Abstract— The fascinating capabilities of the octopus are pushing roboticists in trying to reproduce them in an artificial manner. In the OCTOPUS project a series of soft robotics technologies have been developed to allow the translation of biological insights into an eight-arm artificial octopus, but also to enable and open new perspectives for soft bodied robots.

I. INTRODUCTION

The octopus body has no rigid structures. Thanks to this, the octopus can adapt the shape of its body to the environment and its whole body can be squeezed into very small apertures, limited only by the size of its rigid brain capsule. The octopus has eight arms which can twist, change their length, be bent in all directions at any point along the arm and, despite of the lack of rigid skeletal support, can vary their stiffness to achieve relatively high values and to apply relatively high forces. The control of this large number of degrees of freedom is highly distributed and is simplified by the use of stereotyped movements. The eight arms are effectively used to locomote on the diverse substrates of the sea bottom, to swim within the aquatic environment, and to reach, grasp and even manipulate objects with unexpected dexterity. It is, thus, easy to understand why, from an engineering point of view, the octopus represents a paradigmatic example and a rich source of inspiration for a new kind of robots based on soft mechatronics technologies.

II. FROM BIOLOGY TO ROBOTICS

Thanks to an interdisciplinary collaboration with biologist and neuroscientists, the study of the biological model led to a series of important new insights which have been fundamental for the design of the OCTOPUS robot and they have been translated into specifications for the robot. In particular:

- biomechanical measurements on the octopus arm, with purposively designed bioengineering tools, including elongation and force applied [1-3];
- imaging and biological analysis of the octopus arm tissue (ecography, histology, immunohistochemistry, SEM) [4];
- video analysis of the swimming and of the crawling movements [5];

OCTOPUS is currently the first soft robot which effectively possesses both locomotion and manipulation capabilities (figure 1). Broadly based on soft robotics technologies, OCTOPUS has eight arms able to implement several features discovered in its natural counterpart, i.e. a pushing-based locomotion mechanism [6], an arm structure based on morphological observation [7] and a control architecture which exploits the robot mechanics [8]. The front arms are mainly used for manipulation, elongation, and grasping, while the others are mainly used for locomotion. The speed of OCTOPUS is independent from the ground analysed, and it reaches a top speed of 5 cm/s. This speed is low with respect to traditional legged robots, however it is among the highest speed for legged soft robots.

III. SOFT ROBOTICS TECHNOLOGIES

The ambitious goal of the OCTOPUS project required the investigation of a series of soft technologies which enabled the reproduction of the fascinating capabilities of the real octopus. The main technological challenge has been the identification of the materials for the soft robot, its mechanical structure, and especially the soft actuators and sensors. An important part of the work has concerned the modelling and the control of these soft robot arms, definitely innovative in the robotics state of the art.

Soft actuators. To optimize elongation, reaching and manipulation tasks the front arms counted on hybrid actuation system composed of a braided sheath with cable- and SMA-based actuators whose arrangement reproduces the internal anatomical features of the real octopus arm (muscular hydrostat) [9], and thus allow to perform finely controlled and precise movements [10]. Motion and grasping capabilities have been quantified showing that it is possible to obtain a 3-dimensional complex workspace by combining the local (SMA springs) and the global (cable driven) actuation systems. The other arms, which are used mainly for crawling, are based on silicone and cables, embedding the features needed to obtain an octopus-inspired locomotion broadly based on the octopus crawling movement [6].

Figure 1. The OCTOPUS robot with its main soft-bodied components.
Soft sensors. To perceive the robot spatial configuration and external stimuli the sensing system of a completely soft robot should count on transducers which both do not interfere with motion capabilities and do not affect the softness of the robot. The OCTOPUS robot sensors have been thus based on Electrolycra, an electrically conductive textile material, that is mechanically very similar to the common lycra and whose conductivity depends on how tightly it is stretched. It is very lightweight and capable of being stretched over 100% of its resting length, making it feasible for high deformation sensing and allowing the arm to move without any limitation [11].

New modelling. The dynamics modelling of continuum soft robots lacks both a satisfying methodology and a complete theory. Thus, a rigorous geometrically exact approach has been investigated to completely model both the dynamic interaction with a dense medium and the coupled tendon condition of the cable driven soft manipulator [12]. The validated results demonstrated to well represent octopus movements like: bending, reaching and fetching. The model can be used in the design phase as a dynamic simulation platform and to design the control strategy of a continuum robot arm moving in a dense medium.

Novel control. The solution of the inverse kinematics problem of soft manipulators using iterative methods based on Jacobian matrix guarantees a good degree of accuracy, but it may suffer from singularities, long-term convergence, parametric uncertainties and high computational cost. To overcome this issue a neural network learning of the inverse kinematics of a soft manipulator has been implemented [8]. After the training, a feed-forward neural network (FNN) is able to represent the relation between the manipulator tip position and the forces applied to the cables. The results show that a desired tip position can be achieved quickly with a degree of accuracy of 0.73% relative average error with respect to total length of arm.

IV. DISCUSSION AND CONCLUSIONS

The development of such technologies enabled the possibility to effectively translate the insights found on the octopus and thus to allow the reproduction of the complex behaviours observed in the octopus, but their applicability range is not limited to the OCTOPUS robot. One of the most important achieved result is, in fact, the development of series of soft robotics technologies which can address other fields needs that are already unmet. Soft robots and systems can be applied everywhere a soft but effective interaction with the environment is needed and this is demonstrated by the already existing shift that robotics is experiencing. Just to mention some examples also very different from each other, these novel technologies are already being used in:

- underwater robotics; the use of soft robots in underwater applications represents a very innovative application, perfectly complementary to the current use of underwater robot, as a soft robot can get in contact with the environment, crawl on the sea bottom and reefs, stick on plants or get inside structures to explore. The PoseiDRONE robot [13], is an innovative soft robot able to swim, locomote on different substrates and to manipulate objects in narrow spaces.
- minimally invasive surgery; traditional laparoscopic operations need several trocar accesses because of the limited dexterity, flexibility, manoeuvrability of the available tools. Based on these limitations a different approach has been pursued for the development of the STIFF-FLOP manipulator [14], designed to present elongation, squeezing and large flexibility in bending, but also stiffness changing capabilities.
- realistic simulators of body parts; the accurate replication of soft body parts is enabling the possibility to realize synthetic artefact reproducing natural functionalities but also to deepen the knowledge on the natural systems.

REFERENCES