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Interview with Barbara Mazzolai: Plants, Plantoids, and Active Materials

KK: The research on active matter includes studies in smart materials, hence materials that sense and react to the environment. In your research, you examine the ‘smartness’ of plants and you use these studies for bioinspired robotics. Exemplary is your work on the plantoid: a robot that one might say replicates the behavior and mechanisms of plants. It is part of a new generation of plant-inspired robots – a plantoid does not have a humanoid form but, like a plant, it has not only a trunk, branches, leaves but also roots. These roots grow due to the addition of synthetic material printed in 3D from the inside, and move and orientate themselves in their surroundings thanks to sophisticated sensors positioned in the tips of the roots. Therefore, these robots are able to move by growing and explore the environment with their sensors. But before elaborating on your research on plantoids, maybe you can tell us how you consider robots and their connection to living beings and to plants in particular.

BM: Robots, and more specifically bioinspired robots, can be interestingly linked to living beings and used to better understand how living beings work. One of my research challenges is to use biorobotics as a tool to investigate and explain the strategies and functionalities of natural organisms. This understanding is fundamental to get closer to a full knowledge of a natural system and for its safeguard. With respect to plants, this closeness is particularly absent because, in school, plants are only considered for oxygen and food production, but are not really understood from the point of view of how they work. Robots could help in this respect. This must not be understood only in terms of the promising applications of plant-inspired robots – from exploration and environmental monitoring, to medical applications, to search and rescue in remote or extraterrestrial scenarios – but also with respect to the ways in which robots can bring us back to biology [Mazzolai, Beccai, and Mattoli 2014; Sadeghi et al. 2014; Lucarotti et al. 2015]. Having this in mind, I have investigated characteristics of plants such as growing capabilities, osmosis-based movements, strategies of carnivorous plants, movements based on circumnutations, just to mention a few. Robots, as physical and dynamic systems, could really help in the understanding of the physical interactions between an organism and its environment. In the future, robots could be a sort of tool for scientists who would use them to demonstrate the principle and working functionalities of living beings.

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Fig. 1: The plantoid: a bioinspired robot developed at the Italian Institute of Technology, Pisa, Italy, by The Plantoid Project led by Barbara Mazzolai. © Bioinspired Soft Robotics Lab, Italian Institute of Technology, Pisa, Italy.

KK: Following this, can one say that biorobotic engineering considers plants as smart material – in the sense that they are responsive to the environment – and therefore as active matter?

BM: Plants effectively adapt to the environment and respond to external feedbacks; and this is why are so relevant in biorobotics. Material for me is an essential part of this picture. We need materials which are more similar to natural materials to really interact with the environment by giving different properties and more abilities to the robots. Consequently, we have to look for non-traditional materials that are safer, even intrinsically so, when we need or want to develop a robot to interact with us or with another living system, or with the natural environment. This is something unaddressed in industrial robotics. The reason behind this is that the interaction with the human operator is usually limited. Industrial robots are rigid and strong, since this is the role one assigns them in a society based on production: robots produce the products in a factory. If one would like to see robots in another way, however, as something that shares our environment, our domestic environment – and I do not mean only for cleaning for example, but also for other means of assistance – you cannot make robots rigid. This is one of the trends which will be developed in the future, focusing for example on aspects of softness. This is also one of the important aspects of active material in order to achieve adaptive interaction, compliance, and safety. The material becomes really more and more fundamental in this type of robotics,

which is called soft robotics. Perhaps this is the wrong term. In the past, we called it ‘soft robotics’ in order to distinguish it from traditional ‘rigid’ robotics.

One of our starting models among natural organisms was the octopus [Laschi et al. 2012; Mazzolai et al. 2019]. This animal is considered as a paradigm for soft robotics, since the octopus is completely malleable (Fig. 2), without any rigid structure, and has unique abilities of squeezing and morphing. At the same time, with its arms and suckers, the octopus is able to exert very high forces, to explore the environment, as well as to grasp and manipulate objects. It demonstrates that we do not need rigid structures in every case to carry out an action. Of course, we need to consider it in its environment: the octopuses’ physical abilities and intelligence work very well in aquatic environment, but if we transfer them to our own terrestrial environment, they would certainly not be as smart. What we have to consider in this example is that environment is fundamental. A robot cannot be designed without considering the environment in which it has to act.

