein provided.

2 Motivations

The transfer of robots from inside of factories to the external unstructured world has generated new functional needs in robotics. The adaptation of bodies and behaviour become fundamental features to guarantee a safe interaction between robots, humans and the environment while managing unpredictable conditions. Soft and bioinspired robotics are relatively new approaches to rethink robot endowed with new strategies, new patterns of movement and new sensing or actuation abilities. Among many biological models, plants show extraordinary abilities of perception, motion, and plasticity, meaning functional and morphological adaptation to environmental stimuli. They navigate their surroundings by addition of cells at the apical level, reducing in this way friction and energy consumption, enabling the exploration of clutter environments and the adaptation of the body through obstacles. Particularly, the growth from the tip enables climbing plants to overcome voids and to pass through narrow spaces reducing friction. Their adhesive and anchoring mechanisms allow them to firmly attach or coil around supports and adhere to irregular substrates.

All these features are thus appealing in robotics and potentially useful to develop robots able to self-build their own body, strengthening their adaptive capacity to environmental constraints and task requirements, with more sustainable technology, multi-functionalities, and enhanced explorative capabilities.

Since the design of these robotic solutions is deeply based on a few selected plant features, not only new technology can be produced, but also a new view of **robots for biology** can be envisaged, with the goal to give insights on the organisms themselves and elucidate the basis of complex biological behaviours. In fact, the robot offers the advantage of being programmable and reconfigurable to test different hypotheses and, although in many cases the models can be implemented and tested in software simulations, a robot can help explain the behaviour of biological systems, by evaluating its capabilities in the real world adopting a robo-physical approach. Thus, this project will additionally help to better understand the physics and features of climbing plants, closing the information loop back to biology.

3 GrowBot Scenarios of Use

Starting from the need to enable the negotiation of unknown conditions in robots operating in outdoor/unstructured environment, and taking inspiration from the ability of climbing plants to negotiate those challenges, we envision for the GrowBots three main macroscopic possible scenarios of use: **exploration**, **environmental monitoring**, and **structural consolidation**.

These very general scenarios might be considered both to test robot functionalities and to validate hypothesis of biological systems. More details on the specific selected scenarios and tasks for the validation of the robot, on one side, and of specific plant feature, on the other side, will be successively evaluated. The methodologies and protocols will be described in **D9.1** and **D9.3**, which will be released at months 33 and month 44 respectively.

In this section we will provide a short general description and highlight possible sub-scenarios. From these scenes, we enlightened key features of climbing plants relevant for the robotic solutions. A schematic overview is proposed in Table 1. The selected features will drive the specifications of the GrowBots and will be detailed in Section 4.

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Macro scenario / Features	Exploration		Environmental monitoring		Structural consolidation
Sub-scene	S1	S2	S3	S4	S5
Morphology and plasticity					
Growth from the tip	R	R	R	R	R
Growth over void	R	R	O	O	
Perception and behaviour					
Mechano-sensing	R	R			
Other sensory perception	O	R	R	R	
Tropisms	O	R	O	O	
Support identification					
Circumnutation		R	O	O	
Anchoring strategies					
Coiling, twining, and hooks		R	O	O	
Adhesive mechanisms					
Adhesive pads and roots		O	O	O	R
Energy sustainability					
Low energy consumption	O	O	R	R	O
Energy generation			R	R	

Table 1. *A summary of the key abilities extracted from climbing plants that are required to manage each sub-scene of the proposed scenarios. Exploration in **S1**: archaeology, **S2**: collapsed buildings, monitoring of in situ **S3**: parameters like oxygen, CO_2, light, humidity, temperature, and **S4**: endangered species, **S5**: consolidation of unstable structures. The table contains **R** if the ability is a strong requirement for the scenario, or **O** if the ability can optionally be included.*

The table also suggests the abilities that are mandatory (R), considered fundamental for managing the scenario, and optional abilities (O) that could be implemented, but their absence would not impact the successful accomplishment of the macro-tasks envisioned at this stage.

All the solutions that will be proposed should be deeply grounded on the moving-by-growing paradigm which will enable the safe interaction of the robots with the environment and the navigation in an unstructured area. This will ensure a certain degree of plasticity of the robot, meaning its morphological adaptation according to the constraints found during navigation.

All the abilities listed in Table 1 are also topics of selected investigations aimed at deepening in the biological insights. Biomimetic *ad hoc* robotic platforms will be then implemented and adopted to verify basic working principles of the complex behaviours of climbing plants and to validate hypothesis made on the selected biological models.

3.1 Exploration

In this scenario, GrowBots will address the task of moving in an unknown, complex, and unstructured environment. Possible sub-scenarios might involve navigation in (S1) archaeological sites or (S2) exploring collapsed buildings to look for the source of the damage, or to map the area. In both cases, the robot should be able to adapt its movement-by-growing by exploiting the ground contact and by negotiating voids. While in archaeological sites growing over existing supports might not be ideal (e.g., to avoid heritage damages), during the exploration of rubble, the exploitation of existing structures is

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desirable. Thus, in this context, the implementation of mechanisms improving the possibility to find a support (e.g., using circumnutations) and strategies for the discrimination of the right support to use are highly recommended. In addition, to help stabilizing the robot's body, it will be implemented an adhesive (e.g., root-like structures with pads) or anchoring (e.g., hooks, coiling, twining) mechanisms.

If needed, all the movements of the robots might be guided by external stimuli (e.g., light, humidity, chemical) and by tactile feedback acquired by the system while moving in the environment, mimicking plants' tropism and reactive behaviour. In these scenarios, a relatively slow growth velocity is preferred, since it helps to properly explore the environment without wrecking the surroundings (e.g., ancient and delicate artefacts). Also, energy consumption is not a critical issue in S1 and S2, since the growing apex might be connected to an external (respect to the area of exploration) central unit that can store energy or could be connected to a power source. However, it is generally desirable to put particular attention in lowering energy consumption from growth actuation mechanism, data acquisition and elaboration.

3.2 Environmental Monitoring

A second possible scenario for GrowBot is its use as a monitoring device. Possible sub-scenarios might involve *in situ* monitoring by merging artificial systems with natural plants in the forest canopy and (S3) detecting relevant parameters (e.g., oxygen, CO_2 emission, or light/humidity/temperature level at different height), or (S4) the robot can be used for non-intrusive monitoring of endangered species.

The system can be deployed directly at the target location either with a predefined target configuration or without it. In the latter, the final configuration will be achieved by the robot growing with a tropism-like behaviour, using a mixture of cues (e.g., light, chemical, touch). As for the previous scenario, the speed of motion is not a crucial issue. Instead, taking into account the possible long term monitoring and the great number of sensors which might be integrated, the key issue here is the energy consumption. For this reason, the system should be able to harvest energy from the environment (e.g., exploiting triboelectric effects and microbial fuel cells), and optimise its consumption in order to expand its lifetime. Moreover, to maximize the monitoring area and parameters, and taking inspiration from the plant proliferation and coordination ability to colonize a certain area, this scenario will consider the deployment of multiple robots with communication capabilities to autonomously coordinate themselves, having different specialised sensing units, or exploiting sensors redundancy.

3.3 Structural Consolidation

Inspired by the multiple attachment strategies of climbers, an additional scenario consists in using GrowBots as structural consolidation systems. In fact, letting the robot grow over unstable structures (e.g., friable rocky surfaces, unstable terrains) its adhesive mechanisms can be exploited to anchor each other disconnected parts of the covered area (S5). After the first stabilization, monitoring of the status (e.g., through vibration, sliding detention, or monitoring of position over time) can be also adopted to verify if, when, and where to reinforce the consolidating structures.

