PROJECT PERIODIC REPORT

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Project acronym: OCTOPUS

Project title: "Novel Design Principles and Technologies for a New Generation of High Dexterity Soft-bodied Robots Inspired by the Morphology and Behaviour of the Octopus"

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Periodic report:	**1st X 2nd ☐ 3rd ☐ 4th ☐**
Period covered:	**from month 1 to month 12 (01/02/2009 - 31/01/2010)**

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Declaration by the scientific representative of the project coordinator

I, as scientific representative of the coordinator of this project and in line with the obligations as stated in Article II.2.3 of the Grant Agreement declare that:

- The attached periodic report represents an accurate description of the work carried out in this project for this reporting period;
- The project (tick as appropriate):

  ☒ has fully achieved its objectives and technical goals for the period;

  ☐ has achieved most of its objectives and technical goals for the period with relatively minor deviations[3];

  ☐ has failed to achieve critical objectives and/or is not at all on schedule.

- The public website is up to date, if applicable.
- To my best knowledge, the financial statements which are being submitted as part of this report are in line with the actual work carried out and are consistent with the report on the resources used for the project (section 6) and if applicable with the certificate on financial statement.
- All beneficiaries, in particular non-profit public bodies, secondary and higher education establishments, research organisations and SMEs, have declared to have verified their legal status. Any changes have been reported under section 5 (Project Management) in accordance with Article II.3.f of the Grant Agreement.

Name of scientific representative of the Coordinator: .Prof. CECILIA LASCHI

Date: ..../ ..../ .... (will be inserted upon signature)

Signature of scientific representative of the Coordinator: ....

1 Publishable summary

The OCTOPUS Integrating Project (IP) aims at investigating and understanding the principles that give rise to the octopus sensory-motor capabilities and incorporating them in new design approaches and technologies for building physically embodied, soft-bodied, hyper-redundant, dextrous artefacts. To this purpose, a robotic artefact will be built in OCTOPUS, that can locomote in water over a variety of terrains, explore narrow spaces, grasp objects and manipulate them effectively. The OCTOPUS consortium is deeply interdisciplinary and includes experts in robotics, biomimetic materials, kinematic and dynamic modelling, and different aspects of the octopus biology.

The first three months have been devoted to a focused exchange of knowledge between biologists and engineers and to the creation of a common ground for the next research activities. This first phase consisted of giving a systematic view of the relevant state of the art in octopus biology and in the technologies related to the development of an octopus-like robot, and in jointly defining the specifications for the octopus-like robot, intended to guide the next research activities. This phase (corresponding to WP2) produced 4 main results (deliverables D2.1, D2.2, D3.1 and D3.2). These are documents on the relevant state of the art and tutorials from biologists to engineers, and engineers to roboticists, aimed at exchanging this knowledge. The tutorial meeting included brainstorming aimed at jointly defining the specific aspects to investigate in the next focused research activities and the specifications for the octopus-like robot.

Based on the results of the first phase of the IP, the specifications have been defined both for the overall robotic system and for the different components. They were delivered as a result of WP8, as a document (D8.1).

The observation and measurement of the octopus (corresponding to WP4) has included CryoSEM analysis, histological analysis, ecography, instrumented devices, and immunochemical assays. This has led to the observation of the skin surface, internal tissues of the octopus arm, suckers, and the measurement of the octopus arm elongation and strength.

The biological partners have started their investigation on the neurobiological and behavioural aspects of the octopus motor control and the underlying neural substrate. The results so far are exciting and especially the findings on arm elongation and on the control of a single arm in a guided movement are very promising. All other tasks in the WPs 5 & 7 are encouraging and will lead to several publications.

The work on modelling the octopus arm has included developing advanced algorithms for movement segmentation and 3D reconstruction by extending the previously available 2D dynamic model to the 3D case, developing algorithms for motion primitives extraction from 3D movements, modelling the arm elastodynamic and hydrodynamics, measuring and characterizing the arm morphology and developing models for investigating interactive behaviour and the control of arm impedance. This has led to the development of advanced tools for simulating complex movements using the extraction of motion primitives and classification of these movements, and new insights about the interactions between different muscle activation and contraction strategies. Various geometrical and morphological factors, including the number and shape of arm segments, have also been used in the development of the simulations.

Based on the specifications, the design and development of the artificial muscular hydrostat, of the control system, of the behavioural architecture, and of the sensorized skin are currently on-going. The results so far include the implementation of the basic mechanism of the muscular hydrostat on first prototypes and mock-ups. Elongation has been passively obtained by decreasing the diameter of the structure by using radial actuators; shortening is obtained by contracting longitudinally arranged actuators; bending can be performed selectively contracting longitudinal actuators. The structure is composed of soft, compliant, materials and structures with graded mechanical properties have been implemented to introduce embodied intelligence, delivering an array of movements with only simple actuation modes. The design of a robotic octopus behavioral architecture is inspired by the behavioral and neurophysiological study of *Octopus vulgaris*. It integrates sensory inputs and produces suitable motion sequences to low level controllers to achieve suitable behaviors. Since the interactions between peripheral and central nervous systems contribute significantly to most octopus behaviors, the Dynamical Systems approach is proposed to synthesize and implement the architectures. Meanwhile, the interface between high level and low level controllers is under developing using an open source software platform.

The OCTOPUS project has already reached a good visibility, at the international level, through the pubblications by the different partners and through specific initiatives like Special Sessions at the FET Conference in April 2009 and at the Annual Conference of the Israel Society of Neuroscience in November 2009.

The OCTOPUS IP is already educating a large number of PhD students, working at the different institutions, and it is organizing a Summer School for next June.

The collaboration with the other EMBODYi projects has been carried on through a web site (www.embodiedintelligence.eu) and it has been concretised in the Special Session at the FET Conference, where the 6 EMBODYi Projects have been presented with posters and in the EMBODYi Cluster Review event organized by the OCTOPUS IP in Livorno (Italy), on March 16-18, 2010.

The IP results on track with respect to the planned activities and very much able to achieve the expected results. Most WPs and Tasks are on schedule, in some cases there are additional activities and activities in advance, and in few cases there are activities which differs from the planned ones or are late, but able to match the next deadlines. The IP is also showing a great potential for bringing to further findings that may result from several additional investigations stimulated by the work in progress.

2 Project objectives for the period

The OCTOPUS IP aims at investigating and understanding the principles that give rise to the octopus sensory-motor capabilities and incorporating them into new design approaches and technologies for building physically embodied, soft-bodied, hyper-redundant, dextrous artefacts. To this purpose, a robotic artefact will be built in OCTOPUS, that can locomote in water over a variety of terrains, explore narrow spaces, grasp objects and manipulate them effectively.

Two WPs started at the beginning of the IP, in parallel, devoted to the survey and systematization of the relevant knowledge, from the biological and engineering viewpoints:

- **WP2** aimed at collecting the knowledge on the octopus relevant to the design and development of an octopus-like artefact; this includes knowledge about the anatomy, neurophysiology, biomechanics, behaviour;
- **WP3** was devoted to a survey of the robotics and ICT technologies that can be applied in the design and development of a robotic octopus, including current sensing technologies, smart actuators, bio-inspired control techniques, and soft materials.

Both WPs had a relatively short duration (3 months) and had the objectives to produce, as deliverables, one document and one tutorial each, to be given by biologists to roboticists and roboticists to biologists.

After the end of the first two WPs, 3 WPs (**WP4 to WP6**) started in parallel, to study specific aspects of the octopus anatomy, biomechanics, neurophysiology, kinematics, and dynamics, and will produce results beyond existing knowledge. For this reason, these WPs were planned to start after the end of WP2 and after the tutorial delivered by WP2, with a brainstorming session by all partners, which could take into account the results of WP2 and aim at jointly identifying the major topics of further investigation, specifically relevant to the robotics purposes.

This set of WPs will last for 12 months and will bring new knowledge on the octopus. Deliverables in this case are written reports, which will be developed into full papers due at month 16 of the IP.

From a conceptual point of view, **WP7** belongs to this set of WPs, as it aims at focused research and new knowledge on the octopus behaviour. It uses the results of WP2, as well, but it started earlier than its completion, i.e. at the beginning of the proposed IP, with a preparatory phase of collecting and acclimatising animals as well as a re-adjustment of facilities. The duration of this WP is 24 months and it will produce new science disseminated through scientific publications.
The tutorials and the brainstorming meetings planned in WP2 and WP3 were held in the format of one plenary meeting, which all partners were requested to attend. It was a two-day full-immersion intensive interaction among all partners, possibly involving both the senior scientists in charge and the young researchers of each institution, giving the best opportunity to share knowledge and to start the next phases of joint research on a solid common basis.
However, intermediate results at month 12 can be identified as follows:

- WP4: cryoSEM observation of the octopus muscles and suckers, biomechanical characterization of the octopus arm tissues, investigation of the octopus arm grasping and manipulation though instrumented devices, measurements of octopus arm elongation and force, histological analysis of the arm and sucker tissues;
- WP5: the activities in this WP concentrated on the neurophysiological investigation of the higher motor centres of the octopus as well as on aspects of the sensory systems of the octopus arms with special focus on the tactile sense. Further studies were done on the neurophysiological organization of the nervous system of the arm. In the kinematic studies we worked on the characterization of reaching movements with special emphasis on reaching correction and elongation process during reaching movements;
- WP6: development of algorithms for nearly-automatic video segmentation and characterization of backbone movements, development of algorithms for the extraction of 3D movement primitives and their clustering, simulations of 2D and 3D bend generation and fetching movements, measurement and characterization of arm morphology, development of a Finite Element analysis program used to model the elastodynamics of the muscle hydrostatic arm and developing mathematical modelling tools and techniques as part of the computational fluid dynamic methodology used to model the hydrodynamics of the octopus arm;
- WP7: the work on the behaviour of octopus in the first 12 months included the preparation of facilities for present and ongoing experiments especially on the culture of octopuses. We conducted several experiments that characterize the ability of the octopus to control the movements of its arms. We carried out two different maze experiments that involved learned tasks (the fact that learning was needed to complete the task ensures the octopuses have to use feedback from the CNS to complete the tasks) requiring complex movements. This showed us that unlike what was previously assumed the octopus can use central control to reshape and control peripheral movements of a single arm. In addition to these experiments we started one experiment on the online control of reaching movements and another on the coordination of arm use;

Concurrent with the work in WP4-WP7, **WP8** started and involved all partners, in the definition of the biomechatronic specifications of the whole robotic octopus, intended as an integrated system with a body and 8 arms, with all its components, like the sensory systems, actuators, and control. This WP especially relied on the results of WP3 and the tutorials delivered by that WP. Analogously to WP4-WP7, it also started with brainstorming by all partners, analysing and discussing the potential and the limitations of current robotics technology, to better steer the next phase of design and development of the robot components.
WP8 lasted for 4 months and matched its main objective of producing the specifications for the robotic octopus, forming the starting point for a set of parallel engineering WPs, namely **WP9 to WP12**, targeting the design and development of the actuators, the sensors, the control schemes, the behavioural architecture, the soft materials, and the kinematic and dynamic modelling. Their objectives for the first 12 months were, in synthesis:

- WP9: definition of the overall design of the structure and the fabrication of simple and specific mock-ups able to implement the basic mechanisms of the muscular hydrostat. These 2 tasks are intended to be finished within the first 12 months of the project, but several others are going on that are not yet finished. The analysis of the most suitable materials should be at an advance stage, mainly with results on their passive mechanical properties (static and dynamic). The soft actuators for the muscular unit should have a stout modelling and its principal performances should be characterized. Stretch sensors coupled with actuators should be tested and evaluated, in order to choose the most suitable sensing technologies;
- WP10: development of the controllers for a single arm, inspired to the peripheral control system of the octopus and considering the characteristics of the artificial muscular hydrostat;
- WP11: to propose a control architecture to realize an efficient use of octopus body and an appropriate interaction between peripheral and central nervous system. To survey learning techniques to make the octopus robot`s behavior robust and adaptive. To develop a simple mock-up system and simulator to evaluate the proposed control architecture;
- WP12: development of prototype skin materials and comparison with octopus skin properties, with particular emphasis on the requirement for constant volume;
- WP18: internal and external dissemination activities (tutorials and brainstorming meetings, publications in Journals, participations in European and international conferences, website and public press), training activities (exchanging of students among partners, organization of courses or seminars), one-day scientific workshop at the Review Meeting (organized on March 17th).

3 Work progress and achievements during the period

An overview of the work progress carried out in the reporting period for each WP is reported hereafter, (except project management, which is discussed further below).

3.1 WP2 – Analysis of existing relevant knowledge on the octopus

WP Leader: HUJI

WP Members: WEIZMANN, IIT

Progress summary

WP2 was completed and its deliverables were submitted at the end of April 2009, on schedule.
The objective of WP2 was to survey and systematize the knowledge on the octopus (*Octopus Vulgaris*) available in literature and to understand which aspects should be further investigated in detail for the improvement of the biological knowledge specifically relevant to robotics. As planned, the researchers involved in this WP gave tutorials at the 2-day OCTOPUS meeting (26-28. 04. 2009) at FORTH. The biological data on the muscular hydrostat and the details of the neuromuscular system paints a clear picture of what we know and what still needs to be investigated. Research in the subsequent WP was thus largely influenced by the findings summarised in the deliverables of this WP.
Due to the lecture and the analysis of the results of WP2 the importance of the octopuses’ learning ability for the control strategies became apparent. It became clear that the interaction and coordination between the octopus body and arms in the aquatic environment must be better understood. Therefore, combined efforts need to be made for an in depth study to reveal further details of how control and hydrodynamics influence each other in octopus.

Significant results

Task 2.1 Biological data described by the relevant members (muscular hydrostat; neuromuscular system) – month 1-3 (HUJI, IIT)

This deliverable is for internal use as a quick reference for the existing knowledge on the octopus biology and a guideline to define the work on the WPs 4, 5, 6 and 7. It is also for external use as a guide to aid project evaluation.

The construction of architectural models aims to predict design aspects of a system based on functional demands and physical principles. One of the factors which play a major role for the mechanical function of an octopus-like muscular hydrostats is the dimensions and arrangement of the muscle fibres and connective tissue into muscle groups.

We collected most of the relevant information about the organization of the octopus arm anatomy with particular interest to its function as a muscular structure. We provided a fulfilling description of:

- The octopus arm anatomy
- The arm muscle fibre morphology and arrangement
- The neural control properties of the arm neuromuscular motor system
- The neural control properties of the arm sensory system
- The arm sensory receptors

Anatomical characterization of the octopus arm is important for the understanding of its function as a biomechanical device. A key aspect for obtaining a comprehensive view on functional organization of the muscular hydrostat is the morphological characterization of different muscle groups, the distribution of muscle and nerve cells along the arm and the connective tissue/muscle relation. Here we offered a useful schema and description of the 'basic' morphological arm construction.

Task 2.2 Organization of the higher motor centres (somatotopic organization – month 1-3 (HUJI, IIT)

The groundwork on the anatomy of the octopus brain was carried out by Young and his collaborators. Their studies provide a very detailed description of the structure of the nervous system. Such histological and anatomical analyses reveal the structural basis of the connections between peripheral and central nervous system and between the various brain lobes.

The octopus brain is composed of two central neural masses, the supraoesophageal and the suboesophageal masses, which are separated by the oesophagus. The central nervous system of the octopus arouse out of simple molluscan ganglia that fussed and developed into the most complex and centralized brain in invertebrates. Remaining questions on motor control were pointed out and are presently addressed in WP 5 and WP 7.

The insights from this past research are important to shape the experiments of biological research as well as help the engineers to better understand the biological background of the octopus.

Task 2.3 Biologically driven motor control principles in stereotypical movements (stereotypical movements kinematics and dynamics analysis, modelling) – month 1-3 (Weizmann, HUJI, IIT)

Achieving efficient control of flexible structures is extremely complex, both in biological and robotic systems, because such systems have a virtually infinite number of DOFs. This requires special strategies for solving the inverse kinematic and dynamic problems, which are believed to be the necessary steps for achieving a proper control of open loop systems. An efficient experimental approach to study this by combining behavioural, kinematical, physiological and modelling techniques was developed. Using this approach we have shown that although reaching and fetching movements are very different in nature (bend propagation vs. articulate-like rotation), the control strategies evolved are similarly based on restricting the controlled variables to just 3 DOFs.