Fig. 2: An artificial octopus-like arm with suckers. See also: [Mazzolai et al. 2019]. © Bioinspired Soft Robotics Lab, Italian Institute of Technology, Pisa, Italy.

MF: So you would say that one of the characteristics of active materials is exactly this adaptation to the environment?

BM: Exactly. One may say that the mechanism is in the design because, in the design, environment is already included. This is something entirely characteristic of natural systems. If you consider plants as another paradigm of active materials, you can even see motion in dead organs. For example, the pine cone is dead but it continues to move. What is impressive from my point of view is that the life of plants is perpetuated by structures that are dead but continue to work. Energy use is anticipated in the design phase.

KK: Could one say that in the case of the pine cone, the energy is stored in its anisotropic material structure and when triggered by the environment in the right way this energy is consumed for a certain activity?

BM: Precisely. The pine cone is activated and releases the seeds when the environment provides the right conditions for this: in terms of humidity, in terms of temperature, and so on. The pine cone is thus ‘designed’ to release the seeds only when they will find the conditions to germinate. In this way, the pine cone spreads the seeds in the environment because the conditions are right. This is amazing because one can reduce the energy strictly to the design phase. Subsequently, pine cones take their energy from the environment.

More generally, of course, if you have to do very complex tasks, you need a control system and you need external energy. But you can optimize the movement, you can optimize the control using this material. This is something completely missing in current robotics because most of the robots that we use are either made of rigid material or now soft material but without particular properties. Currently, we use most of the silicones available; because they are soft, they can in some way express this softness. In many cases, however, they do not have the proper functionality. What I mean is that they cannot really interact with the environment.

KK: Would you say that the research on active materials and especially on bioinspired materials will change our understanding of nature – nature per se but also nature as a source and a counterpart for engineering? And how do the more classical biologists look at this kind of interdisciplinary research?

BM: There are certainly people who want to collaborate and who are attracted by this multidisciplinary. But we also have to recognize that there is a lot of talk about multidisciplinary while in actual fact it is hardly done at all. However, one has to remember that people in the past did work in a multidisciplinary fashion. Take Leonardo da Vinci for example, or even the entirety of the Renaissance. They carried out their work precisely in this way and created great things.

I know that much of the technology that we use is not bioinspired. I do not want to say that we can solve the problems of the world by means of bioinspiration. You have to select when it is needed. What I mean is that we should have a critical approach. In some cases, you quite simply do not need bioinspiration. A traditional approach can sometimes be more convenient. That said, I think there are many great bioinspired examples that we use every day. We simply do not recognize that they spring from such sources. Hence, this is the goal: to have something novel that can also be used in new contexts and that can open up new fields.

MF: I would like to return to the example we started with: the plantoid (Fig. 1), a robot that was developed in part as a result of a ‘simple’ question: how do roots behave? Can one argue that with this example there is a new conception of the plant? As you mentioned before, the plant was considered in the past as something that was not, so to speak, intelligent. What is this new conception that you are introducing here with respect to roots, and how is this then translated into robotics?

BM: I arrived at the study of plants through my experience in biophysics. When I moved from biology to biophysics I began by studying the impact of pollutants, particularly heavy metals, on human beings and the environment. I carried out experiments with natural samples, such as our blood, principally to detect and understand the impact of mercury, but also of other heavy metals. When I moved to engineering, the first idea I had was why not create a technology for detecting and understanding such things? Quite simply there were very poor technologies for monitoring in situ: for detecting polluted air, water, food, soil, and so on. Thus, I developed several robots. First, a sensor to detect mercury, then a sensory device, and only then did we move on to robots. We did so because robots are mobile. Hence, the idea was to have robots with sensory capabilities that can cover and detect a large area. One of the central problems, however, was that of the soil. Soil is so complex. How can we send a robot into the soil? This is the reason why I returned to biology. I determined that the best living beings that can carry out this task were in fact plants and not animals. Not only do plants penetrate efficiently into the soil like other animals such as the earthworm (e.g., the *Lumbricus terrestris*), the mole, and so on, but they also create a network. Plants really produce the best system to probe the soil because they develop a capillary system that penetrates it so thoroughly. We began by studying how plants accomplish this, and we used a robot to validate the biological system. We know from biology that plants grow at their extremities, but there is no evidence for why they do this. What we then did was to compare two identical robotic systems: one system able to move from the tip and the same system pushed from the top [Sadeghi, Mondini, and Mazzolai 2017]. In this way, we demonstrated that in the first condition we could save energy and reduce energy consumption during the soil penetration. We arrived at plants quite reasonably because in terms of application in the environment they are the best. With these insights, one can at least consider the possibility of using plants as a model for robotics.