A single robot might not be sufficient to cover the whole surface of a large area. In this case, multiple GrowBots can be used to simultaneously grow following a predefined path (computed off-line before the deployment of the system), and adapting it to the abrupt changes of the environment.

4 Specifications of GrowBots and Enabling Technologies

This section will provide specifications by deepening in well-characterized features of climbing plants. In fact, the anatomical development and mechanical properties of plant tissues determine the size, height,

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and the stiffness or flexibility of plant stems. Thus, climbing plant functionalities, material properties and the relation between these parameters, dimensions and weights, will be taken into strong consideration for the design of the GrowBot robots.

A general overview of the biomechanical benchmarks extracted from climbing plants is reported in Table 2. The table groups the plants by their adhesive or attachment mechanisms: **twining plants**, which twist around the support, **leaf-climbers**, having twining-like leaves, **tendril-bearers**, with tendril structures coiling around the support, **root-climbers**, having cluster roots and **hook-climbers**, using hook-like structures. For each plant it is highlighted the **attachment force** (relative to the substrate adopted), to be considered when selecting and designing the actuation mechanisms, the **Young or bending modulus**, to be considered for material selection and implementation, and the typical **support** and **habitat** of the climber. The latter is a crucial factor since it plays a relevant role in defining the strategies of adaptation implemented in the biological model, and might help to address the specific features of a selected plant for a particular scenario.

Species (common name)	Attachment force (mN) (sample and substrate)	Young or bending modulus (N/mm^2) (sample)	Typical support	Native habitat (continent)
Twining plants				
Dioscorea bulbifera (Air potato) [1]	100-300 (squeezing force of shoot on a pole)	690 ±100 (stem, @600 mm from the apex)	Regular structures for vertical growth (e.g., host plants, poles and rods)	Forest, grasslands, riverbanks and shrublands (Africa and Asia)
Ipomea purpurea (Morning Glory) [2]	167 ±46 (squeezing force of shoot on slender pole) 185 ±90 (squeezing force of shoot on thick pole)	Data not available		Forest, ruderal areas and wasteland (South America)
Maripa scadens (Liana) [3], [4]	Data not available	3000-5000 (young stem) 2000-500 (old stem)	Large structures for vertical growth (e.g., trees)	Tropical rainforest (South America)
Leaf-climbers				
Flagellaria indica (Whip vine) [5], [6]	2000-3000 (Tensile force of tendril-like leaf on thick aluminum rod) 8000-38000 (Tensile force of tendril-like leaf on slender aluminum rod)	1153.4 ±991.1 (young stem, @ 0–1 m from apex) 5192.7 ±1308.1 (young stem, @ 4–13 m from base) 11673.9 ±2030.1	Horizontal/vertical structures for coiling (e.g., host plants, poles and rods)	Tropical and subtropical forest (Asia, Africa and Australia)

		(old stem, @ 0-1 m from base)		
Tendril-bearers				
Parthenocissus tricuspidata (Boston ivy) [7], [8]	7590 ±2530, max F=14000 (Pull-off force of pads on plaster)	Data not available	Smooth and micro-rough objects using irreversible chemical adhesion (e.g., trees, rock and walls)	Hillsides, mountains and urban areas (Asia and North America)
Root-climbers				
Hedera helix (English ivy) [7], [9]	3810 ±2410 (Pull-off force of cluster roots on tree bark)	109 (individual root)	Smooth and micro-rough objects using irreversible chemical adhesion (e.g., trees, rock and walls)	Forest, riverbanks and coastal areas (Europe, Asia and South America)
Hook-climbers				
Galium aparine (Cleaver) [10], [11]	5 (Pull-off force of single adaxial hook using a Kevlar loop, 90°) 8.8±1.8 and 21.9±13.4 (Friction force of adaxial leaf surface on plastic mold and foam, respectively) 20 (Pull-off force of single abaxial hook using Kevlar loop, -45°) 33.3±15.1 and 71.4±24.6 (Friction force of abaxial leaf surface on foam and VELCRO Vel-Loop, respectively)	235±116 (basal stem) 2020±1500 (fruit hook)	Micro-rough objects using reversible mechanical adhesion (e.g., host plants)	Forest, hedgerows, wasteland, arable field, grasslands and roadsides (Europe, Asia and North America)

Table 2. *A summary of main biomechanical properties of climbing plants which help characterizing plant materials and functionalities.*

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4.1 Morphology and Plasticity

Differently from animals, plants are made by iterative sub-units, have indeterminate growth, protracted for their entire lifetime and well localized at the apical region of roots and shoots, referred to as primary growth [12]. Since they are sessile, they have to explore the surrounding environment for supplying water, (mineral) nutrients, light or even – in case of climbing plants - for structural support [13]. Particularly, the aerial part of climbing plants is constituted by (Figure 1) an apical meristem where cell division occurs and a proximal spatially extended area where cells divide, elongate and differentiate while maintaining turgor [14], [15]. Typically, this area is extended up to the third internode in the stem, after which there is the older mature part, less flexible with respect to the apex. In many climbing plants, the young developmental stages, where young shoots extend into spaces, are known as *searchers* [16]. The searcher often is a thin, lightweight but stiff structure and can extend across voids in order to deploy attachment devices. It grows towards attractants and away from repellent stimuli (i.e., positive or negative tropism respectively [17]). In some climbers, the apical part of their axes can be capable of exaggerated circumnutation movements which improve the probability of getting in contact with a support [18].

The growth from the tip is actually a strategy enabling their continuous growth, even after their attachment to a support. In addition, the strategy allows crossing voids. In fact, by just moving the apical part, it is possible to use the stiff structure at its back as support. Moreover, the addition of new material at the apical level has been proven to be a less expensive (in terms of energy consumption) and more effective strategy (reaching higher depths) enabling motion even in dense medium by reducing lateral friction [19]. This approach will indeed enable the motion of robots into narrow spaces and debris, or through voids.

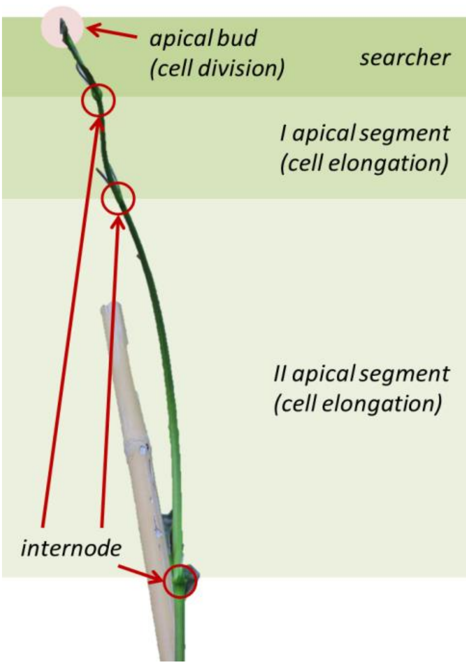

Figure 1. *Apical components of climbing plant shoot.*

Diverse climbers have evolved a wide array of structural innovations to develop: (a) searcher stems that are stiff, and (b) various “gradient” modifications in the stem that allow “cheap” but effective “supply tissues” development to cross voids. In addition to this overall organisation, “active mechanisms” of movement towards or away from environmental cues, as well as active and passive forms of strong or weak attachments, are additional design features which need to be integrated into a growing truly climbing artefact. Many climbers have evolved a “two-step” attachment process where passive attachment via hooks or spines can stabilize and lodge the growing stem before active mechanisms such as twining, or tendril organs can form a strong attachment. Changes in stiffness and rigidity can involve completely different mechanisms among different species: changes in outer shape geometry from circular to star shaped cross-sections (*Hylocereus setaceus*, Cactaceae), changes in wood growth from highly stiff to highly compliant wood types (*Condylocarpon guianese*, Apocynaceae) and from a stiff outer primary fibre layer and an internal growing cylinder of compliant wood (*Clematis vitalba*, Ranunculaceae). First step attachment of stems to stabilize the growing stem can generate static friction coefficients from 0.75 to over 4.0 via tiny hooks that are up to 0.2 mm in length. Irreversible, long-term, high strength attachments via twining tendril like hooks in *Strychnos* sp. (Loganiaceae) and *Bauhinia* sp. (Fabaceae) can generate up to 130 N of attachment force with just 3-5 g of hook biomass.