To understand the neural control strategies involved, EMG recording was used to correlate the patterns of muscle activation with the kinematic features of arm movements. For the reaching movements, it was found that the variables best correlated with the EMG are the two global variables, peak acceleration and peak velocity, and these two variables can be predicted from the level of muscle activity, regardless of when this activity is measured during the movement. These results suggest that the level of activity is the parameter dictating the extension velocity and that a feed-forward control mechanism may be responsible for generating the movement. In contrast, EMG recording during fetching revealed that the level of activity is not correlated with kinematic parameters, but rather with the length of the segments. This suggests that in fetching, stabilizing the articulated structure against the large normal drag forces is the main control variable. This energetic load is probably the price for achieving end-point accuracy.

Based on those physiological and kinematic studies a 2D dynamic model of the octopus arm aimed at exploring possible strategies of movement control in this muscular hydrostat was developed. The arm was modelled as a multi-segment structure, each segment containing longitudinal and transverse muscles maintaining a constant volume, a prominent feature of muscular hydrostats. The input to the model was the degree of activation of each of its muscles. The model represented the external forces of gravity, buoyancy, and water drag forces. It also included in its description the internal forces generated by the arm muscles and the forces responsible for maintaining a constant volume. This dynamic model was then used to investigate the octopus reaching movements and to explore the mechanisms of bend propagation that characterize this movement. Based on computer simulations it was found that: 1) A simple command producing a wave of muscle activation moving at a constant velocity is sufficient to replicate the natural reaching movements with similar kinematic features; 2) The biomechanical mechanism that produces the reaching movement is a stiffening wave of muscle contraction that pushes a bend forward along the arm; 3) The perpendicular drag coefficient for an octopus arm is nearly 50 times larger than the tangential drag coefficient. During a reaching movement, only a small portion of the arm is oriented perpendicular to the direction of movement, thus minimizing the drag force. This model was further used to investigate the neural strategies used for controlling the reaching movements of the octopus arm. Sending a simple propagating neural activation signal to contract all muscles along the arm produced an arm extension with kinematic properties similar to those of natural movements. Control of only 2 parameters: the amplitude of the activation signal and the activation travelling time (the time the activation wave takes to travel along the arm) were sufficient to fully specify the extension movement. It was also found that the same kinematics could be achieved by applying activation signals with different activation amplitudes all exceeding some minimal level. This suggests that the octopus arm could use minimal amplitudes of activation to generate the minimal muscle forces required for the production of the desired kinematics. Larger-amplitude signals would generate larger forces that increase the arm's stability against perturbations without changing the kinematic characteristics. These modelling studies suggested that the octopus arm biomechanics might allow independent control of kinematics and resistance to perturbation during arm extension movements.

3.2 WP3 – Analysis of relevant existing technologies

WP Leader: UZH

WP Members: SSSA, IIT, UREAD, FORTH

Progress summary

WP3 was completed and its deliverables were submitted at the end of April 2009, on schedule.

The work package was divided into a set of surveys to investigate existing technologies that were considered to be relevant to the construction and development of the robotic octopus. At the end of this WP, the survey results were integrated into a tutorial for the consortium, specifically targeted to provide a common ground between the technological and biological partners. The tutorial was organized in the context of the OCTOPUS meeting in Greece, hosted by FORTH. Rolf Pfeifer gave a presentation with the title "AI in robotics: Sensory-motor behavioural architectures and biomimetic robotic systems". Cecilia Laschi gave a presentation with the title "Robotic technologies for sensing and actuation", Darwin Caldwell and Nikos Tsagarikis presented "Proprioceptive Sensing and Fluidic and SMA Actuation Technologies", Richard Bonser illustrated "Soft biomimetic materials", and Dimitris Tsakiris reported on "Bio-inspired robot control and reactive behaviours". These tutorials served as a brief update for partners specialized in Engineering and as a simple and practical approach for partners specialized in Biology. The tutorials were followed by a lively debate and Q&A session. Every partner demonstrated a deep interest in the presented topics and the brainstorming between engineers and biologists has led to very profitable ideas and suggestions. The results of this work have been integrated in Deliverable D3.1, submitted as a comprehensive review in the area of robotics and ICT technologies that could possibly be applied in the design and development of a robotic octopus. The survey included state of the art technologies in sensing, actuation, soft materials, and bio-inspired sensory-motor control and is intended to be a comprehensive tutorial on the larger field of biomimetic and bio-inspired robotics and, in particular, the technologies pertinent to the OCTOPUS IP.

With due consideration to the multidisciplinary expertise of the consortium, as well as the specializations of the partners involved, this survey has individual sections dealt with in detail by the respective research groups specializing in those areas. The survey thus represents a balanced analysis of the various technical challenges involved, providing a strong foundation for the design and development phases to follow. It is also hoped that it provides a broad introductory overview of the area for the partner research groups specializing in biology, thus enabling an equitable sharing of knowledge thereby further aiding the subsequent tasks. The survey also cites some of the best-known published literature in the various research areas dealt with.

Significant results

Task 3.1 Survey of sensing and actuation technologies – month 1-3 (SSSA, UZH, IIT, FORTH)

This task has produced a systematization of the literature in the field of bioinspired sensors and actuators based on the experience of the involved partners with the addition of some experimental activities in which few selected different technologies, potentially suitable for the octopus-inspired sensors and actuators, have been tested and compared.

The most relevant artificial sensing systems have been identified and divided into 4 main groups:

- Inertial sensors
- Haptic sensors
- Proprioceptive sensors
- Vision sensors

All the most suitable technologies used in these fields have been widely documented.

The survey on actuation has been selectively restricted to those technologies which have the possibility to match the required capabilities (active and passive). This has excluded many traditional and not suitable technologies and, on contrary, ranged on many innovative technologies, most of which not yet well explored and in particular:

- Hydraulic actuators
- Pneumatic actuators
- Piezoelectric actuators
- Shape Memory Alloys
- Electro Active Polymers

Many subgroups of these technologies have been investigated and many numerical examples have been reported to allow a direct comparison.

Task 3.2 Survey of bioinspired control schemes – month 1-3 (IIT, FORTH)

In biological systems with rigid non redundant skeleton structures the execution of motions is initiated by a series of commands generated by the nervous system. These commands are sent to the corresponding actuators which finally move the limb toward the target while constrained by the non redundant rigid skeleton structure. This process is very different from that found in biological systems which are lacking of a rigid skeleton structure such as the hydrostats. Due the theoretical infinite DOFs soft biological systems use more complicate procedures when controlling their motions.

Robotic systems with a (very) large number of degrees of freedom, whose morphology is analogous to that of snakes, eels, elephant trunks and tentacles are called *hyper-redundant*, Chirikjian (1994, 1995, 1995a). Over the past several years, there has been a rapidly expanding interest in the study and construction of them.

Inspiration for the development and motion control of hyper-redundant robotic locomotion systems stems from organisms such as snakes, eels, marine worms, nematodes, larvae, etc, with the prime biological paradigm being that of the snake, hence the prevalence of the term "snake-robot" in the literature.

The kinematics of hyper-redundant robots have been modelled by a number of different techniques, including formulations based on the Denavit-Hartenberg convention Poi (1998), backbone continuous curves Chirikjian (1990, 1991, 1994) and models exploiting non-holonomic constraints, for undulatory systems employing wheels Krishnaprasad (1994, 2001), Ostrowski (1996,1998) and Bayraktaroglu (2006).

Gait generation (open-loop control):

By far the gait most widely studied is locomotion via lateral undulations (also referred to as *serpentine locomotion*), involving the propagation of a lateral travelling wave along the mechanism. In the great majority of robotic prototypes, both terrestrial and aquatic, retrograde (head-to-tail) waves are employed for forward propulsion.

Sensor-based reactive behaviours (closed-loop control):

Regarding closed loop control schemes, *trajectory tracking* for, mainly wheeled, snake-like robots, has been studied, either assuming that perfect system state information is available, or using position information from an external (static) vision system. However, on-board exteroceptive sensors are necessary in order to enhance the autonomy of undulatory robots, so that they become able to operate in the complex environments for which they are intended. In this case, sensor-based closed-loop control schemes for navigating these robots, via the modulation of the joint oscillation parameters, are needed.

Some first steps in this direction explore, at a lower level, the use of sensors to identify substrate properties for modulating the parameters of the travelling wave Inoue (2007), or selecting an appropriate gait over varying terrain, Li (2004).

At a higher level, exteroceptive sensors (e.g., distance, vision) allowing the implementation of more complex behaviors (e.g., path following, obstacle avoidance) have been considered.

Evolutionary Design of Bio-inspired Systems

The aim of research in the field of biologically-inspired systems is to uncover the working principles of natural organisms and help implement artificial agents that can successfully tackle real-world situations. Existing approaches emphasize the impact that physical dynamics have on biological organism morphology and control strategies, extracting useful guidelines, which are further interpreted in a computational context to support artificial system design. Well-established knowledge, regarding the natural mechanisms triggered to produce some specific behaviour of biological organisms, significantly support the design of artificial models. However, many aspects of the natural systems' operation remain unknown and cannot be directly integrated into the system.

In order to avoid arbitrary human assumptions (that can potentially harm the implementation process), we may provide the artificial systems with some internal plasticity dynamics, and let them self-organize, according to the physical properties of the environment, similar to the biological evolutionary process. Following this approach, bio-inspired system design emphasizes the reciprocal coupling of the control mechanism (i.e., of the central nervous system), of the body of the agent and of the operating environment.

In order to sufficiently explore alternative hypotheses, an automatic mechanism is necessary to identify and validate possible configurations. Evolutionary algorithms may provide an effective and systematic means to address this issue, mainly due to their well-known capacity to explore the problem domain in a global, rather than a local, manner. Therefore, artificial evolution can be used as a powerful tool for exploring natural working principles. In the past, evolutionary processes have been used extensively in designing artificial neural networks, considered as the computational counterpart of the biological central nervous system, for the case of artificial agents. Additionally, evolutionary processes have been employed in studying the situated robotic characteristics emerging from agent-environment coupling, including aspects of neural control, developmental maturation, and morphological design.

Task 3.3 Survey of behavioural architectures – month 1-3 (<u>UZH</u>)

An extensive survey has been carried out to study the existing behaviour/sensory-motor architectures, with a special address on those closely related to bio-inspired systems.
The following behavioural architectures were investigated in detail:

- Extended Braitenberg architecture
- Subsumption architecture and behaviour based methods
- Dynamical systems
- MOSAIC
- Probabilistic models
- iCub modular bio-inspired architecture
- Body dynamics
- WalkNET

It was found that there was no uniform definition and classification on behavioural architectures, some efforts were also devoted to tentatively define some terms as "architecture" and give a rough classification of these architectures.

Task 3.4 Survey of bioinspired soft materials – month 1-3 (<u>UREAD</u>)

The provided survey had the aim to identify existing biomimetic technologies, that may be appropriated in fulfilling the project criteria. Additionally, other technologies potentially interesting in contributing to the requirements of the compliant skin of the octopus artefact have been considered.
The survey included a review on the role of fibres in biology, considerations on technologies for fibrous skins with sensors and a review relevant to biomimetic skin technologies.
The work highlighted the presence of limited reference to biomimetic technologies addressing the technical problems faced in the fabrication of the skin for the octopus artefact. Whilst this means there is no 'off-the-shelf' solutions giving the desired performance characteristics, giving to the OCTOPUS consortium partners the exciting opportunity to develop a new class of biomimetic, compliant skin-like materials.

3.3 WP4 – Focused research on the octopus arm anatomy and biomechanics

WP Leader: IIT

WP Members: SSSA, HUJI, UREAD

Progress summary

This WP concerns anatomical and biomechanical studies of the *Octopus vulgaris*. WP4 is planned to deliver its main results at month 16. The work in progress results are in line with the work plan, and the achievements to date match the final delivery results.

Relevant information concerning the anatomical structure of the octopus arm has been outlined during the first year of activities. These investigations have been carried out by:

1) histological analysis;
2) Cryo-SEM technique;
3) new devices and set-ups developed for characterising the mechanical properties of the octopus arms;
4) immunohistochemical assays.

The main important results achieved during the reporting period are presented below. They are in line with the planned activities and, in some cases, additional investigations have been carried out, stimulated by the work in progress and by the discussions among partners.

Significant results

The most important results of WPs have been published in the papers:

- Zullo L, Sumbre G, Agnisola C, Flash T and Hochner B (2009) Nonsomatotopic Organization of the Higher Motor Centers in Octopus, *Current Biology*, (19) 19, 1632-1636.
- Margheri L, Mazzolai B, Cianchetti M, Dario P and Laschi C (2009 a) Tools and Methods for Experimental In-vivo Measurement and Biomechanical Characterization of an *Octopus vulgaris* Arm, *Annual International Conference of the IEEE Engineering in Medicine and Biology Society* (EMBC'09), Minneapolis, Minnesota, USA.
- Margheri L, Mazzolai B, Laschi C and Dario P (2009 b) Methods and Tools for Experimental In-Vivo Measurement and Characterization of the *Octopus vulgaris* Arm Mechanical Properties, *the Israel Society For Neuroscience 18th Annual Meeting*, Eilat, Israel.
- Margheri L, Ponte G, Mazzolai B, Laschi C and Fiorito G (2009 c) In-vivo investigation of the arm nerve cord morphology of the *Octopus vulgaris*, using ultrasound techniques, *the Israel Society For Neuroscience 18th Annual Meeting*, Eilat, Israel.
- Zullo L., Fossati S.M., Hochner B. and Benfenati F. (2009) Physiological characterization of octopus arm and sucker *J Mol Neurosci* 39 (Suppl 1):S1–S132.
- Fossati S.M., Benfenati F., Hochner B and Zullo L. (2009) Morphological characterization of the octopus arm relevant to robotics *J Mol Neurosci* 39 (Suppl 1):S1–S132.

Task 4.1 SEM analysis of octopus muscle and sensilla – month 4-7 (SSSA)

In order to advance the knowledge of the anatomy of the octopus (*O. vulgaris*) arm and suckers cryo-fixation techniques and analysis of bulk and freeze-fractured frozen-hydrated samples by Cryo Scanning electron microscopy were applied. Surface characteristics of the skin and suckers and their internal arrangement of muscle, connective tissues, nerve and sensilla have been analysed in order to better characterize structures and sensory systems. Freeze fracture technique has been applied to expose internal tissues of frozen-hydrated samples of arm, suckers and skin.

A series of Cryo-SEM analysis of frozen-hydrated samples of arms, at different position along it and between different arms (R1, L1, etc.) has been carried out. Structures on the outer surface and internal tissues exposed by freeze fracturing were observed in detail.

Single suckers were isolated and freeze fractured along major axis to expose the internal cavity of infundibulum and acetabulum to observe the denticles structure and development.

Task 4.2: Ex-vivo biomechanical measurements and characterization of the octopus arm 4-7 (SSSA, UREAD)

Five octopuses were bought from market and stored in freezer. Skins were removed from the bodies or arms just before testing and connective tissues were removed from the inner side of the skins. The skin was kept in iced water whenever possible during the preparation process. The thickness of the skin was measured by using a height gauge. The sample was placed on a flat glass panel and the thickness was taken when the sample is slightly compressed by the gauge. The width of the sample is taken at the same time. The thickness of the samples is typically between 0.1 and 0.15mm.
The density of the skin is measured as 1026 kg/m^3. It contains about 84% of water by volume. The thickness of the dry skin is about 0.03mm. ESEM images of the skin show that the collagen fibres are distributed in random directions. The diameter of the collagen fibres is around 3 μm. X-ray Diffraction images show that the skin at the proximal end is almost isotropic, while it shows some anisotropic towards the distal end.
Static tensile tests and instrumented scissors cutting tests have been carried out to study the mechanical properties and fracture toughness of the skin. Properties both along and across the lengths of the body and arms have been studied.
Both the Young's modulus and the toughness of the arm skin changes with position along the length of the arms. The Modulus and toughness are higher in the proximal end than in the distal end. Material properties do not vary with positions along the peripheral direction. There is no significant difference in material properties along the length and peripheral directions.
For the body skin, the material properties do not show any difference along the length of the body. Along the cross section of the body, the back side skin is dark brown and the belly side skin is almost white. The back skin has higher Young's modulus than the belly skin.
The mean values of fracture toughness and peak cutting forces for all five octopuses have been tabulated in Table 1. For the body skin, results are very similar for both longitudinal and transverse direction. For arm skins, the fracture toughness cutting along the length's direction is slightly higher than that along the transverse direction. But their peak cutting forces are the same.