KK: With plants as models for robotics, interesting features start to arise: first, that growth is a way of moving through the environment; second, the idea of a network, or maybe even a multitude; and third, the involvement of plant communication, or at least signaling ...

BM: ... and actuation, because there are also other actuators. It is a revolution simply because for the first time we can start to talk about growth as movement. This is a new paradigm for the concept of actuation. Usually, in bioinspired robots, the model is the animal; consequently, the model for the actuator is the muscle. Plants do not have muscles, but they are able to move and reach with their branches or roots points that are far from their point of germination. What we have demonstrated by contrast is that plants move by growing. They cannot move in a different way. If they have to move from here to there, they have to grow from here to there. Hence, growth is a new form of movement. And, while growing, plants adapt to

their environment – which is also part of the novelty of this kind of robot. Thus, if we are really able to implement this mechanism from a technological point of view with active material – because the secret here is in the material – we can really have a robot that perceives the environment and makes decisions. This is the intelligence of a system that is bioinspired: being able to make decisions concerning movement and direction. There are two different ways to control this robot: either the operator can control it remotely and give it commands such as ‘look for water,’ ‘look for survivors,’ ‘look for chemicals,’ or it is the robot itself that decides on the direction on the basis of high-level control. Plants are the inspiration for this latter behavior. The question is how they can manage all of this information without a brain – but they do indeed do it.

Nor is the movement of plants totally random. One of the initial observations about plants was that they only move around, without a direction. But this is incorrect, since plants have sensors, which they, of course, use. There is no sensor in biology that is not employed, since this would simply be a way of losing energy. But of course, there is a part of the movement that can be random. This is also true for animals, for example, when they do not perceive smell, the pheromone, but move in a certain way until they do perceive it and subsequently modify their behavior. Moths are typical in this respect since, when they perceive the pheromone, they reduce their movement amplitude, their energy. It is the same with plants, which also move at random for as long as they do not perceive anything. For example, when a plant looks for water, it moves randomly for as long as it does not have a gradient or chemicals to follow. Once these are perceived or sensed, however, the plant of course goes in that direction.

KK: It seems to be a situated behavior, hence a behavior that is not, or not only, determined by a DNA program.

BM: Exactly. It is something that emerges by the interaction with the environment, just as in other natural systems [Gagliano et al. 2014].

MF: Can one say that the root system or plant system is always, in a sense, in a state of nonequilibrium since, on the one hand, it adapts to its environment but, on the other hand, it also takes materials from the environment? That is, it is always on the verge of coming into being as an emerging structure.

BM: Absolutely. Plants use chemicals and water for photosynthesis; there is a communication between the roots and the upper parts of the plant. It is a continuous interaction on the basis of internal needs, state of development, and external competition, because they have to compete. It is not possible to simply be and grow; there is also a struggle for resources, competition between plants as well as between plants and animals, or parasites, and so on.

There is also the aspect of redundancy, the fact that plants have built-in redundancy in their organs.

To state the obvious, plants cannot move like animals, they just stay in the place in which they germinate, and there they can only grow. And because of this sessile nature, they cannot escape in case of an attack. This is probably the reason why they do not have a brain, which would make them too much vulnerable. Differently, we could say that plants have distributed ‘command centers,’ as well as distributed sensitive organs, and a unique capability to regenerate and create new structures.

The problem is that we are currently lacking the appropriate terminology. Very often when you talk about behavior in plants people respond that behavior is for animals, or intelligence is for animals. If that is the case, then at least provide us with some terms to describe plants.

MF: Because all of these concepts are actually connected with the idea of a mechanism that controls everything in a centralized way – that is, the brain so to speak.

BM: Exactly. Hence, there is no terminology for presenting or describing this behavior in plants quite simply because all of the scientific terminology is for animals. And this is another issue. How can I describe this behavior if I cannot use the terms ‘behavior’ or ‘intelligence,’ as these terms are strictly preserved for animals?