The importance of size and plant morphology in general and searcher or stem geometry in particular becomes evident when considering the axial second moment of area. This parameter is a mathematical/physical description of spatial material distribution within an object, which - multiplied with the materials Young’s modulus - gives us the flexural stiffness of the plant organ in question. Whereas freestanding trees like oaks or maples show a significant increase of their flexural stiffness, partly by a massive increase in axial second moment of area due secondary growth, partly by a significant increase of structural Young’s modulus during ontogeny, non-self-supporting lianas exhibit a significant decrease in structural Young's modulus in older stem parts, which at least partially offsets the stiffening effect of the secondary growth [20].

4.2 Perception and Behaviours

The adaptive growth of plants is grounded on the ability to perceive, differentiate, and respond to environmental stimuli. Particularly, the sensitivity to contact stimulation (mechanosensing) is vital for climbing plants because they need to rapidly find an external support and understand if it is suitable or not for their growth, otherwise they perish [16], [21].

The exact physiological processes of mechanosensing are still largely unknown; however it seems safe to assume that Ca^{2+} signal transduction pathways are involved [22], [23]. In the case of the touch-sensitive tendrils of *Bryonia dioica*, the authors in [24] were able to identify protrusions of the epidermal cells that presumably act as mechanosensors. These so-called tactile bleps contain conspicuous cytoskeleton rings consisting of microtubules and actin filaments and most probably do not react to pressure but to the sliding movement of a rough surface.

However, plants possess many different types of sensing. Beside touch, they can perceive light, moisture, gravity, and chemicals [17]. Natural environments present many challenges to growing plants, and the consequent signalling that plants perceive from their sensing system can be considered to be extremely complex. This enormous complexity of signalling ensures that no plant behavioural response is automatic [25]. Instead, selection will favour the individuals that can better assess the emergence of a particular behavioural action, and an optimised shape. Particularly interesting is that they accomplish such behavioural actions without the need of centralised control systems. Instead, internal and environmental cues are processed in an organised way at a very peripheral level, so that the final behaviour is largely the result of a sum of single minor decisions. Elementary decisions that plants can take are the directed grows, towards attractants and away from repellent stimuli (i.e., movements named tropisms [17]), essentially by means of anisotropic deposition of structural materials or by turgor changes occurring asymmetrically in a plant organ.

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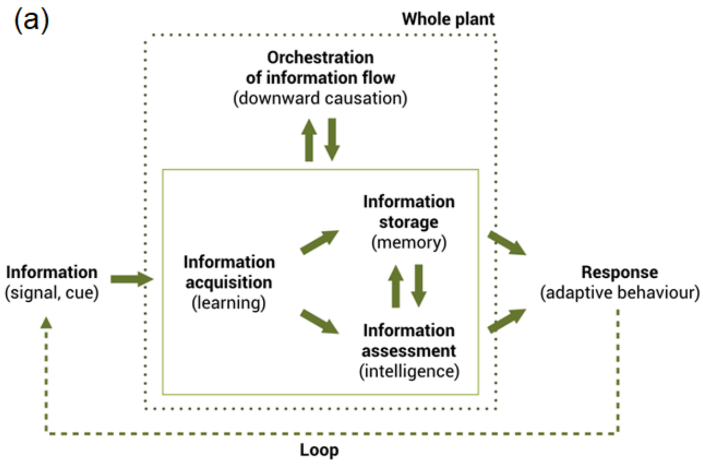
It is generally assumed that plants grow towards light and are therefore positively phototropic. For root climbers and adhesive-tendril climbers, however, this statement is only valid to a very limited extent. Directly after germination e.g., the adhesive-tendril climber *Parthenocissus tricuspidata* exhibits positive phototropism to ensure rapid growth. When the creeping shoots become longer phototropism changes [26]. Since they have to find support (e.g., the base of a host tree) which is usually located in the darker areas of the underbrush, they become negatively phototropic. It seems that they react to a light intensity gradient in their proximity [27].

As the biological counterpart, GrowBot will embed a series of sensors that enable the robot to understand and explore the environment. These sensors will be distributed along the body of the robot, either in the form of multi-functional materials constitutive of the body or as discrete sensory arrays, and will be also embedded in a searcher-like component of the robot.

The complexity of the data processing is increased by the fact that these signals arrive simultaneously. Decisions among often conflicting signals have to be made and priorities are determined on the task that should be performed.

In the robot, all the data will be locally integrated and then transmitted to a computational unit that will activate the proper behaviour.

Figure 2a shows a representation of the information flow involved in the expression of an adaptive behaviour in plants.



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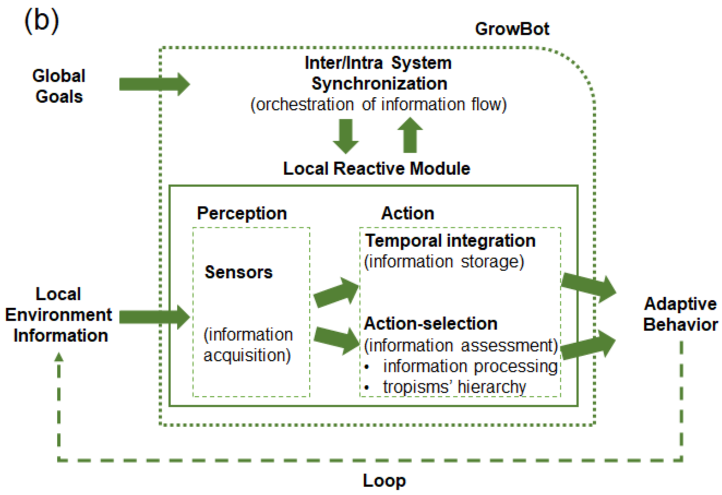

Figure 2. ***(a)*** *A schematic representation of the information flow. Adapted from [25].* ***(b)*** *The proposed control architecture.*

For many plants, the only available forms of action are either growth or discarding of parts, both of which involve a change in the organism size and form [28]. Similarly, GrowBot will be able to move, and adapt its shape according to the stimuli coming from the environment. The proposed actuation mechanism is designed in order to be able to grow in air, to overcome obstacles, and change direction to move toward a specific target.