Table1. Average fracture toughness and peak forces for all octopuses.

Skin	Toughness (J/m2)	Peak force (N)
Arm L	972±198	0.8±0.2
Arm T	930±235	0.8±0.1
Body L	837±66	1.1±0.1
Body T	823±32	1.1±0.1

The average tensile properties of arm and body skin in the longitudinal and transverse directions are tabulated in Table 2. The arm skin is softer than the body skin and has higher failure strain. The ultimate stress of the body skin is much higher than that of the arm skin. But the arm skin shows higher failure strain. Also give in Table 2 are the P-values from two way ANOVAs' analysis. Compared data are statistically significantly different is the P-value is smaller than 0.05.

Table 2. Summary of skin properties from static tensile tests.

	E (MPa)	P-Value	Strain (%)	Max. Stress (MPa)
Arm L	23.7±11.6	0.38	40.3±6.1	5.3±1.4
Arm T	25.3±7.7		39.2±5.6	5.3±0.9
Body back L	42.2±9.5	0.04	34.5±1.5	8.6±1.8

Body back T	50.0±18.9		32.4±2.4	10.9±4.5
Body belly L	38.9±16.4	0.28	34.4±2.8	9.4±3.3
Body belly T	34.6±13.0		33.5±3.0	8.1±1.8

Of the five octopuses tested, results show that octopuses weighing around 600g have higher Young's modulus and fracture toughness. The mass of the octopuses tested ranges from 480-740g.

Task 4.3 In- vivo investigation of the octopus arm tactile sensors – month 4-9 (SSSA, HUJI)

The specific objective of this task is to obtain information on the octopus manipulation ability and tactile approach, through a non invasive analysis of its interaction with objects. The method is to record octopuses during several manipulation tasks with a system of high-speed-high-resolution cameras for the analysis of the movements.

Sensorized soft tools with different shapes (a ring and a cylinder filled with air or with salted water) have been developed for the measurement of the pressure applied by the arms or by the suckers during free grasping and manipulating. Each tool, made of soft material (silicone GLS50, Prochima®), integrates a pressure sensor (Pressure Sensor 24PC Series, 0-15psi, Honeywell).

The measurements and recordings have been done through experimental trials with a living subject. The object is presented to the animal, which is free to play with it with one or more arms. While the sensors would record pressures due to changes in depth, no pressure was recorded due to octopus manipulation. The use of these sensorized tools has demonstrated the incredible ability of the octopus to finely and precisely manipulate objects without the application of any pressure.

Task 4.4 In-vivo measurement and mechanical characterization of the octopus arm – month 4-16 (SSSA)

The in-vivo measurement of the octopus arm mechanical properties aims at measuring active mechanical performances of the arms, in a non invasive way. The results can be used as specifications for implementing similar properties in the robotic arm components (i.e. the artificial muscular hydrostat) and for acquiring data for the modelling of the arm.

New methods and new tools have been defined and realized to directly interact with the octopus and measure mechanical properties as the maximum active strain of the arm and pulling force.

Dedicated tanks for the observation, with a system of high-speed-high-resolution cameras (DALSA Falcon1.4M100), software for video analysis (Stream5) and geometric references for the cameras calibration are used. A series of instruments, different in size depending on the dimension of the animal, has been developed (Margheri et al., 2009 a).

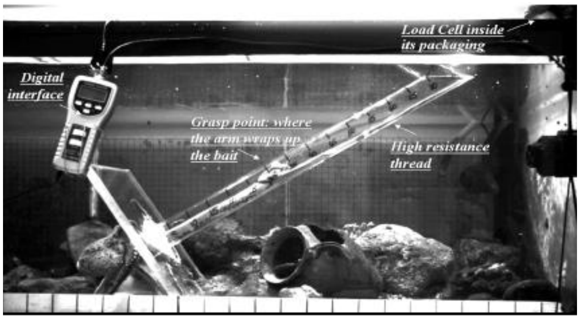
A series of mechanical measures have been carried out:

- Active arms elongation;
- Jet propulsion movement analysis;
- Arms reference length measurement during the jet propulsion trajectory;
- Arms active elongation ratio capability (maximum length in elongation in respect to the reference length during the jet propulsion movement);
- Pulling force capability in respect to the grasp point along the arm.

For each series of measures the setup and the methods have been previously tested on one animal. After that, a well defined measurement protocol has been defined for the training and the measurement of a group of animals, thanks to the collaboration with the Stazione Zoologica in Naples.

For the arms elongation, the reference length and the elongation ratio measurement, the protocol and the measurements have been successfully carried on a number of 24 animals (16 males, 8 females, weight range 146÷560g). The reference length of the arms has been measured during the jet propulsion movement. Then the arms elongation ratio has been calculated.

The mean elongation ratio considering all the animals arms results 70% ($\Delta\ell/\ell_0$). This means that, considering the analytic model for a constant volume conic structure, a diameter mean reduction of the 23% ($\Delta D / D_0$) is enough to obtain the measured elongation.
The isometric pulling force has been measured on two animals (male, 1600g; female, 476g), with the bait at different points of the arm. The same profile of the force ability along the arm has been observed on the two animals, which has the same profile of skeletal muscle fibres (Figure 4. 1). A maximum force of 49.8N (L2 arm) on the male and 20N (arm R3) on the female has been measured.



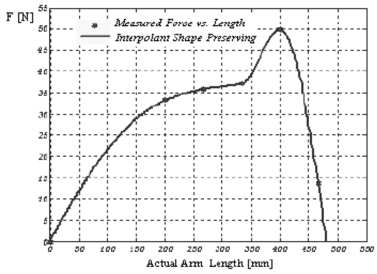


Figure 4. 1 On the left, a frame captured during a pulling force experiment: the octopus inserts one arm inside of the tube, grasps the bait hanged to the high resistance thread and pull. The isometric pulling force is measured by the load cell, showed on the digital interface and recorded in the PC. On the right, the plot showing the characteristic relationship between maximum measured pulling force and the length of the arm: the maximum value is reached at a length equal to 1.2 times the rest length, as characteristic of skeletal muscle fibres (Fung, 1993).

The octopus grasps the bait in a point along the arm corresponding to 0.75 of the total arm length, whereas the distal quarter of the arm is used to wrap around the bait itself. Based on this result, the distal quarter of the robotic arm can be used as end-effector, while the proximal part can be used to exert forces.
Ultrasound has also been applied as a method to study and measure in vivo the behaviour of the internal structures during arm movements. The instrumental setup has been integrated with the probe (a linear transducer, LA435, working at a frequency of 18 MHz) of an ultrasound imager (Esaote MyLab™Five VET).Preliminary in-vivo examination of octopus arms elongation, revealed the sinusoidal arrangement of the nerve cord at the rest length of the arm and its distension during arm elongation (Margheri et al., 2009 c).
Mechanical parameters, such as the active strain of the arms and the pulling force capabilities, have been fixed as specifications for the performance of the arms of the robotic octopus. Kinematics and dynamics of movements will be considered as example to take into account for the control strategies and the movement of the whole artefact.

Task 4.5 Description of the arm muscles, nerves organization and their connections along the arm length – month 4-16 (IIT, SSSA)

In vivo internal morphology of the arm has been investigated using ultrasound. A particular interest has been dedicated to the muscular and nervous tissue arrangement to observe and characterize possible structural advantage for a mechanical and a robotic viewpoint. In respect to other morphological investigation methods, ultrasound allows to measure also the structures in their natural condition with the real proportions.
Examinations with the use of sonography has been carried out in anesthetized octopuses (*O. vulgaris*, N=12), with the animal in a small rectangular tank in transparent Plexiglas. During examination planes and scanning were captured via Esaote MyLab™Five VET ultrasound imager, equipped with a linear transducer (LA435) at a frequency of 18 MHz. Measures of the intrinsic musculature of the arm, the nerve cord height and width or the relative area of the axonal tracts and

the internal neuropil, as the measure of the tissues density have been obtained directly from the images. Histology (Milligan-Trichrome) has been used in parallel to validate and compare ultrasound images and to observe with higher resolution muscular fibres insertions and relative arrangement.
We also evaluated muscle cell orientation within the tissue and we characterized the ratio between muscle and nerve cells at different length along the arm.
To do this we analyzed and reconstructed, both in transverse and longitudinal serial sections, the morphology of segments from basal, central, and apical portion of the arm using basic histological techniques (Nissl staining, Toluidine blue, etc…). The position and areas occupied by the axial nerve cord, ganglia and suckers were measured in each section. This allowed us to estimate the ratio between the volumes occupied by nerve, ganglia and muscle along the arm.
Results from this study showed that the area occupied by ganglia (expressed as a percentage of the total area of the sections) decreases from the base to the tip of the arm while the area of the axial nerve cord increases dramatically from the base to the tip (Figure 4. 2).

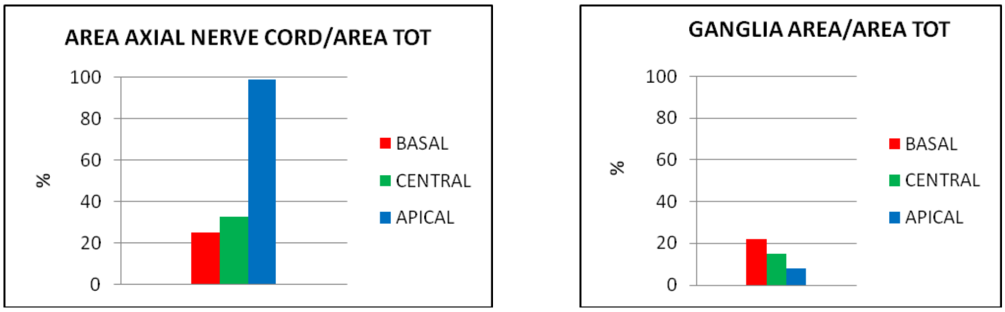


Figure 4. 2 Ratio between areas occupied by axial nerve cord and ganglia in basal central and apical portions of the arm

In order to fulfil the additional information on arm morphology requested by other consortium partners we also measured the length and distance of the ganglia nerves innervating the intrinsic musculature of the arm. Interestingly we found that in basal sections innervations are higher than in central sections.
In addition, in order to better identify muscle and nerve cells along the arm and their organization we decided to run immunohistochemical assays not preliminary planned.
We have been testing antibodies such as 1) Alpha-Actinin 2) Myelin Protein Zero (P0) and 3) BetaIII Tubulin.
All these assays were positive and specific for the different cell types (Figure 4. 3 a, b, c).

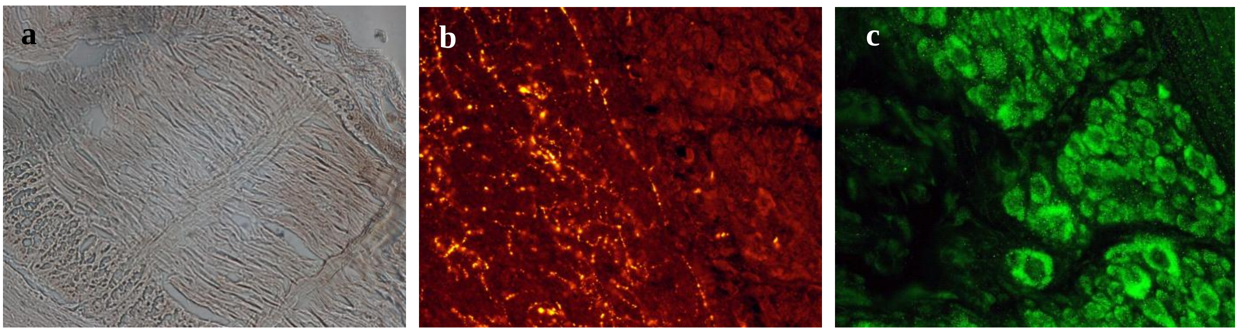


Figure 4. 3 Immunostaining against Alpha-Actinin (a), Myelin Protein Zero (P0) (b), and BetaIII Tubulin (c)

We are also performing Acetylcholine esterase reaction to visualize nerve fiber connection and orientation within the arm. From previous studies Acetylcholine was found to be the main neuromuscular transmitter in cephalopods (Bone et al., 1982) and Talesa et al. (1995) demonstrated that AChE activity is very intense in the axial nerve cord (cell layer and neuropil) and restricted to nerve fibers, to intrinsic muscles of the octopus arm and to nerves of the sucker. These results will be important to define mechanical constraints of the arm muscular hydrostat such as the ratio between longitudinal and transverse forces acting in this special muscle hydrostat structure.

Deviations

The deliverable of WP4 D4.1 was erroneously reported in the OCTOPUS DoW as due at month 12. In agreement with the Project Officer, it has been set at the end WP4, month 16.

3.4 WP5 – Focused research on the octopus neurophysiology

WP Leader: HUJI

WP Members: WEIZMANN, IIT

Progress summary

The objective of this WP is the bottom-up understanding of the neural organization of the octopus arms motor control systems. The work is being conducted in close collaboration with Tamar Flash's group at Weizmann, and Letizia Zullo at IIT. The different tasks aim to better our understanding of the unique system of motor control and motor output in *Octopus vulgaris*. Using an approach that incorporates all biological levels (from the cellular level to the whole organism) as well as reconstruction and modelling of movements this WP will not only provide new biological insights but is also invaluable for the construction of the OCTOPUS prototype.

Significant results

The most important results of WPs have been published in the papers:

- Hanassy S., Botvinnik A. and Hochner B. (2009) Elongation and bend propagation in the reaching movement of *Octopus vulgaris J Mol Neurosci* 39 (Suppl 1):S1–S132.
- Hochner B., Zullo L. and Subre G. (2009) The control of goal directed movements in the flexible arm of the octopus *J Mol Neurosci* 39 (Suppl 1):S1–S132.

Task 5.1 Neuromuscular properties and excitation-contraction characteristics- months 4-16 (<u>HUJI</u>, IIT, Weizmann)

In this task we characterize the passive and active properties of the muscular system both at the level of single cells and in whole arm segments. We are measuring the passive and active forces and shape changes in intact whole arm segments (the intrinsic musculature of the arm). We evoke muscle activation both by stimulating the nervous system and by direct muscle activation. This will give us quantitative information and reveal dynamic constraints emerging from the organization of the longitudinal, transversal and oblique muscle groups and connective tissues. In recent experiments we developed a method for whole cell recording, which allows for continues cell contraction upon stimulation. In the octopus this is feasible as the cells are small enough for single cell voltage clamp, as we have previously shown (Rokni and Hochner, 2002). To achieve this we modified the chemical composition of the internal pipette solution in an amazingly simple manner. Now we have to develop or adapt techniques for single cell force measurements. At this stage of the experiments we are able to characterize the shortening speed. This information is essential for understanding the transformation of neural commands into mechanical output and can provide biologically derived parameters to be used to update our dynamic models (Yekutieli et al., 2005b; Yekutieli et al., 2005a; Yekutieli et al., 2007) and the newly developed 3D model of the octopus arm. In the long run this information will be employed in the construction of an interface between a theoretical neural net and the 3D dynamical model of the octopus arms.

Task 5.2 Kinematic characterization of stereotypical movements - months 4-16 (<u>HUJI</u>, Weizmann, IIT)

The first part of this task deals with the elongation profiles of the reaching towards a moving target. Two sets of data were so far obtained and analyzed, initially (n = 4 animals) using a 3D reconstruction method (n=64 movements). A second set of experiments (n=2 animals, reaching movements n= 30) was studied under carefully controlled conditions, where the target and octopus positions were kept stationary and at predefined distances.