KK: What kind of robot could be created if one thinks of this from the perspective of the plant? Should there be a new kind of communication or movement involved?

BM: Precisely. If one defines the robot as an artefact that can move, communicate, perceive, and control parts of its structure, then all of these features are also true for plants. To demonstrate that we can use plants in robotics, I just have to start to show that they are able to communicate, move, and sense. It must be added that all of these features are *intrinsic* to the plant itself. Thus, we can translate these features into artificial systems that are robots, since they perceive and control movement and actuation.

KK: This translation of the intrinsic features of the plant to robots could entail a completely new understanding of the machine. If you think of the nineteenth century, when one first began to develop, for example, the first self-governed machines, these machines were very simple systems. Admittedly, this is still what people have in mind. For example, we think of the car as a machine; already the idea of a self-driving car is somewhat overwhelming. What you are proposing, however, seems to go even further, in the direction of a ‘growing’ machine; hence, it involves a new understanding of the machine itself.

BM: What I would like to stress concerning this new idea of artificial machines is the importance of materials for their structure and functionalities. Of course, in robotics, we already talk about intelligence, and also about different types of intelligence, for learning, motion control and communication. It must be said that material is still in its infancy in robotics. This is particularly the case when considering soft materials.

We can introduce the concept of softness, but this is still not enough. Quite simply, silicone is inadequate, since it cannot interact with the environment. Thus, we really need to implement the design phase in the material. We should work at this level. This should not only be understood in terms of assembling the components. This is the classical approach where you assemble the sensor together with the actuator together with intelligence and the control, and then only at the end do you think about the energy. And you finally come to an idea of the energy consumption of the robot when it carries out some specific tasks. By feeding this information into the motor – so starting from the motor – you can have a rough idea of the energy consumption, but then the robot is not able to really operate in the real environment. Instead, we need to think about materials that are multifunctional – in terms of sensing, actuation, and energy use – and able to evolve or grow depending on environmental conditions and needed tasks. This is what drives toward a new understanding of machines design and development.

In this direction, a new trend called morphological computation or embodied intelligence is moving. This can be considered a new paradigm in robotics, which gives importance to the body, to the shape, to the material, to the interaction with the environment, and not only to the brain. But what really is the problem? Clearly, the issue is how we are to translate this principle into the rules of design. Currently, we do not know how we can design this kind of robot. We know more or less the principle but not how to design it as such. In my case, I have an AutoCAD model from which I can start, but because the robot needs to adapt I cannot design the final shape. I can just put the design in the material as the basic principle. Essentially, it has to develop by itself. The development should be immanent in the design.

MF: Can one then argue that there is no predefined algorithm that would predetermine all future actions? I would say that there are some algorithms being structured in the design phase of the robot. Perhaps the best way to put it is to say that they are adaptive in a way – which is also the challenge.

BM: Adaptation is the key and the grand challenge for robots operating outside in the real world. Adaptation is fundamental for animals, plants, and all living organisms, and so it is for artificial machines.

Now, for this, the challenge we find in the design phase shows that you need different people like engineers, computer scientists, biologists, material scientists, physicians, and so on from various disciplines working together. This is not easy. How can we collaborate effectively? How can we involve people that work in mathematics in this phase, or people developing the control or the material, together with biologists, together with engineers, in order to work together to structure the rules? This is quite simply a necessity: we need this cross-disciplinary interaction for the design of new adaptive robots.

Unfortunately, in our world, there are many disasters: earthquakes, floods, tsunami, and so on. When observing this fact, one can quickly come to the realization

that there are currently no alternatives to humans or dogs when looking for survivors; there are no robots deployed in this fashion at all. Why is that so?

Were a robot to be deployed in a disaster environment, after a tsunami for example, it would have to have a different configuration [Murphy 2014], it would have to be able to adapt. For example, it would have to be amphibian, because it would need to move in water and on land. This model of robot would need to be able to adapt to conditions that cannot be predicted. After a disaster, the unstructured environment becomes the rule rather than the exception. In such a situation, external conditions cannot be known in advance. This is why a new model of adaptable robot is needed. A robot that can count on adaptive materials with integrated multifunctionalities, allowing it to have an evolving and growing body structure, capable to re-shape or re-form its parts, and with an efficient and sustainable use of energy. Energy is in fact also a key point, because if you collapse after an hour ...