In order to enable adaptive behaviours in the artificial system, we take inspiration from the sensory-motor behaviour in biologically growing systems. The growing appendages in plants base the orientation of their future state by reacting positively or negatively to external stimuli, accordingly to the *tropisms* [29]. Due to their sessile nature, the timescale of sensory-motor loops is significantly elapsed; consequently, their behaviour is inextricably linked to their information processing capabilities. As shown in Figure 2a, it comprises of three key aspects: **(i) information acquisition** - the plant, at the most elemental level, is able to process a wide array of noisy signals arriving from the surrounding local environment. In particular, temporal integration plays a central role in the behaviours of plants shoots [30] since the sensing of a certain stimulus locally causes an effective action or change in the system, provided that it persists throughout a certain time interval; **(ii) tropisms hierarchy** (information storage and assessment) - the plant is able to prioritize and optimize the received signals for achieving optimal growth; **(iii) inter/intra-plant synchronization** (orchestration of information flow) - the plant receives information at different levels of hierarchy, cellular molecules, tissues, plant populations, etc. As the strength of the connection between the hierarchical levels weakens, the plant becomes more plastic to its surrounding environment.

Considering the above description, the basic idea for the control architecture for a growing robot is a distributed architecture comprised of multiple local reactive modules as shown in Figure 2b. The long-term behaviour of the robot is driven by the need to optimize a weighted sum of global goals that computationally represent the desired task (referred to Section 3), for example, maximizing the distance between its actuators in case of exploration of unknown environments, or movement towards a stimulus in environmental monitoring tasks. At the local level, behaviour [30] arises from a reactive architecture which refers to a closed-loop combination between a perception module and an action module. In the perception-module, the information will be acquired via the temporal integration of the stimuli during a plausible time interval, similar to its biological counterpart [31]. Therefore, motor

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commands are a consequence of sensory feedback in an asynchronous and modular manner. However, in contrast to existing reactive architectures where actions are executed as soon as a stimulus is received, the sensory-data fed into the action-module can be exploited for designing a tropisms' hierarchy to choose the optimal action, based on the GrowBot scenario of use (see Section 3). Note that for a given application, this also requires to identify the magnitude (positive or negative) for the most relevant tropistic mechanisms. This is effective to generate intelligent local behaviour, such as optimizing between conflicting signals to achieve a task. The overall behaviour of the robot is a result of the interaction of local reactive architectures via the inter/intra-system synchronization. A traditional view is to consider them as to compete and/or coordinate local reactive behaviours such as through Swarm Intelligence [32]. However, we will investigate new control approaches, which should have a low computational cost but should synchronize the local behaviours based on global information (on the top of Figure 2b).

Note that since the global goals of the system will be accomplished in the long-term, the updating frequency of the inter-intra synchronization module of the system is slower than the one related to the distributed local control modules (on the bottom of Figure 2b). Thus, at the bottom of Figure 2b, the final actuators work at a higher frequency because they should quickly react to the received external information and stimuli, adapting to the unknown and unpredictable environment. These reactive behaviours represent the short-term goals of the robotic system which gives a higher priority to the interaction with the surrounding world and modulates the final next state of the final actuator. The modulation is done by weighting the collaborative command, received from the top of the control architecture (on the top of Figure 2b) with the higher priority reactive actions that each actuator experiences (on the bottom of Figure 2b).

4.3 Support Identification

Climbing plants need to attach themselves to neighbouring plants or other external supports in order to grow vertically and enhance light acquisition [33]. Supports availability promotes climber diversity in forests [34]–[36], and other habitats [37]–[41].

In order to increase the probability to touch a support, some climbers adopt revolving movements [42] whose oscillations were correlated with periodic and partly reversible volume changes, mediated by turgor, in the epidermal cells of the bending zone at the apical level [43], [44]. Such area extends to the two or three internodes below the apical bud (Figure 1) [45] [18], [46], [47]. This part of the climbers is indeed highly functionalized, with enhanced thigmotropism, and sensitive to specific aerial chemical gradients. It also possesses structural modifications enabling the plant to gain a strong grasp on the chosen support. Once a proper contact is detected, the plant starts to grow on the support. From a biological point of view, it is not clear if plants have a precise knowledge of where the contact happened, or how they discriminate between the different stimuli. However, some investigations have been performed to understand to what extend a sort of recognition of the support exists by the use of cues different from touch.

For instance, in [48] the authors evaluated the capabilities of the tropical vine *Monstera gigantea* to localize the host tree by looking at the elongation of the stem, and its inclination with respect to the host of seedlings placed at different positions around the tree. Results show that all the seedlings were growing towards the darkness sector of the horizon (skototropism) produced by the host trees shadow. This attractive behaviour was observed to decrease with the distance to the tree, and to increase with larger tree diameter.

The twining vine *Ipomoea hederacea* (morning glory) was instead adopted to investigate the ability of the plant to distinguish among different objects (corn plants used as host or stakes), and objects with

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different colours (e.g., black, red, blue, yellow, green and white stakes or painted structures) [38]. Greenhouse experiments showed that morning glory plants grew preferentially on corn plants (92%) and over green and yellow stakes (75%). Instead, field experiments showed that the plant grew preferentially on green (67%) and white (64%) structures and corn plants (61%). These results suggest that the reflectance of the objects can affect the preferential direction of growth.

Moreover, experiments on the parasitic climbing plant *Cuscuta pentagona* (dodder) evaluated the role of volatile chemical cues in directing the growth towards a valid support [49]. Particularly the authors demonstrated a preferential attraction of the dodder to natural supports (i.e., plants of tomatoes) (73-80% of seedlings grown towards the target) instead of artificial supports (40% of seedlings grown towards the target).

To mimic similar behaviours, we will implant thigmotropism in a searcher-like component of the robot by integrating a continuous sensing structure. The data will be locally integrated and the decision will produce a change in the global behaviour (i.e., coiling around a support or move the robot toward a specific target). In addition to tactile stimulation, other tropisms can be also envisioned in the apical part of the growing robots, which could be either obtained with constitute body materials (e.g., to perceive and react to environmental humidity, light, chemicals) or through the integration of discrete sensors (e.g., time of flight, chemicals, temperature, light reflectance). These will enable the robot to capture different properties from the environment and thus navigate toward selected targets.

Circumnutation and tropic movements will be implemented taking into account model parameters. A recent work [50] presented a mathematical model relating the dynamics of the 3D geometrical form of plant circumnutation with the underlying differential growth. Assuming that differential growth is synthetically interpreted in GrowBot, the model can in principle be applied, allowing relating desired cricumnutation kinematics with the required differential growth kinematics. As part of **WP3**, TAU is working on developing this in the Frenet-Serret frame based on differential calculus, which is convenient when describing the kinematics of a curve in 3D, and particularly useful for continuum robots [51]. This framework will also include tropic responses, based on previous models [52]. In this context the model will allow to relate the kinematic response to an environmental stimulus, while also providing the required differential growth pattern.

4.4 Anchoring Strategies

Climbing plants have been traditionally classified according to their attachment mode (i.e., twining plants, leaf-climbers, tendril-bearers, hook-climbers, and root-climbers) [46], [53]. The type of attachment determines the extent to which a climbing species mechanically parasitizes neighbouring vegetation [54]. In this section, we will consider only mechanical strategies for anchoring, while in Section 4.5 we will consider adhesive mechanisms.

Twiners are climbing plants which wind themselves around poles, ropes, and rods with their touch-sensitive main shoot, and grow upwards in this way. To find the proper support, twiners use exaggerated circumnutations. When the stem encounters a vertical support, the habit and the rhythmic pattern changes and starts to coil around the support in a helical form. The geometry of the stem changes in a predictable way with the diameter of the supporting structure [55]. On thick supports, the vine makes coils with long wavelengths and small curvature and torsion [42].