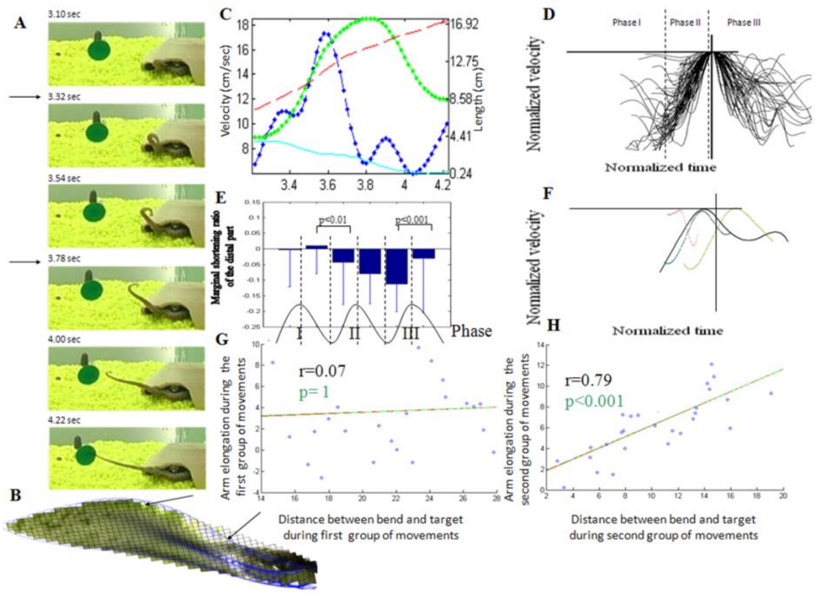


Figure 5. 1 Sequence of snapshots from the right camera during one reaching movement which involves both bend propagation and arm elongation; B. The envelope of the movement 3D midline reconstructions; C. Several kinematics profiles of the movement; D: Superposition of the normalized tangential velocity profiles of reaching movements (n=64) E. Bend propagation during the movements in D. Average distal part's marginal shortening ratio ([Ld(i+1)-Ld(i)]/L0; Where Ld(i) denote the length of the distal part at the end of the half-phase i) per half-phase (6 half-phases). The phases are notated bellow the histogram. P values at the top of the bars where the difference was significant in Paired T-test.; F. Superimposed of the average curves of the three phases as seen in the elongation velocity profiles of the movements in D: phases I (Magenta), II(turquoise) and III (green) and the average curve of D aligned and adjusted according to their average peak time and duration. G-H. Linear regression lines for the elongation of the arm during the second (G) and the third (H) phases of the movement (n=30). Only the third phase's elongation data (second group) is correlated with the initial distance of the bend from the target, at the beginning of that phase; The coefficient of correlation (r) and the p values of the F-test appear at the top left. The data presented in this figure implies that the reaching movement is actually composed of at least two different kind of active sub-movements.

Arm extension involves bend propagation and arm elongation (Figure 5. 1). The extent of this observed elongation is quite substantial and highly variable. Visual observation and subsequent kinematic analysis suggest that the reaching movements can be broadly segregated into two groups. The first group involves bend propagation, which begins at the base of the arm and propagates towards the arm tip. In the second the bend is formed more distally and reaching is achieved mainly by elongation and straightening of the segment proximal to the bend. Analysis of the first group of movements (bend propagations) reveals that while the bend propagates along the arm, elongation and bend propagation velocities are correlated.

In the second group of movements we showed that elongation is significantly positively correlated with the distance of the bend to the target ($\rho=0.79$; f test=23.88; $p<0.0001$).

Our main finding is that arm extension movements involve bend propagation and elongation of the segment of the arm proximal to the bend. The elongations are quite substantial and highly variable; ranging from a strain of -18% up to 180% at the end of the movements (64±28%, n=30 second set of experiments; 57±41% aver ± SD, n=64, in the previous study). Our results suggest that reaching to a target involves two biomechanical mechanisms: **bend propagation** and **arm elongation**. These two motor primitives may be combined to create a broad spectrum of reaching movements. The combination of the two may depend on the initial posture of the arm, distance to the target, required speed and need for correction.

Task 5.3 Organization of higher motor centres in the octopus brain - months 4-16 (HUJI, Weizmann, IIT)

In this task the neural basis of motor control in the central and peripheral nervous systems, as well as the reciprocal relationship between these two systems have been elucidated. In parallel to our efforts to identify movement primitives at the kinematic level, we have been searching for the neural correlates of such primitives and the mechanisms subserving their construction, activation, assembling and scaling. We used ‘in vivo’ microwire recording and stimulating techniques that we developed in behaving animals. This allows us to study how the octopus brain is organized, integrates sensory information and to transform it into motor actions.

Our results show that movements and behavioural responses evoked by electrical stimulation of the higher motor centres belonged to the animal’s behavioural repertoire. We managed to induce stereotypical movements and these were represented in the higher motor centres by a number of overlapping circuits.

We found no evidence of somatotopic motor representation in the octopus higher motor system.

We suggest that a unique organization wherein single cells or groups of cells are dynamically recruited into several different higher control networks take place here. All these results have been successfully published (Zullo et al., 2009) and we can report that this task is almost completed.

Task 5.4 Organization of the peripheral nervous system of the arm - 4-16 (HUJI, Weizmann, IIT)

The construction of architectural models aims at predicting design aspects of a system based on functional demands and physical principles. Two factors play a major role for the mechanical function of an octopus-like muscular hydrostats. These are: (1) the dimensions and arrangement of the muscle fibres and connective tissue into muscle groups (see WP4.5) and (2) the organization of the motor and sensory systems underlying the highly flexible and sensitive octopus arm (WP5.4), which is the subject of this current task.

We have been testing the “labelled lines” hypothesis (central-peripheral pathways that transmit motor commands from the octopus brain to specific locations along the arm). The labelled line hypothesis is particularly relevant to the octopus arm, as it is known that stereotypical arm movements, such as arm extension and fetching movements, can be initiated at any location along the arm. This ability is especially interesting as it is a unique feature of biological and artificial flexible appendages.

First results indicate that in contrast to the labelled line theory there is no one path that goes straight from the brain to certain points in the arm. Indeed the connections seem to be more spread and probably there are set of nerves innervating many points along the arm. This finding does not exclude the possibility that sets of nerves specific for different arm regions do exist. Parameters for nerve stimulation have been extracted in order to evaluate the recruitment of the nerve fibres within the axial nerve cord.

We are now performing additional experiments on dissociated arm nerve cords and we aim to give a precise description of the axial nerve cord/muscle interaction.

Following interest from various consortium partners on the issue of movement control such as for ‘fetching’, we decided to perform an additional test to study the generation of this movement. This deviation will see the design and set-up of a system to induce fetching movements by mimicking double muscle wave activation. We will perform double stimulation at different levels on a whole/long segment of an arm and video-record the movement induced. We aim to do a three-dimensional reconstruction of the motion and check for its consistency with the stereotypical fetching.

Task 5.5 Correlating kinematic parameters with muscle activity for understanding dynamic aspects of movement generation and control – months 4-16 (HUJI, Weizmann, IIT)

In these experiments the stereotypical movements are filmed with two cameras at stereo configuration. This allows reconstruction of the movements in 3D from the two images. In the same time one or two thin Teflon coated stainless steel wire electrodes are threaded through the arm musculature at a desired location and glued to the arm with markers that help to locate the electrodes site. A section of the insulation is exposed to allow EMG recording from a small muscle group (Gutfreund et al., 1998). Kinematic parameters of interest are calculated from the images at the same time as the recorded intensity and velocity of EMG signals. This experiment allows us to test for significant correlations between kinematic parameters and integrated EMG signal. Finding such a correlation would point to the dynamic characteristics of the control mechanism. For example in arm extensions we found correlation between EMG activity and maximum velocity; suggesting a feed-forward motor program (Gutfreund et al., 1998). A similar technique is feasible for the dynamic characterization of other movements.

Task 5.6 Sensory systems of the octopus - month 4-16 (HUJI, IIT)

In this task we have been characterizing the mechanisms of transmission and processing of sensory information and motor input at different levels of the peripheral nervous system.

As methodological achievement we managed to set up a system for recording/stimulating sucker ganglia while performing various protocols on a dissociated arm/sucker preparation. We also set up a system for mechanical stimulation of sucker and arm muscle while recording from axial nerve cord/arm ganglia/sucker ganglia. This allows us to extract the activation threshold of single sucker and suckers' reflex responses in response to tactile/electrical stimulation of the suckers.

Our first aim is to monitor the signals travelling from sucker to sucker and along the axial nerve cord of the arm. To achieve this we mimic sensory output from the area of the sucker by stimulation of sucker ganglia and record at different levels along the axonal tract. Mechanical and chemical stimulations of the one sucker to reproduce sucker electrical output and mechanical displacement while extracellular recording from either the sucker ganglion or from the axonal tract are taken.

As experimental achievement we performed recording form the axonal tract while we electrically stimulated the sucker ganglion and the sucker rim (point 1). First results indicate that threshold for obtaining a response irrespectively form the distance between the sucker ganglion stimulated and the axial nerve cord was around 50V. Summation of the response during a single stimulation train has been observed. We also obtained an increase in responses as an effect of consecutive stimulation trains. Recordings evoked were proportional to the amplitude of the stimulation. The same stimulation protocol was applied at different location along the arm while recording form the same position. This allows us to study the transmission of the waves of activation along the arm.

We next have to characterize the sucker cup behaviour and the transition of local reflex to neighbouring suckers (point 2).

In order to study the transmission of motor inputs from the brain at different levels of the peripheral nervous system of the arm we are now performing experiment to mimic motor input to the muscle and sucker ganglia by:

1. Stimulating axonal tract and record from sequence of sucker ganglia
2. Stimulating arm ganglia and record from sequence of sucker ganglia

We are now examining our first test recordings and designing fine stimulation experimental protocol. Further results will be presented in the Deliverable D5.1.

Task 5.7 Assessing the division of labour between the central and peripheral motor control system - month 4-16 (HUJI, Weizmann, IIT)

We started several experiments dealing with the characterization of the kinematics movements in regenerated arms. We collected a set of movements produced by an animal with two regenerated arms. At present further experiments are being conducted. As we proposed, the ability to study regenerative arms in the octopus is an unprecedented opportunity to isolate and study physical and neural constraints involved in movement generation and control.

In this task we also study movements requiring the coordination of arms such as crawling. We currently use a mirror array to film the animal simultaneously from the lateral view and from bellow. This enables us to look into which suckers are activated at what time and how crawling is achieved. We hope to use this technique to describe the kinematics of crawling and the rhythmical phase relation between the functioning arms.

Additionally we started experiments on the interbrachial commissure. Using both electrical stimulations and either behavioural/kinematic analysis or neurophysiological recordings we aim to characterize reflex arches and the way arm movements are coordinated at this level. We developed a procedure for making localized and specific lesions to this commissure. The effect of such lesions on arm coordination in freely behaving animals will allow characterizing the role of this inter-arm nervous system in the control of crawling behaviour and other multi arms behaviours. Previous studies (Altman 1971, Ten Cate 1928, Young 1971) showed the involvement of the commisure in reflexes like the "recruiting rule of neighbourliness". Further studies are necessary to understand how other more complex movements, like crawling, catching prey or swimming, are processed at this level.

3.5 WP6 – Kinematics and dynamics modelling of the octopus arm

WP Leader: WEIZMANN

WP Members: HUJI, IIT, FORTH

Progress summary

Within WP6 new methods for 3D motion tracking and reconstruction were developed including the development of a nearly automatic motion tracking system for reconstructing the arm's backbone Efforts were also directed at kinematic analysis and modelling of the octopus movements. Computational algorithms for decomposing the motion into elementary 3D primitives were also developed. The biologically inspired 2D dynamic model of the octopus arm (Yekutieli et al., 2005) was extended to 3D and was used to simulate fetching and other complicated movements in order to gain new insights into their control and as a possible source of inspiration for the control of the robotic arm. The 2D and 3D models are also currently extended to study object grasping and manipulation tasks and for choosing appropriate arm impedance. Other efforts were aimed at developing detailed computational models of the octopus arm elastodynamics and hydrodynamics and the arm was also studied from a morphological viewpoint to approximate and emulate its properties within a robotic arm.

Significant results

The most important results of WPs have been published in the papers:

- Tsakiris D. (2009) Bio-inspired motion control for pedundulatory robotic locomotion *J Mol Neurosci* 39 (Suppl 1):S1–S132.
- M. Sfakiotakis and D.P. Tsakiris, "Undulatory and Pedundulatory Robotic Locomotion via Direct and Retrograde Body Waves", Proc. of the 25th IEEE Intl. Conference on Robotics and Automation *(ICRA'09)*, pp. 3457-3463, Kobe, Japan, May 12-17, 2009.

- G. López-Nicolás, M. Sfakiotakis, D.P. Tsakiris, A.A. Argyros, C. Sagüés and J.J. Guerrero, "Visual Homing for Undulatory Robotic Locomotion", Proc. of the 25th IEEE Intl. Conference on Robotics and Automation *(ICRA'09)*, pp. 2629-2636, Kobe, Japan, May 12-17, 2009.
- I. Zelman, M. Galun, A. Akselrod-Ballin, Y. Yekutieli, B. Hochner, and T. Flash (2009) Nearly automatic motion capture system for tracking octopus arm movements in 3D space, *Journal of Neuroscience Methods*, Volume 182: 97-109.

Task 6.1– Characterization and modelling of motion kinematics – months 4-16 (Weizmann, HUJI)

A nearly-automatic marker-less motion capture system that successfully tracks octopus arm movements in 3D space was developed. The system integrates segmentation, skeletal representation and 3D reconstruction methods. Its input consists of a pair of video sequences recorded by two video cameras. Then three steps are performed; image segmentation is applied to each video sequence and the segmented arm images are represented by silhouettes. Then, a skeletal representation is extracted for each arm silhouette, resulting in a pair of backbone curves. Finally, each such pair of curves is used to reconstruct a 3D curve describing the arm configuration as a function of time (Figure 6. 1). Only 2 user's actions are applied once during the analysis of the entire video sequence independently of its length.

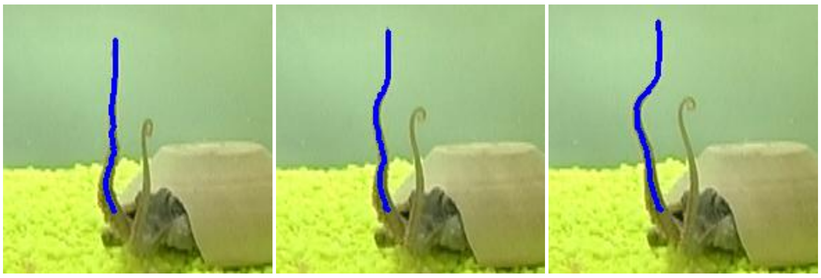


Figure 6. 1 Detection results for an octopus arm movement.

Task 6.2 Studies of complicated motion patterns – months 4-16 (Weizmann, HUJI)

Computational algorithms were developed to decompose 3D octopus arm movements into underlying motion primitives. The movements were represented based on the curvature and torsion values along the arm's virtual backbone. For a time dependent sequence of 3D backbone curves a pair of surfaces describing the curvature and torsion values along these curves were constructed. These surfaces were then decomposed into kinematic units which can be characterized as the underlying kinematic primitives, which can be combined by synthetic rules in order to generate a variety of motor actions. Finally, the octopus arm behaviour was classified into sub-groups based on the combination of primitives associated with each movement. The decomposition algorithm involved the use of a Gaussian Mixture Model and the EM algorithm. A clustering algorithm was applied to the resulting Gaussians. The data consisted of 60 3d reconstructed movements and was separately analyzed for pre-extension, extension and post-extension phases of the movements.

Task 6.3 Development and implementation of arm dynamic models - months 4-16 (Weizmann, IIT, FORTH)

A 3D dynamic model of the octopus arm was developed based on the formerly developed 2D mass-spring model (Yekutieli et al. 2005a,b). The arm is modelled as a hexahedral multi-segment structure, each segment containing longitudinal and transverse muscles and maintains a constant volume. The model includes muscle forces, constant volume constraint forces, gravity, buoyancy, and water drag forces. The input to the model consists of muscle activations. The 3D model was used to validate the approach, since the constant volume constraint was calculated differently for the 3D versus the 2D cases, and to investigate bend creation (Figure 6. 2) It was found that: a) Bending can be produced by activating the transverse muscles along with a differential activation of the longitudinal muscles and can be controlled by the choice of bend location, activation amplitudes and the arm length differentially activated. The 3D dynamic model was also used to simulate fetching movements (Sumbre et al. 2005, 2006) by finding the middle of the arm as the collision point between two waves starting at the base and at the tip and propagating towards each other. The simulated movements had similar kinematic characteristics to the observed behaviour.