MF: ... it is hopeless.

BM: But this is the situation. I blame it on the fact that we think in a very complex way. This is what makes our robots too complicated. We embed materials, sensors, and actuators, and then energy is the last point we address. But living beings do not work in this way.

MF: Hence, we are coming to the point where we realize that new robots, new machines should actually be much simpler and not just a very complex imitation of 'the way nature works.'

BM: Yes, I believe this is the real issue: to understand what is needed. We need to understand what is really useful and not just copy the shape of a human to have a humanoid. Why should our ideal robot be a humanoid? Why is the human form necessary in this environment? It is not the best. It cannot move in debris. Why do I want to develop a humanoid for rescue in an environment that has been destroyed? There are many living beings that are better than us. Why not then develop new creatures? In robotics, you can also go beyond nature. We should just take what is needed for some kind of application and not simply try to copy them. If I want to copy a plant, for example, I put a trunk in my plantoid because it is needed in order to relay a message, not just to demonstrate that it is a plantoid. Of course a trunk is clearly part of a plant and not of an animal, but the concept goes beyond the shape of the plant. The shape is just for pure representation. The message that I want to send requires growth, but the root does not need the trunk or the branches with the leaves. If I want to do something, to move in this environment, only the concept of growth is needed, whether what is grown be branches, roots, or something similar is not important.

MF: So, we could say that these new materials are inspired by nature, but also go beyond nature insofar as they are not simply copies of it.

BM: In the end, we use an approach very similar to a 3D printer to translate growth. But the difficulty lies in understanding the secret of growing as such. We developed several prototypes before trying a mechanism. Roots also inspire this design because they release dead cells and then move inside this interface they create. So we tried to imitate this because it was a really efficient system. We needed to be able to reduce the external friction because, when you dig in soil, after a few centimeters the system collapses from the internal friction. So, it was clear that this was not enough. In the end, we realized that growth was the key problem. But how can we imitate the addition of cells, since plants develop by means of cell division? By absorbing water from the external environment, plants also extend. Thus, they grow and then elongate.

For example, depending on the soil impedance, what occurs more: cell division or cell elongation? And for these two, what are the important factors for movement? We therefore attempted to implement growth in our robot [Mazzolai et al. 2020]. But before we had to understand that the 3D printer approach, the manufacturing approach, was in some ways a suitable solution, so we used it for the robotic root growing and bending. It took more than a year, several prototypes and experiments, and in the end, we used thermoplastic materials. The latter were not the best in terms of mechanical properties, but we could anyway use them to implement growing abilities in a machine, and demonstrate that if there was a uniform deposition in the soil, the robot could move (i.e., grow) vertically. Moreover, if we deposited the material in a differential way, bending occurred at the robotic root, as natural systems do where more cells are on one side with respect to the other one. So, imitating this feature, we implemented this differential growth also in our robot.

So, first we need to understand the key principles at the base of a functionality that we want to imitate from the natural system, and then how to translate them into an artificial system.

KK: In living systems, growth can mean different processes. There is the growth of trees, which adapt to internal needs or external conditions by adding new cells with various geometries and cell wall structures in relevant parts. There is the remodeling of bones in living organisms, which works quite differently because it includes degrowth. What kind of adaptation processes, and hence what kind of activity and agency, do you intend to translate, or maybe reinvent, in the technical sphere?

BM: So, once more the material and adaptation strategies come back to the center. Plants move in different environments, while they explore them. One of the movements they use with this aim is circumnutations, that is, elliptical or circular paths made by the apical regions of both roots and shoots. We study circumnutations in the aerial part and in the soil. For example, climbing plants use circular movements to look for support or to reduce the friction during movement itself. We are also implementing this behavior in our growing robot. Thus, the point is to understand how we can have a sensing capability in a system that is growing. First of all, you

can add sensors in the tip. There are discrete elements: chemical sensors, sensors of temperature, and so on. Yet this part is fixed; it does not change. More difficult is to add sensors in the growing part, since it continuously changes. This is why the aim is to embed sensing properties in the structural material, used to create the robotic body. Consequently, we look for a 3D structure in which these materials have a specific functionality, like a sensing capability and so on.