Leaf-climbers are a class of plants that climbs using sensitive petiole as aid. These sensitive organs include modified branches or peduncles, which changes their thickness in response to pressure or friction [56]. Similar to twiners, leaf-climbers perform circumnutations to search for a support. Once a contact is established, the sensitive petioles bend and clasp the support.

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Another class of climbing plants consists in **tendril-bearers**. Tendrils are long, slender, filiform, irritable organs, derived from stem, leaves, or flower peduncles [46]. The movements of the tendrils to search for a support can be classified in three main phases: i) circumnutation, ii) contact coiling, and iii) free coiling. The contact coiling involves perception of mechanical stimulus. As a result, the tendril starts to coil around the support after touching it. In the free coiling phase, the tendril develops helical coils along its axis that draw the stem closer to the support [57].

Hook-climbers use recurved spines, hooks, or thorns as aid to support the plant weight while growing. Differently from other climbing plant, hook-climbers may not have spontaneous revolving movements [46] and passively attach by landing on other vegetation. As a consequence, the attachment is not firm on the support.

Among the just described anchoring strategies, we find that the twining plants with their coiling behaviour are the most promising to integrate in the GrowBot artefacts. In fact, these strategies allow exploiting the whole body of the robot as an anchoring mechanism while maintaining growing capabilities. A searcher-like subsystem will be adopted to identify and to guide the growth of the robot toward a valid support, and some passive strategies will be also implemented to lock to different substrate by imitating the hook-climbers.

4.5 Adhesive Mechanisms

A different attachment strategy implemented in climbing plants is the use of a viscous adhesive secretion. This adhesive mechanism allows **clinging climbers** to ascend supports of almost any diameter or texture [35], [46], [58], [59]. However, it is unusual for this type of climbers to extend to more than the primary host because the mode of attachment requires close contact with the surface to adhere. In this class of climbing plants it is possible to find **root-climbers** that use aerial root hairs with adhesive pads to attach to the substrate, and **tendril-climbers** with specialised organs that produce adhesive pads that are used to attach themselves quite strongly to a support. In case of e.g., *Parthenocissus tricuspidata*, the attachment structures consist of a coiled main tendril axis, bearing several side axes terminating in attachment pads. Under tensile load, first the coiled tendril gets extended before individual attachment pads start failing. Rather than maximizing the system's maximum failure strength, this increases the amount of energy the attachment system is able to dissipate without failing [7].

From the literature it emerges that the secretion of the cementing substance and the complete development of the adhesion pads might depend upon touch stimuli [59]. The adhesive secretion – mainly composed of polysaccharides – may be produced from modification and remobilization of wall components of the papillate cells [60].

Attachment is one of the key points to allow GrowBot to overcome vertical walls and thus reach a great height. We plan to implement these adhesive strategies by using a miniaturized multi-head spinner capable of producing fibrillar material (**D5.3**) in combination with a polymer that enables adhesion (**D4.3**).

4.6 Energy Sustainability

Taking inspiration from the ability of plants to preserve, store and generate energy for powering their functionalities, GrowBot aims at developing multi-modal energy harvesting systems, primarily based on Microbial Fuel Cells (MFCs) and plant-robot interfaces for energy harvesting.

The research activities on plant energy harvesting aim at investigating the possibility to gather energy from the aerial and underground structures of plants.

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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.

MFC technology with plants leads to Plant-MFC technology (PMFC), where the continuous source of organic compounds dissolved in the medium are not externally dosed as in standard MFCs, but it comes from the proteins and sugars generated during the photosynthesis and after excreted by plant's roots, in a process called rhizodeposition. The net carbon (C) metabolized during photosynthesis are used for plant's breathing and growth, but up to 60% of this Carbon ends up in the soil excreted through the roots as exudates, and most of such compounds (lysates, mucilages and glucose derivatives) are kept in the plant's rhizosphere, where they will be used as fuel for the cells. The energy production of the microbial fuel cells would depend on the availability of organic compounds in the soil and the anode surface in the cell. Power output can be expected to be 12-15 mW/cm2, when using C4 plants with suitable rhizodeposition yield, such as *Paspalum vaginatum* and *Zoysia japonica*.

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. In order to obtain a higher energy output, there will be an initial assessment to combine MFC technology with other sustainable technologies to implement a bio-based hybrid system. For instance, a hydrogen reactor, which similarly to the plants utilises water and sunlight (harvested by solar panels) to obtain hydrogen, would be used as fuel. The main advantage of this technology is that it avoids CO_2 production and the hydrogen can be stored for on-demand requirements. The combination of both technologies could offer a tailored bio-based hybrid system to obtain renewable energy to be able to meet the GrowBot energy requirements.

In order to implement an energy harvesting system that uses the interaction of real plants with GrowBots, artificial leaf-like structures are developed based on thin layers of silicone elastomers (0.5 mm) deposited on flexible electrodes (0.2 mm ITO-PET). The leaf-like structure will be assembled close to real leaves in a manner to create a mechanical contact between the two when moved by wind or rain. By mechanical impact between real and artificial leaf, charges are generated on both leaves surfaces due to the triboelectric effect. The shape of the artificial-leaves will match sizes and shapes of real ones.

In order to establish a proper connection between the GrowBot artefact and the plant, an electrode must penetrate the inner plant tissue or contact the outer plant surface in a way that a connection to the inner tissue is provided. For this, soft, compliant thin-film electrodes based on conductive polymers will be developed based on previous systems [61]. The energy yield will be a function of the availability of environmental mechanical energy, i.e. wind speed. A power output of about 15 $\mu W/cm^2 * N$ (per leaf area and impact force) can be expected, for example by a leaf of ~70 cm^2 reaches 1 mW [62]. Several leaves will be coupled to multiply the power output by increasing the total surface area. In general, the methodology is not limited to certain plant species as a feature (cuticle-tissue double layer) apparent in all land plants is used to convert the energy [62]. Nevertheless, most suitable plant species for the plant-hybrid energy harvesting strategy are the ones that combine features like large leaves and mechanical stable leaves (such as e.g., *Rhododendron, Nerium Oleander,* etc.).

An ad-hoc electronic system will be developed to combine the MFCs and the plant-robot hybrid energy source to reach a positive power balance. This will allow powering selected functionalities of GrowBot such as the sensors distributed along the robot body which can be activated selectively and only when needed.

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5 GrowBot Integrated Design

Some of the above mentioned functionalities will be integrated to fit the requirements of the proposed scenarios of use (Table 1). In fact, besides independent artefacts proving basic working principles of climbing plants, GrowBot consists in the development of three different highly specialised robotic artefacts: 1) an **ivy-robot**, 2) a **twiner-robot**, and 3) a **vine-robot**. The three systems will be designed to address specific tasks (e.g., overcoming voids, detecting a support) and to demonstrate unique behaviours (e.g., crawling vs. climbing) characteristic of climbing plants. Even if the technological compartment will be highly specialised, the systems will share common biologically inspired strategies for sensing, moving-by-growing, energy harvesting, and adaptive behaviour. In the following, we will present the key aspects of each of the proposed devices and their preliminary architectures.

5.1 Ivy-robot

Ivy is an evergreen, ground-creeping plant that can climb over different types of surfaces and then reach a great height. The juvenile shoot of the plant possesses small aerial roots used to affix the shoot to the substrate. This ability is the main inspiration for this robot that will result from the integration of the structural material developed in **Task 4.1** and the microfabricated spinner of **Task 5.1**. Ivy will be able to grow over and attach to different surfaces by extruding from its tip a combination of materials that can be shaped either as circular section of the growing structure, or out of that to create mechanical connections with external substrates. The small diameter (expected size in the range of 20-40 mm) and the ability to attach on uneven surfaces make Ivy a perfect candidate for the scenario S5 of **structural consolidation**.