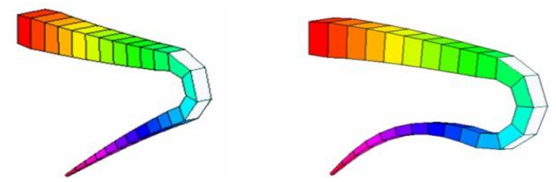
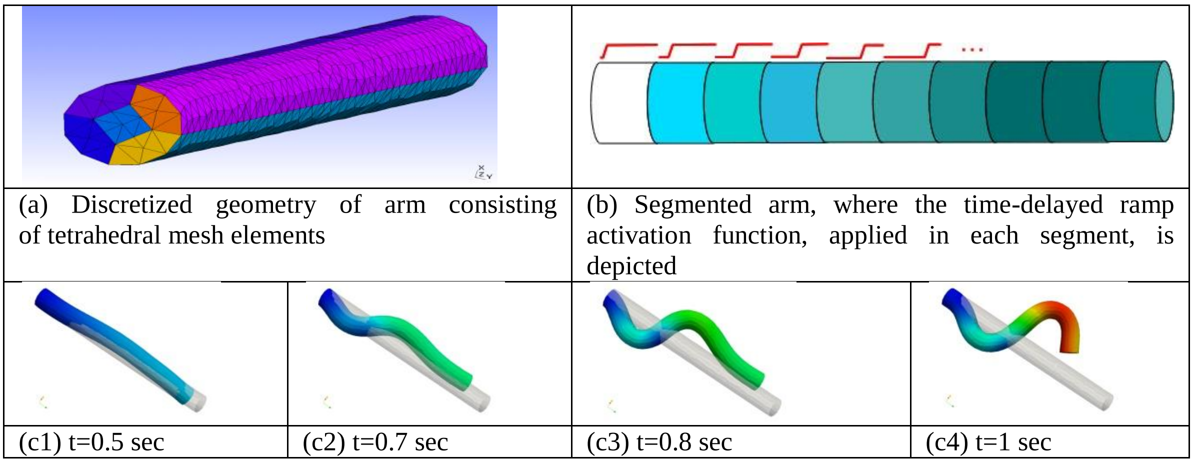


Figure 6. 2 Simulated local bend using differential activation in a local area of 3 and five segments.

In conjunction to the above studies, more detailed models of the elastodynamics and hydrodynamics of the octopus arm were developed. To model and simulate the elastodynamics of the octopus arms, an open source Finite Element Method analysis program was used, capable of solving 3d transient non-linear elastic solids of muscular hydrostats, with large displacements and strains, is being developed in C++. An explicit time marching technique (Bathe, 1996) is utilized to solve the transient phenomena, as in (Liang et al., 2006). The muscular tissue incompressibility criterion is directly imposed on the constitutive equations (Sussmann & Bathe, 1987). The muscular behaviour is modelled via active and passive properties, as proposed in (Van Leeuwen & Kier, 1997), while the biomechanical properties of the squid tentacles, as provided in that paper, are used as a first approximation of octopus arm properties. The corresponding passive stresses are modelled via a Mooney-Rivlin constitutive strain-energy function (Zienkiewicz & Taylor, 2005), where incompressibility of the material is taken into consideration. As a first step in the FEM analysis, an idealized cylindrical geometry for the octopus arm was considered. It contains four active longitudinal muscles and a passive central core. The tangential, helical and circumferential muscular tissues are, for the present time, neglected. In order to discretize the cylinder in space, a uniform mesh, as shown in Figure 6.3 (a), was utilized, consisting of 8750 tetrahedral four-node finite elements. Indicative results are presented next. In order for the arm to perform a bending movement, one longitudinal muscle is forced to contract, activated via a ramp-function of time of 50msec duration. If the arm is considered to be divided in ten equal segments, as in Figure 6.3 (b), the activation function is applied with a time delay of 0.05sec per each segment (solid red graphs). The total time observation of the arm deformation is one second.



(a) Discretized geometry of arm consisting of tetrahedral mesh elements

(b) Segmented arm, where the time-delayed ramp activation function, applied in each segment, is depicted

(c1) t=0.5 sec

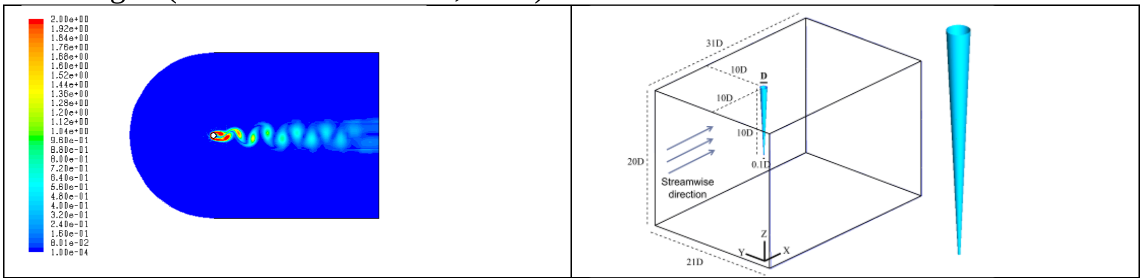
(c2) t=0.7 sec

(c3) t=0.8 sec

(c4) t=1 sec

Figure 6. 3 Finite Element analysis of deforming arm for one-muscle contraction, at consecutive time instants. The transparent grey cylinder indicates the initial shape of the arm.

The hydrodynamics of an octopus arm in an aquatic environment was investigated by computational fluid dynamic (CFD) methods. In 2D and at specific 3D configurations (perpendicular to the flow and at small flow incidence angles), the octopus arm possibly acts as a bluff body to the flow field and produces vortex shedding (Braza et al., 1986; Williamson & Brown, 1998; Tritton, 1959; Roshko, 1961; Nishioka & Sato, 1978). Idealized configurations of the octopus arm are considered, first, to examine the flow development in its wake.
Initially, flow past a two-dimensional circular cylinder was considered, in order to validate the methodology and determine the mesh requirements for capturing vortex shedding and the CFD boundary conditions. The ICEM-CFD (ANSYS, Canonsburg, PA) and the Gambit (Fluent.Inc) packages were used for geometry and mixed element mesh generation. The lift and drag coefficients of flow past a two-dimensional circular cylinder were found in agreement with previous published results (Braza et al., 1986), allowing estimation of the mesh requirements and boundary conditions. Figure 6.(a) shows contours of vorticity magnitude at a specific time point after time periodic response was obtained after long time integration for Reynolds number Re=100. Periodic vortex shedding was established and the vortical structures in the wake of the cylinder were visible and well defined. Based on the shedding frequency from the lift coefficient, the Strouhal number was calculated as 0.166, almost identical to the experimentally obtained value of 0.165, for this case, according to (Williamson & Brown, 1998).



(a) Vorticity magnitude at t=177 sec, for 2D circular cylinder at Re=100.	(b) Computational domain for 3D frustum (left). Octopus arm (right).

Figure 6. 4 (a) Vorticity magnitude. (b) Computational domain for a 3D octopus arm positioned perpendicularly to the flow direction. Octopus arm (right).

Subsequent developments used a simplified geometry of an octopus arm, approximated as a frustum with rigid walls, and positioned perpendicularly to the streamwise direction (Figure 6. (b)). The incompressible Navier-Stokes equations were used and Newtonian rheology was assumed, to study flow at low Reynolds and Strouhal numbers, using Fluent.Inc. Preliminary results of flow, past the three-dimensional geometry of the frustum, showed similar generation of alternating separation of vortices in the wake of the frustum, which were convected and diffused away. The objective of these studies is to enhance our understanding of the octopus arm hydrodynamic environment, and, in conjunction with other parallel studies on the elastodynamics of the octopus arm, contribute to the design and control of octopus arm-like robotic artefacts.

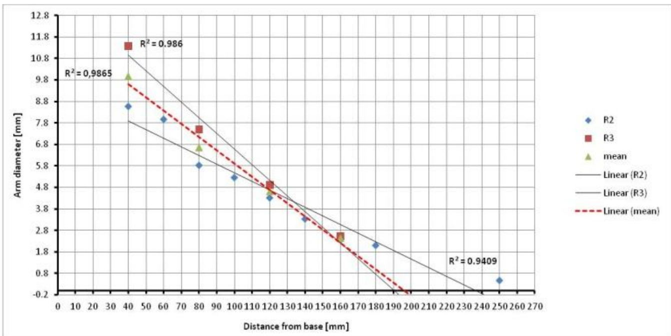


Figure 6. 3 Relation between arm diameters and their distance from the base of two sample arms (R2 and R3), and their average.

Other efforts were directed at approximating the morphology and the properties of the octopus arm continuum structure with a finite number of pneumatically-activated extending and contracting artificial muscles according to the octopus arm anatomy. The design concept is based on joining a number of flexible segments each one having three longitudinal muscles and three radial muscles, spaced at 120° in the corresponding plane.

Figure 6. 4 schematically depicts the geometrical structure of two segments. The geometry is axisymmetric.

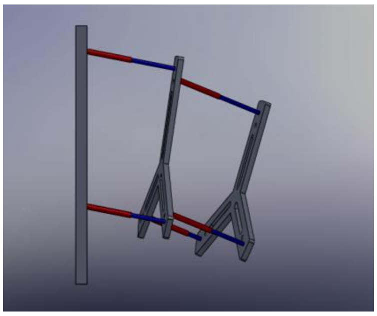


Figure 6. 4 Octopus arm geometrical structure with two segments.

The system is assumed to have all muscles independently controllable and the segments can become stiffer in a sequential manner. To design a multi-segmented structure it is necessary to find a kinematic design relationship that relates the maximum deflection achievable per segment as a function of the segment geometry and number of segments. In steady-state (see Figure 6. 5) if the longitudinal and radial muscles are both pressurised the max achievable rotation $\Delta\alpha$ of the (n+1)th segment can be calculated as:

$$\Delta\alpha_{n+1} = \tan^{-1}\frac{\Delta L_n}{R_n[1+\cos(\frac{2}{3}\pi)]+\Delta R_n}$$

where L and R are the extension and contraction of the *n*th longitudinal and radial muscles respectively.

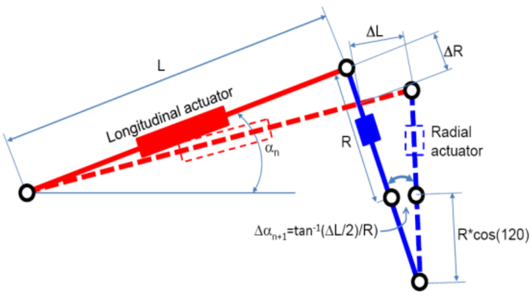


Figure 6. 5 Rotation of a segment when the longitudinal muscle expands and the radial muscle

Using the aforementioned 2D and 3D simplified dynamic models of the octopus arm the relation between arm geometry and arm bending was studied. This analysis considered different rectangular shapes for the segments involving either tall, square or elongated segments (Figure 6. 6,). For each arm a simple activation scheme for the longitudinal muscles was used: all dorsal muscles were activated to one level and all ventral muscles to another level. To separately examine geometric versus dynamic factors simplified conditions were considered: free base and rectangular segments, no gravity and high drag forces. The results showed that arms with short-segments bend more. Increasing in the transverse activation resulted in a larger bending angle. There was a linear relation between the log of the transverse activation and the bendability of the arm.

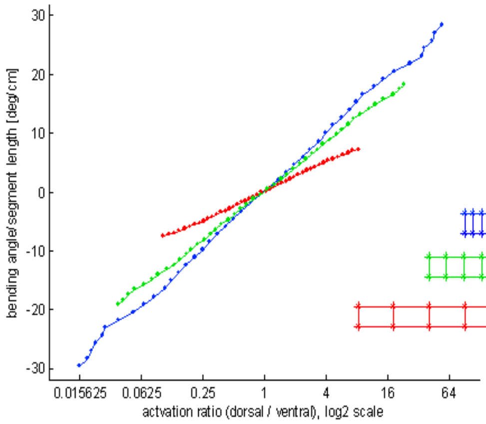


Figure 6. 6 Bending of three different simulated arms (inset) as a function of the log activation ratio of dorsal to ventral muscles.

The simulations were repeated with trapezoidal segments (see Figure 6.7). Here the simulations were for a full length arm with fixed base, realistic values for gravitation, buoyancy and drag forces. The arm segments had either a fixed length or a trapezoidal shape that is scaled down from its maximal size at the base to its minimal size at the tip (a,c). The terms fixed length and fixed shape refer to the initial segments' shape.

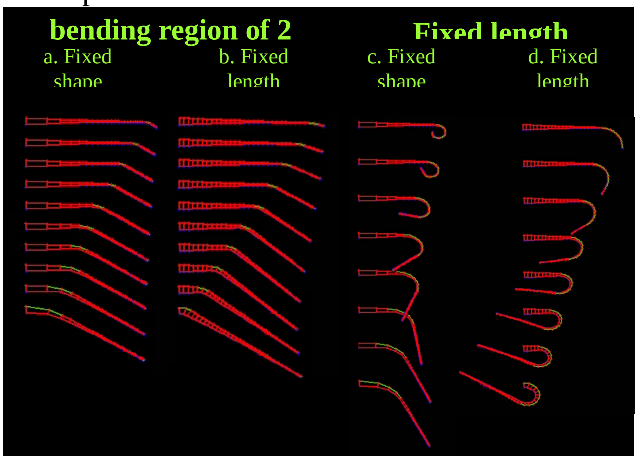


Figure 6. 7 Simulations of local bend for arms with fixed shape segments (a,c) and fixed length segments (b,d). The bending region was either 2 segments long (a,b) or about a third of the arm (c,d).

The bending region location along the arm was varied. For a fixed number of segments (2 segments), the arm with fixed shape segments had the same bending angle all along the arm in contrast to the arm with the fixed length segments, which had different bending angles - the smallest near the tip. For a bending region with a fixed length (a third of the arm), for the arm with fixed shape segments, the curvature of the bend region was positively related to the number of segments in the region. Hence it had a tightly curved bend near the tip and a low curvature bend near the base. For the arm with fixed length segments the maximal curvature bend was near the base. The 2D dynamic models (Yekutieli et al. 2005) were also used to infer muscle activations from kinematics. In Yekutieli, et al., 2005, muscle activations were guessed based on EMG measurements (Gutfreund, 1998) and the resulting kinematics was compared to the observed motions. Currently an algorithm was developed enabling to directly compute the activations from the observed kinematics. Given the other forces, the constraint force needed to keep the volume constant has both passive and active components. Its active component can be combined with muscle forces to determine their total contribution. Given that the system is under-actuated Moore-Penrose pseudo-inverse was used to find the closest approximate solution of muscle forces and assuming a linear muscle model with known parameters and a constant rest length, muscle activations are calculated. This technique was verified for simulated movements and is also applied to measured movements. This technique will also be used to analyze the errors obtained from unmodeled dynamic factors (e.g., ignoring the oblique muscles).

Task 6.4 Investigation and modelling whole arm grasping and compliance control – months 4-16 (Weizmann, IIT, FORTH)

A model based control scheme was developed in which a backbone curve for the arm is prescribed as the desired kinematic input. The required actuator forces are computed for the static case as the ones that set the arm configuration and stiffness to minimize the global potential energy. This control scheme is suitable both for the unconstrained and compliant tasks. In the latter case, interaction with objects is based on employing compliance specified by the arm's structure and/or selected for the task. This control scheme involves two phases: I) A desired model configuration is extracted for the input curve II) the forces required to achieve the desired model configuration are computed. The segments' configurations were sequentially derived from the base onwards towards the tip. To minimize the potential energy with a pre-given area constraint the segment must have a cyclic quadric-lateral shape. The computations of arm configuration are currently done analytically, in O(n), n being the number of arm segments. The subdivision of arm into segments involves a numerical maximization of the smoothness of the resulting configuration while maintaining legal structure. Then in phase II muscle forces and stiffness needed to achieve the desired configuration are derived. Once the arm configuration is determined a trajectory for the backbone is planed and the arm is quasi-statically moved between the initial and final configurations.