The other challenge to consider is the interaction of the material with the environment in time. Thus, we can go beyond the concept of 3D printing, toward a 4D approach [Khorsandi et al. 2020]. The material can provide this 4D aspect, so the robot can change its 3D shape and behavior over time. In the current version of the robot, we miniaturized a 3D printer machine inside the robotic tip and we used thermoplastic material to create the robot's structure. In the next future, the goal is to develop materials that include sensing properties.

KK: I wanted to further emphasize this point concerning interaction and sensing by asking how such a robot would be controlled. Obviously, there has to be a new understanding of control: a local control and autonomous system – a kind of ‘soft computer.’

BM: Exactly, we need to rethink how to embed the control, or better how to ‘embody’ it. It is something that must really be integrated into the material. The goal is not only to have sensing, which is fundamental, but also to associate this sensing to a form of behavior. Such mechanism is evident in plants, for example in the tropisms. This could be understood as tropism, as we have implemented it in the plantoid robot. Tropism means that the roots or branches move by turning toward or turning away from environmental stimuli. We have implemented this behavior in the roots of the plantoid, integrating sensors and using an adaptive material for growing. Another example is also in the case of behaviors that are independent of the direction of the stimulus, as is the case of the fast closure of the leaves of the *Dionaea muscipula*, the Venus flytrap. Its leaves have tactile hairs, and when a prey touches at least two hairs within a period of 20 s the plant closes, trapping the insect. The tactile feedback triggers the mechanism, and the movement is associated with the structure and properties of the leaves' material, to the system instability and to osmosis. There is therefore a motion associated with sensing – closing the leaves, movement by growth, and so on – and the ‘soft’ computer is embedded in the material.

In robotics, we still have to work on this to reach something similar. There have been a few examples, but these have occurred outside the field of robotics. The central issue is how can we merge these technologies in the robot in order to have skin/body, materials, and so on that really embed all of the needed functionalities?

MF: Can one say that the plant does not add more and more mechanisms in order to grow but that growth itself is already self-propelled in a way by the mechanisms intrinsic to the material itself? Is this the point of the design you were referring to?

BM: That is correct. I cannot add another motor because the material itself is the motor. And the sensing should also be in the material. Hence, I need a soft computer in order to implement the intelligence associated with the sensing capabilities. This is difficult, so we need to have some idea of how we can register tactile feedback in a body that is growing or in humidity and so on, because I have to perceive and register this stimulus and then implement the behavior. This could be as simple as giving one direction or another as well as the interactivity with the environment that is implied. But you are correct, the motor is not needed there, the motor is the material.

MF: In other words, to translate plant mechanics into soft robotics one does not need to centralize the control to have everything dictated or programmed in advance. The material does not even determine this, but rather reacts to the environment to make its own structure.

BM: Yes, I do not need to apply additional functionality, since it is already contained in the material. Of course, this is true for a form of functionality such as growth. But it could also be used in the case of sensing properties. The softness that we mentioned should also be present in terms of the interaction with other organisms, because I cannot work with a rigid robot.

KK: Reorienting robotics and mechanics on the basis of the research on plants provides a new paradigm for engineering. Does it also make a difference if you understand the living system as a multitude with distributed intelligence? What happens to robotics when you understand the inspiring material, the plant, no longer as a closed system but as an open one?

BM: This is precisely what one sees when one compares the root to animals that move in the same environment. There is another way to collaborate, to cooperate, not just as ants or fish or bees do, as the main examples of the swarm intelligence paradigm. There are groups of scientists working on the latter form of behavior to develop new algorithms for cooperation between robots based on this paradigm. In the case of roots, we also have this kind of cooperation for a specific task, but they are part of the same system. Thus, there are millions of agents that cooperate for the survival of the plant by having different aims. Insofar as I see it, it is much more efficient to develop a robot that can explore the environment. Why should we use just a probe?

KK: Could we think the root – its structure, properties, and in general its agency – through the environment? Could we understand the environment as part of the physiology of the plant?

BM: Plants and roots are also able to perceive vibrations, gradients. In the end, gradients are essential because plants follow them. It seems that plants also perceive vibrations. When you have an animal that moves in the soil, it does not have eyes since it has no need of them. The same is true of plants; they have no need of such

things, since the roots move in soil. But all of these animals perceive vibrations, and plants perceive vibrations as well. This is new as a sensing capability. Thus, it is a further demonstration that these systems are adapted to the environment. One cannot say that there is here a less intelligent implementation and that for other living beings there is a more intelligent implementation: it depends on the environment in which one moves. And so for *that* environment, for that task plants are actually the best adapted. This is the best shape, the best thing that can be implemented for that environment. But very often, because they do not have eyes, because they do not have a centralized system as we have, we consider them ...