Attachment of growing organisms to surfaces often makes use of compounds called catechols. Catechols are aromatic diols that – partially through H-bonding and metal chelation, partially because of oxidative polymerization – interact very strongly with a staggering amount of substrates [63]; the best-known example is possibly the use of catechol-rich proteins in the adhesion of mussels [64]. In plants, catechols are predominantly used as precursors of structural elements, e.g. being converted in lignin through oxidative polymerization by laccase [65]. However, although not yet brought to light, they may alsohave an adhesive role: catechols are present on the surface of many plants including ivy (urushiols), and chemically they behave similarly to animal-derived catechols, e.g. they polymerize oxidatively to produce lacquers.

However, although not yet brought to light, they may also play an adhesive role: catechols are present on the surface of many plants including ivy (urushiols), and chemically they behave similarly to animal-derived catechols, e.g. they polymerize oxidatively to produce lacquers.

What is, however, certain is that ivy and other climbing plants attach on vertical substrates also by secreting pectins and arabinogalactan protein-based nanoparticles [66], which penetrate substrate crevices and there interlock upon hardening through calcium cross-linking. This mode of adhesion possibly combines with the above-mentioned mode of action of catechols.

In the ivy-robot, both these modes of adhesion will be combined, utilizing i) a pectin-based resin as spinnable material [67] to fill crevices of substrates and ii) co-solubilized catechols and appropriate enzymes such as laccase, resulting in the *in situ* oxidative polymerization of the catechols [68]. The resulting adhesive material will be completely environmentally friendly as it is only derived from naturally occurring and plant-based materials.

To achieve this adhering behaviour while the ivy-robot is growing, two different strategies can be used; leveraging micro/nano electrospun fibres as adhesive. In the first method, nano fibres of the pectin-

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based adherent can be deposited through the holes of a robot body skeleton fabricated by a coarse 3D printer (e.g. fused deposition modelling, bioplotting, low-temperature extrusion-based additive manufacturing) on the growing module. The fibres are spun from the internal part of the robot toward the grounded skeleton and may be pushed out towards vicinal substrates using a coaxial gas jet, thus creating a continuous matt from the internal wall of the robot to the substrate. This method of adherence is schematically described in Figure 3.

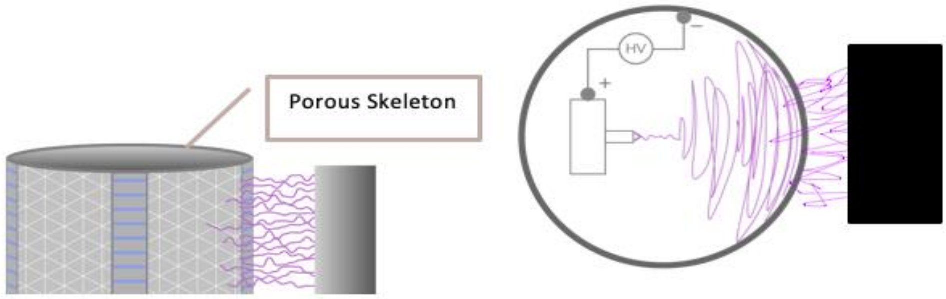

Figure 3. *Adhesion using nanofibers throw porous skeleton; exterior view (left) and a top-down cross-sectional view (right).*

A second possibility to use nanofibres to establish a strong adhesion with surrounding substrates, although less geometrically precise, is to deform the robot body itself to grow close to the substrate and to adhere to it directly using the same nanofibers used to build the robot. Thus a composite material of robot body with glueing component can be co-electrospun forming a body adapted to its environment and adhering to any contacting surface. As a robot body material, crystalline polymers could give the necessary supporting function. If these are also degradable (e.g. PLLA, PGA, PCL) the materials will be temporary and environmentally processable (no long-term waste left behind). Also in this case, a gas assisted electrospinning will help the creation of the structure and the concept can be envisaged as in Figure 4.

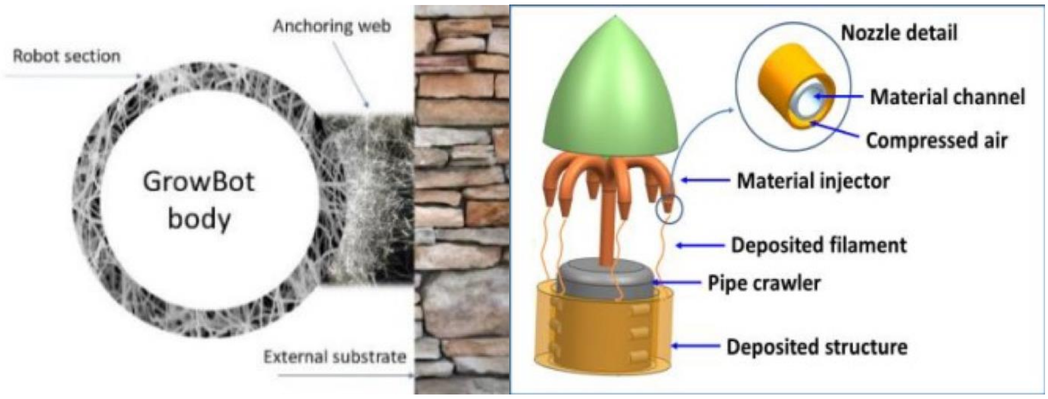

Figure 4. *Deformable body completely made with nano fibres which comprise structural as well as adherent components; overview of the robot structure (left) and more detailed schematic of the self-building/growing robot (right, electrospun fibers could be depositied from the pipe crawler).*

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5.2 Twiner-robot

A twining vine is a plant that climbs by its shoots growing in a helix, in contrast to vines that climb using tendrils or pads. Taking inspiration from this class of plants, the Twiner will integrate the growing mechanism developed in **Task 5.2** interconnected with the soft searcher-like robot of **Task 5.4**.

Its slender shape (final expected diameter size in the range of 20-60 mm) gives the Twiner the ability to move in narrow spaces, to grow in any direction, negotiating obstacles via creeping and climbing, spanning voids, and searching for targets. These features will enable the Twiner to easily accomplish **exploration** and **monitoring** tasks.

The Twiner will integrate the technologies developed among several project work packages. In particular: energy harvesting subsystems (**WP7**), structural functionalized materials (**WP4**), growing mechanism (**WP5**) and the searcher-like unit (**WP5**). Robot behaviour (**WP6**) will be implemented in the searcher module and it will guide the robot movements. A trunk-like body will be developed (**WP8**) to manage the material distribution and to collect energy. Communication among different units will be performed by BlueTooth links and the robot high level behaviour will be managed by a user through an ad hoc developed GUI. The Twiner general architecture is shown in Figure 5.