To analyze the force distribution of the octopus arm/manipulator during grasping and manipulation the effects of different factors such as arm geometry and the intrinsic variables being controlled were investigated. Elongation patterns of the octopus arm were observed during reaching movements (see WP5). When using the 2D model in which muscle activation affects only muscle stiffness an unrealistic ratio of 19x10-4 longitudinal to transverse muscle activation ratio is required to simulate elongation movements. Biological findings have shown that the passive and active biomechanical properties of the transverse and longitudinal muscles fibres are quite similar (Matzner et al., 2000; Rokni and Hochner, 2001). This led us to examine a model whereby neural activation controls not only muscle stiffness but also its rest length thereby affecting both muscle force and stiffness. Using this modified model arm elongation of 128% during reaching could be achieved using a value of 1.0 for the ratio of longitudinal versus transverse muscle activation. An alternative model of muscle hydrostats by Crago (1992) was implemented in the 2D dynamic model and search is conducted for suitable model parameters to achieve a wide range of arm elongations. Additionally different strategies of muscles' co-contraction are examined to analyze their effect on force production and stiffness control.

3.6 WP7 – Octopus behavioural experiments

WP Leader: HUJI

WP Members: SSSA, UZH

Progress summary

WP7 is performing purposive behavioural experiments to study how the morphology and physiology of the octopus affects the development of its motor skills and intelligence. We address questions of motor control and sensory integration by applying tasks that are natural to the octopus. Additionally, we are currently starting to raise octopus paralarvae to investigate their transition from a free swimming pelagic lifestyle, using their arms to catch and manipulate prey, to a bentic lifestyle on the ocean floor where they use sensory, manipulative and locomotor actives like an adult. Investigating the animal as it develops the traits we are interested in will help the roboticists to develop a robotic octopus that incorporates these capacities and traits. Close collaborations exist especially between the teams at HUJI and UZH. Further collaborations between HUJI and SSSA will help to integrate findings of the two groups that could be of great importance for the prototype. To date all experiments worked out according to plan. The results of two tasks are currently prepared for publication and will be submitted within the next 2 months.

Significant results

The most important results of WPs have been published in the papers:

- Gutnik T., Byrne R.A., Hochner B. and Kuba M.J. (2009) *Octopus vulgaris* visually guides complex arm movement *J Mol Neurosci* 39 (Suppl 1):S1–S132.

Task 7.1: Adaptation of facilities and collecting of animals – Month 1-3 (HUJI, SSSA)

We finished massive reconstructions in our animal and experimental facilities allowing us to house up to 32 animals. In addition we established a new system of 7 aquariums ranging from 350 l to 550 l for kinematics, neurophysiological and behavioural studies.

Task 7.2: Culture – Month 4-24 (HUJI)

Due to the seasonal cycle of *Octopus vulgaris* we were able to collect our first eggs in the end of February. The raising of the larva will take place in the adapted facilities at a college for aquaculture on the Mediterranean Sea. Recent advances in marine culture of octopuses provide us protocols to raise *Octopus vulgaris* paralarvae. During the first months of its life the juvenile octopuses have to transform from a pelagic paralarvae, having very short arms with few suckers, to a small benthic octopus identical to an adult. We will be able to observe when and how these juveniles start developing their typical motor primitives and to what extend the dexterity of arm use is acquired or reshaped during ontogenetic development.

Task 7.3: Visual coordination of motor output– Month 4 -16 (HUJI, UZH)

Complex arm movements, like those used for searching and probing, have been hypothesized to be largely autonomous and not directly controlled by the central nervous system. Previous studies that attempted to teach octopuses an operant task have been only partially successful. In the octopus the availability of proprioceptive information and other feedback information during arm movement has been widely debated.

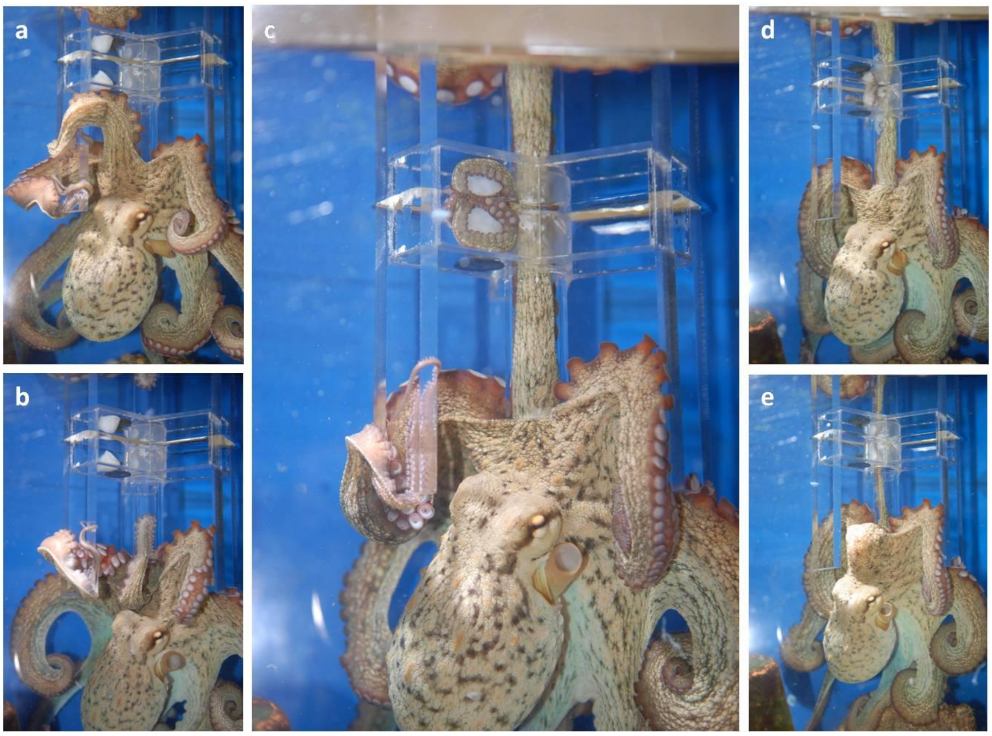


Figure 7. 1 Octopus approaches maze (a), inserts a single arm (b), makes a correct choice (c) and retrieves the food reward (d-e)

We used an operant behavioural task that utilized an adaptation of a natural movement to investigate the relationship between CNS and PNS during directed complex arm movements. 9 adult octopuses were trained to insert a single arm through a tube for a food reward. Next, the three-armed Plexiglas maze was introduced into the tank with all boxes baited and visually marked (Figure 7. 1). These initial phases accustomed the animals to reach through a tube, out of the water and into a goal box in order to retrieve food. In the experimental phase a food reward and visual marker was be placed in only one of the three compartments. Octopuses were required to guide a single arm to the reward compartment. 6 of the 9 animals tested reached the criterion for learning, five correct trials in a row, within 61-211 trials. Using a binary logistic regression (R2=0.136, n=5) we found a strong negative correlation (-0.923 p=0.000) between not seeing the target and success. After criterion was reached 20 control trials were performed using an opaque maze, where the animal could not see the food and visual cue. During control trials the animals' performances returned to chance level.

This study clearly shows the ability of *Octopus vulgaris* to learn an operant task. It is the first behavioural experiment to show that octopuses can learn to visually guide arm movements that are not restricted to the control of few degrees of freedom (like reaching). Control of complex arm movements, such as those required in this maze, require constant input and feedback. We suggest that octopuses, unlike previous claims, are capable of central control of arm movements and perhaps cross-reference between different sensory inputs and motor outputs.

Task 7.4: Coordination of arm use– Month 4 -16 (<u>HUJI</u>, SSSA)

This task focuses on the well-known task of jar opening and series of motor learning experiments. We use the jar opening experiments to characterize different strategies to open the jar. Performances of octopuses in the jar opening experiments have been little affected by learning. Still the performances of individuals show huge variation. We focus on how the use and coordination of several arms related to better performance in complex tasks. Additionally we will use a jar fixed to

a transparent Plexiglas plate to be able to do a 3D reconstruction of the octopuses' performance and its coordination of the movement of multiple arms to complete the task.
In a next set of experiments we investigate the ability of the octopuses motor output programs to adapt to new tasks. In one task we teach the animal to remain in a fixed location and reach to a moving target. We want to investigate at what point in the reaching to target movement the octopus is able to correct the trajectory of the movement and adapt it to accurately hit a target. Furthermore we conducted a set of experiments that affected either, bend propagation or fetching movements by introducing a physical constrain to the base of the octopus arm. To do so animals were placed inside a transparent Perspex box (40x40x40cm) with a hole at the centre of every surface that allowed the insertion of a single arm only (1.5cm ∅). During the experiment the subjects had to reach out through a hole to retrieve a food reward offered outside the box. In the 3 animals tested thus far, the performance of the reaching towards a target movement did not improve in consecutive experimental sessions. However, the accuracy and speed of fetching movements improved both within and across sessions.

Task 7.5: Proprioceptive feedback to control arm movement – Month 4 -16 (HUJI, UZH)

This experiment investigates the ability of the octopus to learn to navigate an arm inside a two way choice maze based on proprioceptive information only. Using a Plexiglas plate with a Y shaped tube glued to it the octopus must insert only one arm into the maze and bend it to the correct direction to reach a baited goal-box. The animals received neither chemical nor tactile information on the direction of the turn. Therefore the correct decision to turn left or right inside the maze could only be made based on proprioceptive information on the position of the arm. All animals tested managed to learn the task within 54 to 72 trials. The criterion for successful completion of the test was 20 trials with a rate of correct trials higher than 80 %. In cooperation with SSSA further analyses will be conducted in on arm use and how arm extension might affect success rates in these experiments.

Task 7.6: Tactile discrimination learning - Month 14 -24 (HUJI, SSSA)

The experiment is supposed to start at month 14. It will use a modified version of the maze used in task 7.5 to investigate texture discrimination capacity of arms and suckers. Into each of the two stems different textures will be inserted. The octopus must insert an arm and learn a texture associated with a reward. The transparency of the apparatus will enable us to investigate the use of the arm and the suckers as they explore the textures and move up and down the maze. Our colleagues at UZH will use details of these movements and modellers to better understand sensory processes.

3.7 WP8 – Biomechatronic specifications of the robotic octopus

WP Leader: SSSA

WP Member: All beneficiaries

Progress summary

WP8 was completed and its deliverables were submitted at the end of July 2009, on schedule.
This WP led to the definition of the specifications of the whole octopus-like robotic artefact. WP8 relied on the results of WP2 and WP3, i.e. on the survey of the knowledge on the octopus biology and on the relevant technologies, as well as on the results coming from the plenary brainstorming meeting that was held in Crete, after the tutorials, on April 27-28, 2009, where all partners contributed to and agreed on the general structure and requirements of the artefact.
WP8 led to the specifications of the octopus-like robotic artefact starting from the tasks expected the robot accomplishes. The tasks have been defined based on selected movements typically

performed by the *Octopus vulgaris* and of interest in robotics. Some of these movements are well characterized in biology and provide specifications for the shape, materials, muscular structure and its functionality, control techniques, and behavioural architecture of the robot. The resulting specifications are a good example of translation of biology into engineering.

Significant results

The final result of WP8 is the submitted deliverable D8.1 ("Biomechatronic specifications of the robotic octopus"), i.e. a document describing the specifications for the whole OCTOPUS system and containing one section for each component, representing a reference, in terms of specifications, for the next phases of design and development.

The document is the result of the integration of the preliminary specifications already included in the original proposal and all the other supplementary and more detailed specifications discussed and decided during the brainstorming meeting held in Crete.

Task 8.1 Specifications of the whole OCTOPUS artefact – month 4 (SSSA, all)

The specifications of the whole OCTOPUS artefact have been derived starting from the analysis of two of the most studied movements in octopus, which are the reaching and the fetching movements. Many other complex movements can be observed, but from a biological and engineering point of view, 5 tasks have been selected as a target of the final artefact, because many data are available and comparisons could be carried out in the final phase of the project to evaluate the robotic platform.

Task 8.2 Specifications of the OCTOPUS central head and behavioural architecture – month 5-6 (UZH, FORTH)

Based on the IP objectives and output of the survey conducted in WP3, a set of requirements for an implementation of the robot central body and behavioural architecture has been defined. A series of criteria drawn from Embodied AI will be followed, always keeping in mind one of the key concepts: the sensory-motor control architecture is closely coupled with the morphology and material properties of the embodied artefact being controlled.

The development of an effective sensory-motor control architecture for the control of the robotic octopus based on these principles is needed and will need biological evidences supplementing it. Thus, the importance of accomplishing behavioural experiments in collaboration with groups specialized in biology has been highlighted.

Task 8.3 Specifications of the OCTOPUS arm control techniques – month 5-6 (IIT, Weizmann, FORTH)

This task provided the detailed specification requirements for the control of a multi-degree of freedom robotic arm. The aspects that have a larger impact on the specifications of the control techniques have been identified and well described.

To manage the execution of motion/stiffness profiles as those observed in the biological OCTOPUS and considering the actuation and sensing characteristics, detailed specifications are defined for the peripheral and the central control of the robotic OCTOPUS arm. These control requirements do not specifically target only one control solution, on the contrary, different control strategies will be identified and their relative merits will form part of the output.

Task 8.4 Specifications of the OCTOPUS artificial muscular hydrostat structure – month 5-6 (SSSA, HUJI, Weizmann, IIT, UREAD)

This part of the work provided the specifications to take into account designing and developing an artificial muscular hydrostat unit to use in the development of an OCTOPUS arm. The importance of understanding and making clear how an octopus can perform the different arm movements and why we have to replicate its muscle arrangement has been highlighted previously and must be completed before defining the design constraints. After this analysis, a series of specifications have been identified. This includes specifications for the mechanical structure, soft actuators and the materials used in fabrication of the actuators and artificial muscular hydrostat.

Task 8.5 Specifications of the OCTOPUS sensorized skin – month 5-6 (UREAD, SSSA)

The definition of the characteristics of the external skin enveloping the whole OCTOPUS artefact body has started with some preliminary experimental tests, in order to obtain important information on the octopus skin. These several data tests have been used to better define mechanical specifications for the artificial skin behaviour. Moreover a series of sensing requirements have been identified and some technologies has been proposed.

3.8 WP9 – Design and development of the artificial muscular hydrostat

WP Leader: SSSA

WP Members: IIT, UREAD

Progress summary

The first deliverable of this WP is scheduled at month 18, but several results have been already reached. While most of the details have been left for that document, here the most relevant results obtained till now are reported.

Significant results

The most important results of WPs have been published in the papers:

- C. Laschi, B. Mazzolai, V. Mattoli, M. Cianchetti, P. Dario, "Design of a biomimetic robotic octopus arm", *Bioinspiration & Biomimetics*, Vol.4, No.1, 2009.
- M. Cianchetti, V. Mattoli, B. Mazzolai, C. Laschi, P. Dario, A new design methodology of electrostrictive actuators for bio-inspired robotics, Sensors and Actuators B: Chemical 142 (1) (2009) 288-297.
- C. Laschi, B. Mazzolai, V. Mattoli, M. Cianchetti and P. Dario (2009) Design and Development of a Soft Actuator for A Robot Inspired by the Octopus Arm, in Experimental Robotics, The 11th International Symposium, O. Khatib, V. Kumar, G. Pappas (Ed.s), Springer Tracts in Advanced Robotics (STAR Series), Springer, pp.25-33.

Task 9.1 Design of the artificial muscular hydrostat – month 7-9 (SSSA, IIT)

In the design of the robotic arm, the longitudinal muscles and the transverse muscles, as well as their reciprocal actions have been specifically taken into consideration. The design proposed at the beginning of the project has been maintained in terms of components: the longitudinal artificial muscles run all along the arm length and transverse muscles are arranged on a plane perpendicular to the longitudinal muscles. Therefore, the robotic arm consists of 4 longitudinal muscles and a number of transverse muscles in parallel, whose number depends upon the total arm length. The only fundamental variations concern the arrangement of the transverse muscles: even if macroscopically the anatomical structure of the transverse muscles seem to follow an arc (Figure 9. 1a) more detailed images revealed that every muscle is actually almost straight and interweaving with other fibres (Figure 9. 1c). Thus, the previous representation appears too simplistic and it does not take into account the effect of the trabeculae that have a crucial role in the reduction of the diameter. Also from an engineer point of view, it is easy to demonstrate that such a geometry would deform the shape of the section degenerating in a square. For these reasons the adopted arrangement for the transverse muscles will be radial as shown in Figure 9. 1).