MF: ... inferior.

BM: Absolutely. And essentially because they are different from us. Plants have another way of using the environment. The solution is really effected by the environment. In fact, if you compare roots with an earthworm (e.g., *Lumbricus terrestris*), they show similar adaptive solution. *Lumbricus* also has this enlargement of the diameter; it anchors in the soil and then pushes from the tip. It has liquid inside its body and contracts muscles to move. Thus, the worm can elongate and expand according to the contraction of various muscles. Roots have a similar behavior: they enlarge their diameter, they anchor with hairs, and then they push the tip, simply because the environment affects the solution. Even if the body could be different, in the end most of the solutions that living beings implement are given by the environment and the morphology. If you compare an animal with legs to a root, of course it is different, but if you compare an animal without legs to a root you will find they are very similar. Not only is the body similar but the environment is also the same.

We must consider how the environment affects the morphology and the behavior. If our robot is to move in the soil, it needs to have a similar behavior to the worm and the root. The environment is actually the decisive factor. And this is true in the design phase as well.

MF: Can one therefore take movement as an indication of intelligence?¹ Can one in fact make this definition a bit broader and say that a design that already takes the environment into account is an indication of intelligence? That is to say, insofar as a design really does not necessitate a centralized form of control.

1 [Mazzolai 2016, p. 114]: “In animals, behavior usually refers to movements generated by muscles; plant intelligence on that basis does not exist. Movement is, however, the expression of intelligence it is not intelligence itself [...]. Nonetheless, plants respond to internal and external signals. Thus, a simple definition of plant intelligence could be adaptively variable growth and development during the lifetime of the individual. Exploiting adaptive abilities in plants could lead to the development of smart devices to monitor soil – not solely with the ability to sense but with the capability to follow stimuli/gradients and to take decisions to accomplish the needed tasks.” See also: [Trewavas 2003; Trewavas 2004].

BM: I think this is very crucial because what is at issue here is the definition of intelligence that we use. This is an aspect that, with respect to terminology, is very narrow. What I mean to say is that our definition of intelligence is very narrow and it is tied to our own preconceptions of the human being.

We talk about smart or intelligent material. We say that something is intelligent because it may have sensing properties. What is meant, as we noted before, is that the control is in the material itself. Thus, one can say that plants are smart: they use the environment; they are intelligent, since they are aware of processes; they can adapt. More specifically, some scientists have recently demonstrated that plants really are capable of taking decision on the direction of growing or on other adaptation strategies, and do have a memory. Once more, it is not in the brain. And because there is no brain, the scientists cannot locate precisely where the memory is in the plant. They performed an experiment with a *Mimosa pudica*, the plant that closes its leaves once it is touched [Gagliano and Marder 2019]. After a while, the plant did not close its leaves. Some days later, they attempted the experiment once more and the plant still did not close its leaves. The plant in some way ‘understood’ that it is not in a dangerous situation. The question remains as to where the memory actually is. Since there is no brain, it is probably in the tissue of the plant – again in the material. Of course, the experiment does not demonstrate where the memory is located, but since it is certain that there is no brain another part should have this functionality, and probably this is in the material. This behavior associated with the interaction with the environment may be termed ‘intelligence,’ or at least it is another way of conceiving intelligence.

Obviously, the definition of intelligence is contingent. From another perspective, some people can claim that a plant is not intelligent, simply because by definition a plant (or material as such) is not intelligent. But what is intelligent? For me, the plant is intelligent, since another way of conceiving intelligence is in the way plants are adapted to the environment. Accordingly, I try to see the way in which this behavior is implemented by plants. What are the components that allow them to behave smartly in their environment?

Talking about plants as intelligent is probably the most difficult part in this kind of study. This is also due to a problem of observation, to the fact that we cannot see the movement, and we must remember that observation is the first step in the scientific method. Only now that we have technology that allows us to accelerate the movement can we start to talk about this as movement as such. Before this, it was quite simply impossible. Since scientists could not see the movement, plants did not move. Now that we have the technology, we are in the right position to change this preconception, to push its boundaries.

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