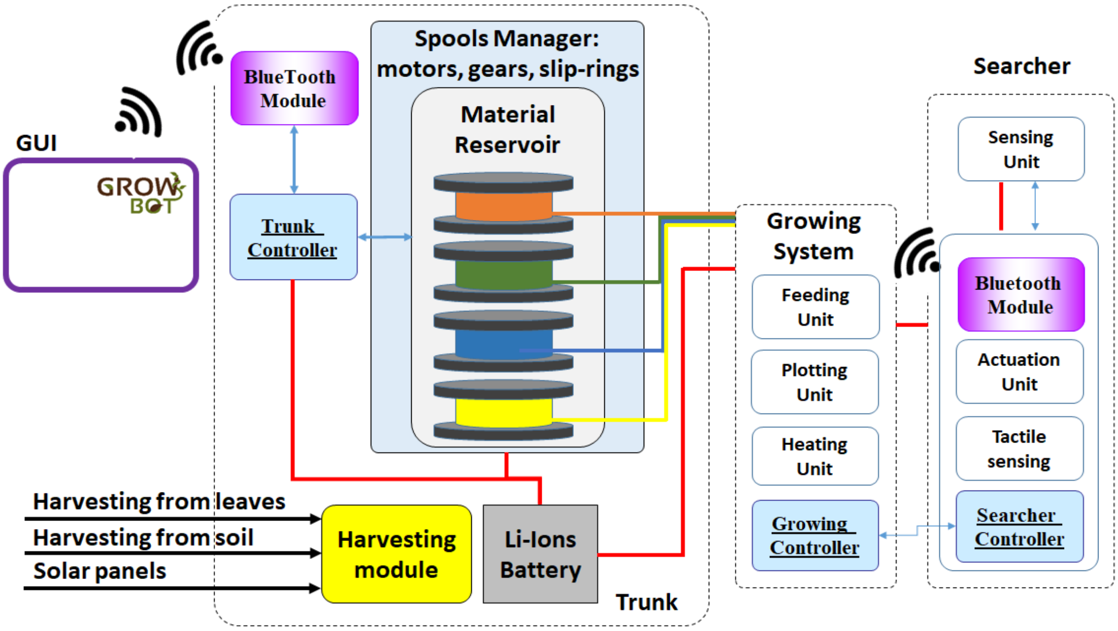

Figure 5. *Robotic architecture of the Twiner.*

The robot behaviour will be located in the *searcher* that will work as a central decision unit. The communication among the robot subsystems will be implemented as shown in Figure 4. Four main subsystems will exchange data among them, the *searcher*, the *growing mechanism*, the *trunk*, and optionally an operator (through a user interface).

The *trunk* stores the high-level configurations to be sent to the *searcher* - e.g., the task to be implemented, or which stimulus to follow. At start up, it sends this information to the *searcher* that sets its behaviour accordingly. On the base of its spatial configuration, the *searcher* sends the growing direction and speed to the *growing mechanism* that adjusts the plotting and feeding speeds. Thanks to a kinematic model implemented on its controller, the *growing mechanism* is able to estimate its position which, together with its status data, is sent back to the *searcher*. In turn, the *searcher* will send its

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relative position and the sensors data to the *trunk* that will provide all the information to the operator. A summary of the communication architecture is shown in Figure 6.

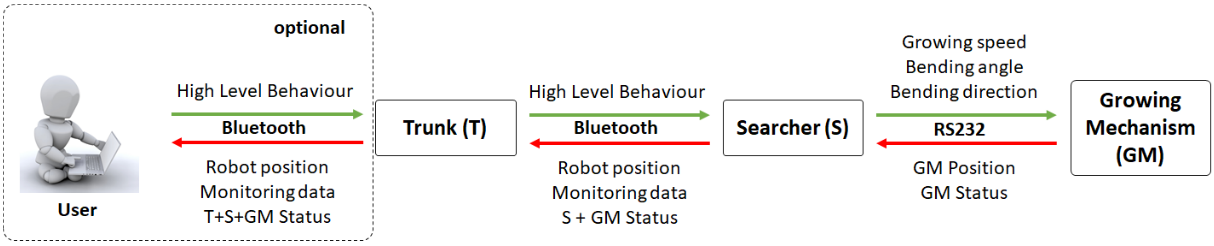

Figure 6. *Data communication architecture.*

The *growing mechanism* will have the capability to manage the simultaneous deposition of various filaments (from 2 to 4) permitting the realization of multi-material body structures. The structure will be realized by fusion and adhesion of the layers together with localized heating performed only at the interface between the old and the new layer. This approach, different from classic 3D fused deposition modelling (FDM), will help to decrease the energy demand and to accelerate the plotting speed. In fact, having multiple extruders working together allows tuning the growth velocity as a function of the number of layers deposited in the same unit of time.

Commercial materials will be exploited for the deposition mechanism, with particular attention to those with lower melting point temperature (e.g., PCL) and other with flexible properties (e.g., NINJAFLEX®). Other functionalized materials developed within the project (**WP4**), like actuators based on fibres, will be also tested to add sensing capabilities to the robot body. Mixing different types of thermoplastic materials (e.g., mixing stiffer layers with flexible layers) will contribute to supply different degree of compliance to the structure, which might enable bending and elongation along the robot body in specific desired points according to the pattern of printing.

In brief the *growing mechanism* will have the following characteristics:

- Diameter: 20-60 mm.
- Filament diameter: of the order of 1.7 mm.
- Heater temperature: from 50 to 250°C (lower temperature will be preferred to decrease power consumption and increase system reliability).
- Control: on board control for the management of growing speed and direction.
- Overall power consumption: 1-10 W.

Two major requirements of the *searcher* are low self-weight and stiffness of the same order of magnitude of the biological searcher. The former is needed if we consider that the *searcher* must be able to hold its own weight or be lifted by a growing mechanism, the latter enables the *searcher* to perform circumnutation and coiling around a detected supporting structure (possibly with low energy consumption). Excessively low stiffness would lead to static instability of the *searcher*, which is undesired. Therefore, its overall stiffness will be finely tuned to obtain the desired mechanical response to actuation, gravity, and to enable the required mechanical deformation. Since the stiffness results from materials and geometrical properties, the selection of an appropriate material and the design of the geometry have to go hand in hand. Moreover, the design of the *searcher* cannot exclude the aspects related to the integration of all sensors and electronic components.

The *searcher* will be designed as a hollow structure, containing all electronics and actuators. The material employed could be either a polymer (e.g., silicone rubber) or a metal alloy with low Young's

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modulus. The hollow geometry must be sufficiently slender to ensure the desired flexibility. A slenderness ratio (length divided by the diameter of the *searcher*) equal to 6 might turn out adequate for the purpose. A smaller ratio would lead to a bulky structure unable to bend sufficiently. For an assessment of the mechanical response of the *searcher* to actuation, gravity and contact with the surrounding environment, numerical modelling techniques will be employed (such as finite element method). From preliminary assessment, the diameter at the base of the *searcher* will be smaller than 60 mm with length around 400 mm, in the first prototype. Later, the size of the system will be reduced by performing structural optimization, if possible. To guarantee a self-sustainment and in order to not burden the below growing system, the maximum weight of the *searcher* is estimated to not exceed 0.8 kg. The position of the centre of mass will be as close as possible to the base to avoid excessive moment reaction at the base during bending motion.

To simplify the assembly as well as to improve the versatility of the system, the *searcher* will consists of two independent components, the actuation and the specialized sensing units, that can be easily attached and detached to test different tropism behaviours and to exploit the best performance according to the considered scenario. However, the two components will be highly interconnected and act as a single interface with the growing unit providing it with the information in order to direct the robot growth motion.

An initial approach to enable mobility to the *searcher* will be using conventional strategies such as tendons-driven approach and pneumatic actuation. Either the solutions must be compliant and should fit in the dimension of the *searcher*'s base.