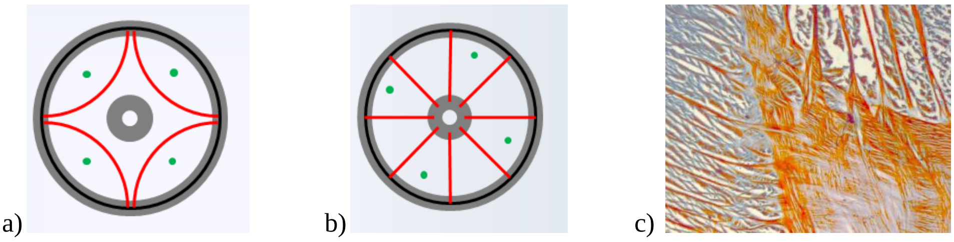


Figure 9. 1 Design of the transverse muscles: previous hypothesis (a), actual arrangement (b), detail of natural transverse muscles (c).

As known, this arrangement provides a significant advantage in the elongation mechanism: when the longitudinal muscles contract and the transverse muscles are relaxed, the arm shortens. On the contrary, when the transverse muscles contract and the longitudinal muscles are relaxed, they are "squeezed", and the arm greatly elongates (Smith and Kier, 1989).

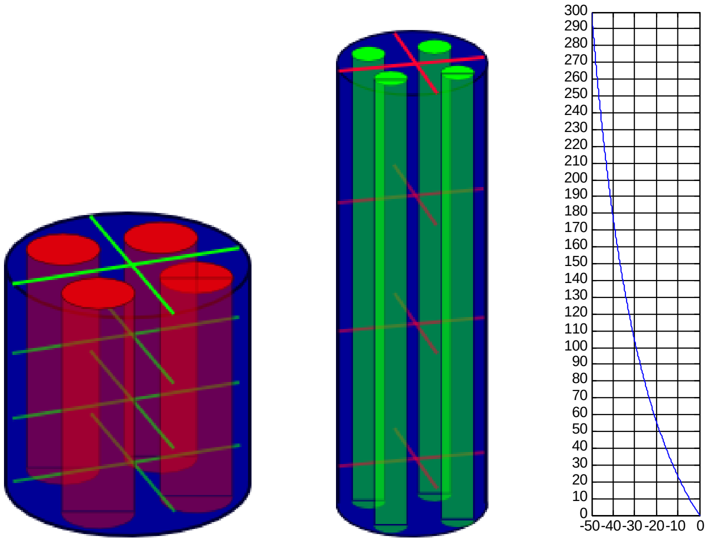


Figure 9. 2 Muscular hydrostat principle: shortened structure under the action of longitudinal muscles (left), longitudinal elongation due the action of transverse muscles (middle) and percentage increase of length as a function of a relative reduction of the diameter (right).

As the ratio between the original length (L_0) and diameter (D_0) is typically higher than 10, with small contractions of the transverse muscles great elongations can be achieved passively.
This relative variation, expressed in percentage, is independent from the numerical values of the geometry and it is given by the following relation:

$$\frac{\Delta L}{L_0} = \left(\frac{\Delta D}{D_0} + 1 \right)^{-2} - 1$$

which is also graphically shown in Figure 9. 2.
The rest of the structure follows a biomimetic design: an internal part dedicated to the cables (arranged in a way that will not interfere with the movements) and an external cover that will confer a mechanical interface for the actuators inspired by the octopus connective tissue. Figure 9. 3 shows the main characteristics and functions of the entire structure.

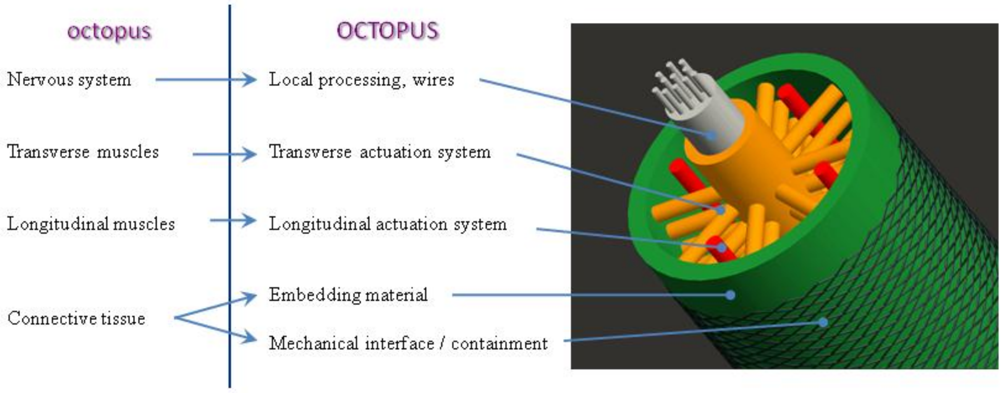


Figure 9. 3 Overall structure and principle characteristics inspired by the octopus.

The study of the octopus muscular hydrostat has led to the development of an engineering solution by IIT, not originally planned in OCTOPUS, for a robot arm that approximates the morphology of the octopus arm continuum structure, but keeps the macro properties of the hydrostatic constraint. The design concept is based on joining a sufficient number of flexible segments (fluidic-actuated extending and contracting artificial muscles) each one having three longitudinal and three radial muscles, all equally spaced at 120° in the corresponding plane.

With reference to a muscle unit composed of a longitudinal and a radial muscle (Figure 9. 4), and considering a radial plane passing through the neutral axis and exploiting the axisymmetry of the system, hydrostaticity means that the strain tensor is diagonal. The diagonal entries ε_{ii} are the monoaxial strains in cylindrical coordinates. The opposite sign of ε_{11} and ε_{33} is due to the hydrostaticity ($\varepsilon_{22} = 0$ because there is no circumferential strain).

$$\boldsymbol{\varepsilon}_{ij} = \begin{pmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{22} & 0 \\ 0 & 0 & \varepsilon_{33} \end{pmatrix} = \begin{pmatrix} \varepsilon_0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\varepsilon_0 \end{pmatrix}$$

By integrating the strain tensor, the muscle displacements can be obtained:

$$u_{11} = \int \varepsilon_{11} dx_1 = \int \frac{\partial u_{11}}{\partial x_1} dx_1$$

and analogously for u_{33}.

If L_0 and R_0 are the original lengths of a longitudinal and a transverse muscle respectively (Figure 9.4a), if the longitudinal muscle expands of the quantity *ΔL* and the radial contracts of the quantity *ΔR*, the new lengths are (as shown in Figure 9.4b):

$$L = L_0 + u_{11} = L_0 + \Delta L \qquad \text{and} \qquad R = R_0 - u_{33} = R_0 - \Delta R$$

The increment and decrement in length of the longitudinal and radial muscle respectively is a function of the control pressure of each muscle. Hence $L = L(P_1)$ and $R = R(P_2)$, P_1 and P_2 being respectively the control pressures of the longitudinal and radial muscles. Hydrostaticity means that the volume *V* is constant that yields:

$$\pi R^2(P_2)L(P_1) = \pi[R(P_2) - \Delta R(P_2)]^2[L(P_1) + \Delta L(P_1)] = V$$

hence

$$\Delta L(P_1) = \frac{R(P_2)^2 L(P_1)[R(P_2) - \Delta R(P_2)]^2 L(P_1)}{R(P_2) - \Delta R(P_2)}$$

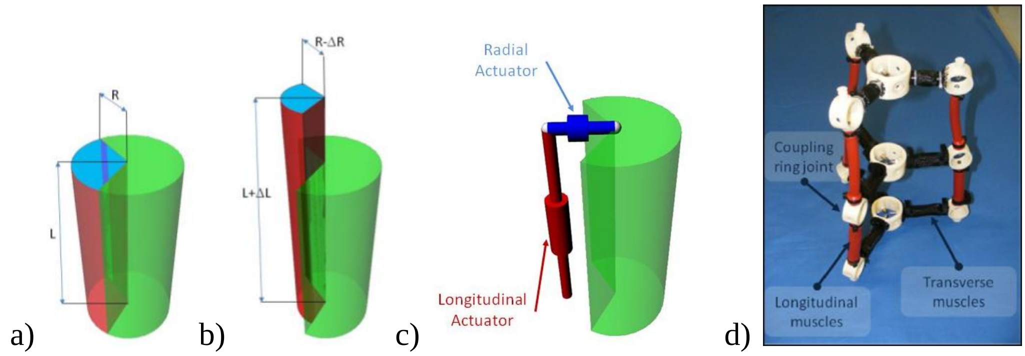


Figure 9. 4 Muscular hydrostat principle: rest state (a), elongated state (b); pneumatic arm prototype: design (c) and physical artefact.

This formula relates the extension/contraction of each muscle to its control pressure and geometry.
A prototype having both longitudinal and radial muscles was built, initially tested with air.
Figures 9.4c and d show its structure (in the final design a cover will be added). The structure has two segments and part of a third (hence the number of DOM is M*N+3, where M=6 and N=2). The longitudinal muscles were made with three silicone hoses whose working principle is similar to pneumatic bellows. The radial flexibility was introduced via three McKibben muscles.
Each muscle is pressure-controlled and driven by a main compressor line where pressure levels for longitudinal and radial muscles can be adjusted in independently.

Task 9.2 Fabrication of a muscular hydrostat mock-up – month 10-11 (SSSA)

This task is mainly focused on the realization of simple mock-ups reproducing the muscles function, as a validation tool of the defined design.
The longitudinal muscles have been replicated in the easiest way: 4 cables connected at the top leaving the possibility to pull them individually at the base (Figure 9. 5). The result (as expected) is a bending capability (when just one cable is pulled) and a shortening capability (when all of them are pulled).

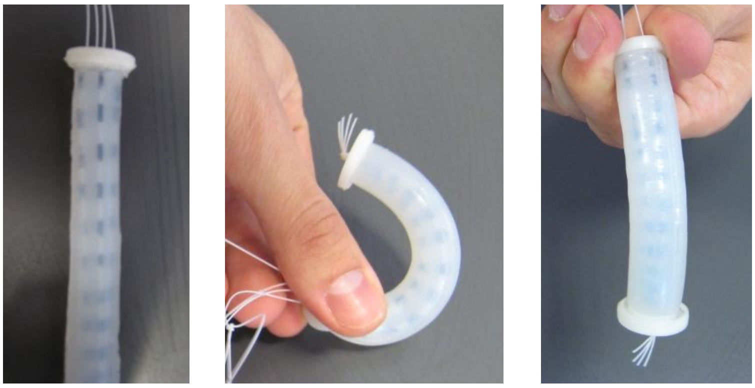
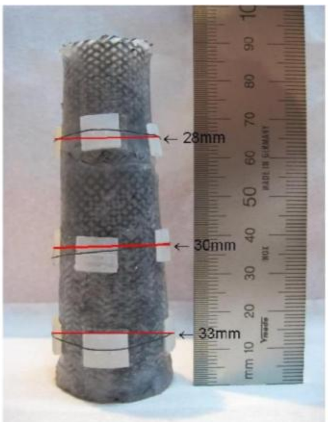


Figure 9. 5 Bending and contracting capability of a simple silicone cylinder actuated by 4 cables.

On the contrary, the transverse muscles required a more complex system: a braided sleeve was chosen as the external structure to provide a mechanical support, since the silicone cannot be used as the only component of the entire arm, because whatever discrete actuation system cannot perform a uniform and continuous radial deformation. As explained below, this braided sleeve has many other very interesting characteristics that are useful for our purpose.
One of the advantages is that during the squeezing, the cylindrical shape is maintained (even applying punctual force to reduce the diameter), because the reduction in diameter generates an extension, but, on the other hand, during squeezing isovolumetricity is generally not maintained. Some geometrical considerations led to the conclusion that this kind of structure can be used if a certain range of deformation is applied and this range contains the requirements the project

imposes. The main parameter that seems to characterize the properties of the structure is the angle between the fibres that compose the braided sleeve.



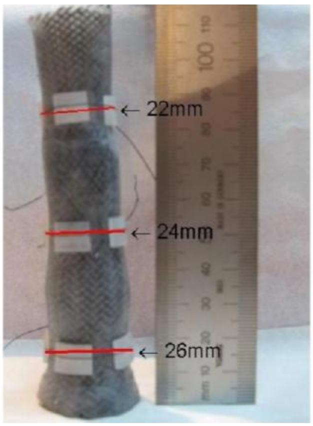


Figure 9. 6 Silicone-braided sleeve composite that is able to elongate when subjected to a diameter reduction. In this mock-up the diameter is decreased by 3 wires that emulate the contraction.

A small prototype was made to validate these hypothesis (Figure 9.6). A part of the arm corresponding to the first 85mm was replicated using 2 different braided sleeve sizes. The diameter at the bottom was 30mm and at the top 22mm. The restriction of the diameter was provided by a wire wrapped around the circumference just to reproduce and emulate the effect of the transverse muscles. A diameter contraction of 20% from the initial state was performed. Distances between the wires were chosen to have a homogeneous restriction.

Task 9.3: Identification, characterization and synthesis of materials for the muscular units – month 7-14 (<u>UREAD</u>)

The aim of this study was to find the most suitable material to build the muscular units. This study was divided into a static evaluation and a dynamic evaluation. With a heuristic methodology guided by qualitative observation a set of mock-ups was tested in static and dynamic conditions. Different kinds of silicone were tested (i.e. 00-30, 00-10 and Dragon Skin - ECOFLEX^{TM}, Smooth-On, Inc.) also in combination with other internal filler. Finally the best filling material was chosen and a combination of this material with an external skin of ECOFLEX^{TM} was tested again.

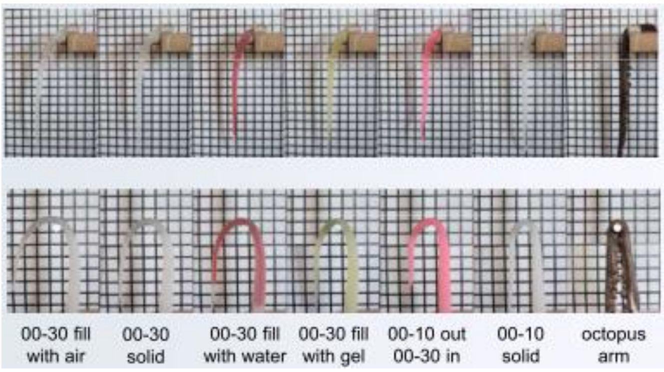


Figure 9. 7 Static test setup of different mock-ups used for a direct visual evaluation and comparison.

The mock-ups were tested with the simple static test showed in Figure 9.7. The grid in the background enables a qualitative evaluation of the material compliance. Then, the various parts of the arms have been tracked during a wave-like planar movement in a dynamic test. Such a test was performed on a set up built in joint collaboration between SSSA and UZH, which allowed one degree of freedom movement at the base of the arm. Nine visual markers were applied to the arms and the wave-like movements and tracked during the movements (Figure 9.8).

A comparison between all the materials has been done to choose the best material combinations, then the silicone mock-ups were reinforced with the braided sleeve previously mentioned and tested to investigate the influence of this second structure.
A visual analysis allowed the observation that the influence of the braided sleeve is more evident in the distal part of the arm. Furthermore, it seems that the return (up to down) movement of this arm is more restricted than movement of the previous arm (without braided sleeve). These considerations will be taken into account to develop the next arm prototype.
For the moment the most important aspects of the investigation on materials concerns their elastic capability, their ability to maintain constant volume and the easiness of workability. These studies cannot be considered complete till the entire robotic arm can be tested, because the complete artefact (not only the embedding material) should replicate the same characteristics. But in order to compare and extract quantitative data the development of such tools are necessary.