In brief, the *searcher* will have the following characteristics:

- Diameter: 20-60 mm.
- Length: 150-400 mm.
- Control: on board control for sensing and actuation.
- Overall power consumption: 400-600 mW.
- Communication: BlueTooth Low Energy.

The trunk will host battery and material together with the mechanism to manage the filaments deployment. It will be connected wireless through a BlueTooth link to both the *searcher* and to an external computer, or tablet, for exchanging data and commands.

In brief, the *trunk* will have the following characteristics:

- Number of hosted spool: from 2 to 4.
- Amount of filament: to grow at least 5 m.
- Battery: Li-Ion battery 11.1/14.8 V with at least 5 Ah.
- Communication: BlueTooth Low Energy.

5.3 Vine-robot

The term *vine* indicates a plant which displays a growth form based on long stems that is used to grab rocks, other plants, or other supports to unload the plant's weight instead of investing energy in a lot of supportive tissue. This allows the plant to reach sunlight with a minimum investment of energy. In addition, a vine can root in the soil but has most of its leaves in the brighter, exposed area, getting the best of both environments. Vine will be based on *in situ* fabricated soft actuators for bending and

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elongation in relation to environmental changes. This will enable Vine to move by growing within debris and rubble, negotiating obstacles via creeping and climbing, spanning voids, and following targets. Vine can also anchor around tubular structures to sustain its structure and negotiate complex environments. This will be enabled by a controllable circular micro-extrusor that will deposit viscous polymer solutions (**Task 4.2** and **Task 5.3**). These features enable Vine to be used in situations that involve **exploration** and **monitoring** tasks.

The Vine-robot will combine the technologies created within the work packages **WP4** (structural functionalized materials) and **WP5** (growing mechanism and searcher-like unit). The motion of the robot will be controlled by environmental triggers (e.g. changes in temperature, intensity/wavelength of light, or humidity) initiating directed movements by deformation via bending or elongation of the on demand created soft actuator stem. Anchoring structures based on a polymeric solution of high viscosity will be generated by an integrated micro-extrusion process in order to support the movement of the soft actuator stem. The robot will be equipped with two separated material reservoirs including the actuator forming components and the viscous polymer solution. The activation of the material reservoirs will be enabled by electrical signals of a sensor device (sensing changes within the environment and calculating distances to anchorable structures) and the exchange of information within the utilized units of the demonstrator will be facilitated by BlueTooth links. The *growing unit* including the soft actuator system together with the *anchoring unit* equipped with the micro-extrusion device will determine the robot behaviour, whereby the *growing*, *anchoring*, *sensor*, and *material reservoir unit* will exchange information (Figure 7).

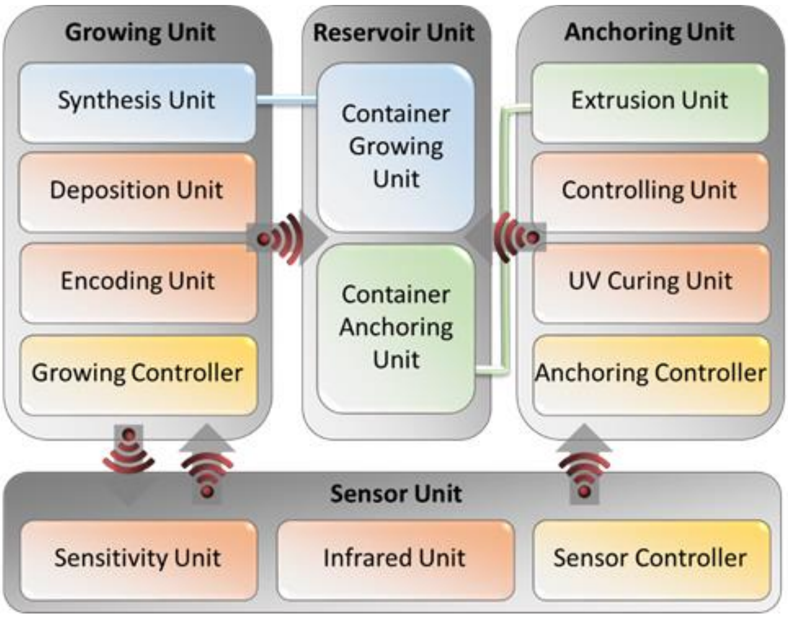

Figure 7. *Schematic illustration of the Vine-robot architecture with data communication structure.*

The *sensor unit* sends information about changes in environmental conditions to the *growing unit*, which will activate the *material reservoir unit*. Additionally, when the *growing unit* initiates the fabrication of the soft actuator stem, the information about the stem movement (direction, degree of movement, and speed of movement), which will be controlled by the environment and the kinetic of environmental changes, will be noticed by the *sensor unit*. According to the generated movement of the Vine-robot, information about distances to and the position of anchorable structures will be collected by the *sensor unit* and once, a distance falls below a defined value, the *anchoring unit* will be activated to produce micro extruded structures.

The growing motion will be realized by the *growing unit*, which will enable the *in situ* fabrication of the controllable soft actuator as a structural material. The *growing unit* will provide an integrated approach combining material synthesis, a controlled deposition (e.g. via a pneumatic process), and encoding (programming) the actuation information. As printable actuator materials, already established polymeric systems, e.g., based on crosslinkable PEVA / PCL or blends thereof, polyurethane foams, and thermoplastic, crystallizable (co)polymers, which can be activated via changes in temperature between 10 °C and 60 °C will be explored. As another material concept, temperature-, photo-, and humidity-sensitive hydrogel actuator systems will be designed by incorporating thermo-sensitive (e.g. crystallizable polyesters), photo-sensitive (e.g. gold nanoparticles), or humidity-sensitive (e.g. hydroxyethyl cellulose or hydrogels) micro- or nanofillers will be utilized for the in situ fabrication process.

The anchoring capability will be realized by a controllable circular micro-extruder within the *anchoring unit*, which will be directed by the sensor data collection about distance and position of anchorable structures. The micro-extruder will be controlled via temperature and pressure and includes a 360° rotating extrusion head, which is equipped with a multi-lumen die enabling the deposition of polymeric materials in well-defined circular geometries (e.g. layered or core-shell structures). The creation of numerous anchoring architectures will be realized by adjusting the feeding temperature and pressure, speed of extrusion head, and by the material distribution during the extrusion process. The local actuating capability of the generated Vine-robot elements will be enabled by the deposition of oriented macromolecules via spatial control of the applied extrusion shear stress. As a special feature, the extrusion head will be equipped with an on demand addressable UV curing device providing in situ crosslinking of the deposited material. The *anchoring unit* will be connected to the *material reservoir* containing single/multiple polymer melts, polymer solutions of high viscosity, or gel forming components. In order to realize interfacing the actuator components and the activation of, e.g., a thermo-reversible movement, conductive fillers such as silver, carbon black, carbon nanotubes or graphite can be incorporated into the *material reservoir*.

The *sensor unit* will contain sensors able to identify environmental changes, e.g., in temperature, light, or humidity, and will additionally include an infrared-sensor module providing information about distance and position of anchorable structures.

The *material reservoir unit* will contain two separated material containers including i) the polymer melts, polymer solutions of high viscosity, or gel forming components and ii) the crosslinkable/thermoplastic (co)polymers or the stimuli-sensitive hydrogel actuator systems. The containers will be connected with the *growing unit* and the *anchoring unit*.

The different *units* will have the following characteristics:

- Diameter: 20-60mm.
- Control: on board control for sensing or actuation
- Overall power consumption: 1-10W.
- Communication: BlueTooth Low Energy.

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