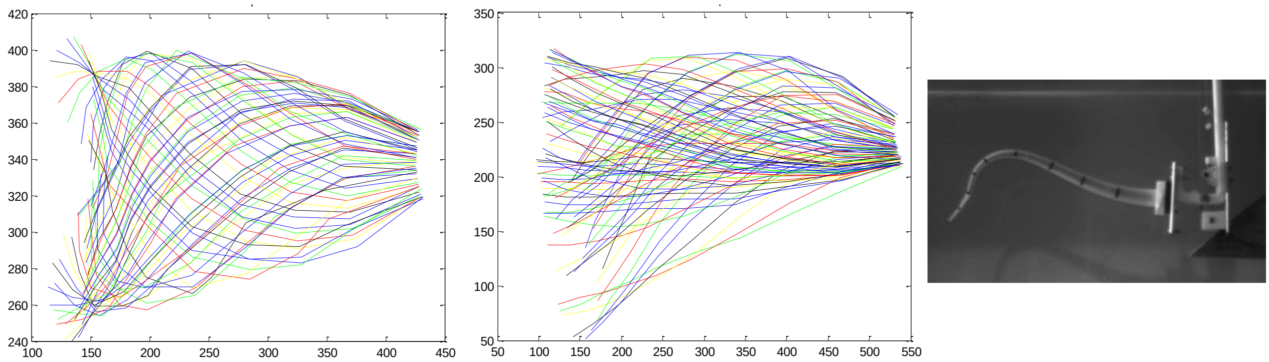
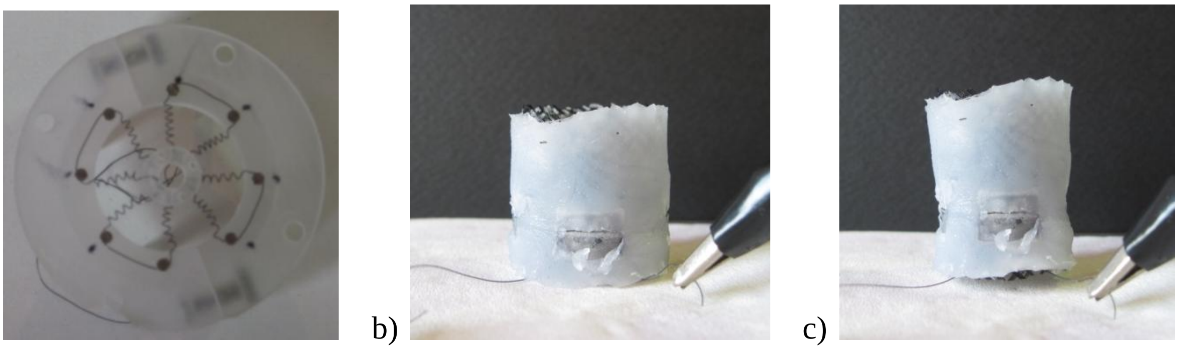


Figure 9. 8 The midline for the 00-30 silicone arm filled with water (left) and for the braided arm (centre): bottommost midlines represent the starting position; example frame of the tracking procedure (right).

Task 9.4 Design and development of the soft actuator for the muscular units – month 9-14 (SSSA, IIT, UREAD)

The solutions took into consideration that fabrication of soft actuators as contracting units for the muscular hydrostat are quite different, but they underline some peculiar aspects of the structure.
One of the solutions is based on Electro Active Polymers (EAP). A deep study has been conducted on this area, starting from the literature and selecting the most suitable technology. One particular class seems to be very interesting and has a lot of potentiality to be used as contractile element: Dielectric Elastomers. A theoretical model has been developed and validated. Smart solutions for the fabrication process have been adopted and first prototypes have been realized and characterized (Cianchetti et al., 2009). Despite their performance follows the theoretical model very well, the fabrication process is lengthy and costly and suitable prototypes with the characteristics needed to meet the requirements (especially the thickness of the EAP) are not reachable. Further efforts should be done in order to improve the electrical characteristics of the dielectric material, without affecting its softness.
Shape Memory Alloys (SMA) seem to be another interesting solution that can be used to realize linear actuators (active springs) to integrate in the muscular hydrostat. These springs have been mainly used to replicate transverse muscles and they can generate a radial force causing the reduction of the diameter. They have to be mechanically connected to the exterior skin of the arm and internally to the other springs. The dimensioning of the springs can be performed optimizing all the geometrical parameters (number of coils, wire diameter, spring index) in relation to the available space inside the arm and the force that had to be exerted. A model to predict forces and spring constant was developed and validated with a material testing machine. Measures on springs in martensitic and austenitic phase provided data for trend and maximum of both strain and force.
The maximum force needed for the contraction measured in the first three section was around 1 N, in a configuration of 8 radial springs for section.

Contraction speed depends on the heating power generated by current. From the material data sheet contraction speed is around 1 second, and to prevent overheating a PWM for the current source was implemented.
For the fabrication of the springs a particular methodology was implemented, in order to improve the precision of the geometry. Because of the wire cannot be easily soldered, for each transverse section a single wire of SMA was used, wrapped around the same core. Moreover this allows an electrical series connection with parallel mechanical coupling (Figure 9. 9).



a) b) c)

Figure 9. 9 Disposition of the springs during manufacturing phases (a); demonstration of the main effect: the diameter reduction and the length change is evaluable by comparing the structure before (b) and after (c) the springs activation.

A single section prototype has been successfully manufactured. The mechanical fixtures for the springs were realized with rapid prototyping method: internally the eight springs are connected together by a little ring, externally by small plates that help to distribute the force.
The two extremities of the wire are both at the centre of the section, and the same wire also provides the connection to the power supply. The contraction shows a reduction of the diameter of 19%.
Electromagnets have been also taken into account as a possible solution. A short pilot study has been carried out to test the possibility to use a combination of electromagnets and permanent magnets. These tests highlighted the limit of their use: from one side electromagnets can be manufactured, but actually the magnetic field produced is not enough strong for our purpose and even if ferrofluids have been used, the attraction force remains too weak; on the other side the use of coupled electromagnets and permanent magnets is easy to obtain, but the force in this case is too strong and usually nonbackdrivable.

Task 9.5: Development of the mechanical interface between the soft actuator and the muscular unit – month 16-18 (SSSA, UREAD)

When the actuating elements did not allow for a direct connection with the silicone matrix, a structure with intermediate elastic properties (that would correspond to the rule of natural connective tissue) has to be provided. In the use of SMA, for example, this interface covers a key role in the success of the mechanism. SMA are usually used in the form of wires and their application point is very limited. The solution adopted consists of using the already mentioned braided sleeve. In fact this not only provides a perfect mechanical support, but also has containment functions and propagates longitudinally the deformations.
The springs are mechanically fixed to the external structure with small plates constructed using rapid prototyping. The braided sleeve is cut in correspondence of the external fixtures to let the wire come out; then the small plates are inserted. Silicon provides stability to the connection.
Improvements are needed to reduce or substitute these rigid elements and also a solution to avoid the cutting of the braided sleeve will be needed in future.

Task 9.6: Integrated stretch sensors – month 9-14 (SSSA, IIT)

Because of the radial disposition of the transverse actuators, the first solution could be to arrange the sensors in parallel to them. The internal part of the muscular hydrostat will be composed by

silicone and the tested materials have the property to be optically transparent. This feature can be exploited in order to produce a very small stretch sensor based on optoelectronics: a photodiode as light source, a phototransistor as receiver and the silicone as propagating means.
This technology already exists and it has been developed at SSSA (Persichetti et al., 2007).
Alternatively, more traditional Hall effect sensors could be used: a permanent magnet positioned in the centre of the structure will produce a magnetic field sensed by the sensors placed on the external surface and generate an electric signal depending on the distance from the magnetic source. In this case no internal silicone in required and the springs do not need to be stronger.

3.9 WP10 – Design and development of the robotic arm kinematic model and control system

Progress summary

WP10 is focused on developing a model inspired by the octopus anatomy and morphology that is relevant to control of the peripheral sensory-motor control schemes for the arms of the robotic octopus using inputs provided by the biological data.
WP10 had all the tasks active during the first year period with the primary effort being devoted on the development of:
- Task 10.1 Development and implementation of Controllers for Single Arm
- Task 10.2 Whole arm grasping and compliance control
- Task 10.3 Control of the suction
- Task 10.4 Control of locomotion/propulsion
- Task 10.5 Multi-limb coordination

During the first year the activities in WP10 were devoted along three main lines of research that address specifically the control of the structure based on fluidic actuators presented in WP9 by IIT, as a preliminary study with respect to the investigation on the biomimetic control techniques required for the OCTOPUS prototype. Such activities are namely:

- At a component (actuator) level the investigation of the performance of fluidic muscle as an actuating device was studied and their performance assessed using air and water as pressurizing means.
- A set of kinematic relationships of increasing complexity were defined for sizing calculation (achievable bending, extension).
- Using the system and the tools above logic were implemented to test octopus motion.

A simplified model for a hyper-redundant arm and a simulation environment have been proposed in the reporting period, to be used for the development of the OCTOPUS control techniques in WP10.

Significant results

Task 10.1 Development and implementation of controllers for a single arm - Month 7-14 (IIT, UZH, FORTH)

Kinematically continuum robots offer the advantage of allowing for a simpler system configuration.
Unfortunately continuum robots do have kinematic disadvantages associated with their design. This can lead to problems in the development of accurate real-time controllers. This complexity and need for highly flexible and compliant manipulation also makes material and actuation development difficult.
Traditionally conventional robots use relatively few DOF equal to the number of actuated joints in the system. This results in a manipulator that lacks flexibility and manoeuvrability when compared to continuum robots that utilize a much higher number of DOF. This increased DOF allows for a much more flexible manipulator, but also greatly increases the complexity associated with their control.

With reference to the fluidic-actuated hydrostatic structure presented in WP9, firstly simple 2D and 3D kinematic models were developed to determine position and angular movement of the arm for given actuator extensions. As these are intended to be tools for pre-sizing calculations, it is assumed that the actuator displacements will be linear in nature, and that the structure will not bend as it displaces. This is possible if the overall height of each modelled segment is relatively small. The models are then built into a full structural system by placing them one on top of the other and implemented in simulation software for controller evaluation.

Two Dimensional System

The simplest model for the arm is to consider the structure as a 2D system. This means that there are an upper and lower platform with two actuators attached to them for displacement purposes. You can further split the model into two separate systems to account for the rotational change in actuator connection to the upper or lower platform. In the first model the actuators are connected at a fixed 90° angle to the base and allowed to rotate about the upper platform. The second model contains an actuator to base connection with rotational freedom, but the connection to the upper plate is locked at 90°.

a. Fixed Base

The first model contains a system where the actuators are connected at a fixed 90° angle to the base and allowed to rotate about the upper platform as shown in Figure 10.1

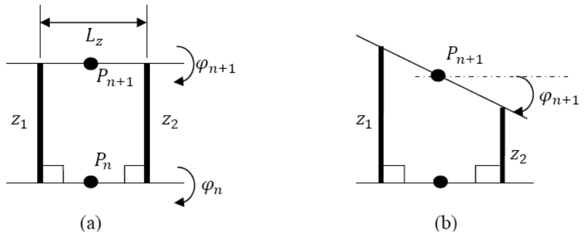


Figure 10. 1 Initial (a) and final (b) displacement of the structure for given actuator lengths z1 and z2 assuming no displacement of the actuator from vertical at the base.

b. Fixed Upper Structure

The second method for modelling the structure in 2-dimensions is to assume that the actuators will remain fixed at 90° to the upper plate, but experience an angular movement in the horizontal with respect to the bottom plate. Figure 10.2 shows the initial and final positions of the platform for given actuator lengths z_1 and z_2 for such a system. This model is then essentially the reverse of the one presented above.

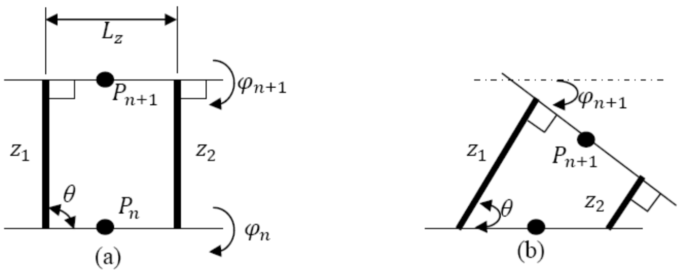


Figure 10. 2 Initial (a) and final (b) displacement of the structure for given actuator lengths z1 and z2 assuming the actuator will not remain vertical at the base when displacing

The resulting height at P_{n+1} has been generalized as:

$$P_{n+1} = \left(P_{nx+1}, P_{ny+1}\right) = \begin{Bmatrix} \left(z_2 \cos\theta + \frac{L_z}{2} - \frac{L_z}{2}\cos\left(\frac{\pi}{2} - \theta\right)\right) + P_{nx}, \\ \left(z_2 \sin\theta + \frac{L_z}{2} + \frac{L_z}{2}\sin\left(\frac{\pi}{2} - \theta\right)\right) + P_{ny} \end{Bmatrix} \quad (1)$$

Simple Three Dimensional Model

In 3-dimensions a similar process can be utilized to determine structural displacements. The case where angular motion is allowed at the base is much more complicated with the addition of the third actuator. Instead of building both models it is desirable to approximate the displacement of the structure using only a system where rotational freedom is allowed on the upper platform. This is can be done if you ensure that the overall segments of the full actuator are relatively small. It will mean an increase in the number of Degrees of Freedom (DOF) for a given system. But it allows for a far simpler calculation to be used in the final simulation. The resulting models are then stacked one on top of the other. Figure 10.3 shows the model used for a simplified 3-dimensional structure.

The resulting height at P_{n+1} has been generalized as:

$$P_{n+1} = \frac{\left(\frac{z_2+z_3}{2}\right)+z_1}{2} + P_n \tag{2}$$

The angle at $\varphi_{n+1}$is:

$$\varphi_{n+1} = \tan^{-1}\left(\frac{z_2-z_3}{L_z}\right) + \varphi_n \tag{3}$$

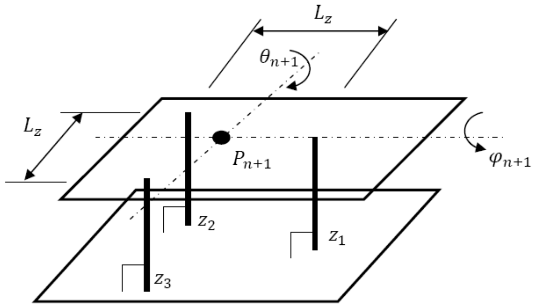


Figure 10. 3 Simplified model for a 3-dimensional structure assuming angular motion at the base to be fixed and free on the upper structure.

The angle at θ_{n+1} is:

$$\theta_{n+1} = \tan^{-1}\left(\frac{z_1-\left(\frac{z_2-z_3}{2}\right)}{L_z}\right) + \theta_n \tag{4}$$

In order to implement a control system for the fluidic-actuated hydrostatic structure proposed in WP9, a mechanical hardware architecture must be defined and actuator chosen. McKibben actuators were considered and, as the octopus is designed for underwater operations, their performance was tested not only with air but also with water. The measured stiffness with water increases as expected, being this a non-compressible medium.

Modelling control and simulation of modular hyper-redundant systems

The objective of the work by FORTH in the context of WP10 is to develop computationally efficient models, appropriate for control and design purposes, develop control systems of octopus arms in an aquatic environment, and test them in simulation. Such models may be appropriately simplified versions of the ones being developed in the context of WP6, where the objective is accurate modelling of the elastodynamics and hydrodynamics of octopus arms and of their movement in an aquatic environment.

A software framework, based on the SimMechanics toolbox of Matlab/Simulink, is being developed by FORTH, to allow modelling and simulation of hyper-redundant multi-link mechanisms, whose morphology and functionality draws inspiration from the octopus arm.

Models of such hyper-redundant systems are comprised of rigid, cylinder-shaped segments, serially connected via spherical joints with 3 actuated rotational degrees of freedom (DOFs), enabling a wide variety of configurations for the mechanism. The interaction of each segment with the aquatic environment is described via a hydrodynamic force model considering decoupled force components in the tangential, normal and lateral directions, as well as the effect of buoyancy forces. Each DOF in these spherical joints may be actuated via either torque signals or by prescribing appropriate joint angle trajectories, allowing the implementation of a variety of strategies for motion control of the system. To demonstrate the features of the developed computational tools, simulations have been set-up for a 57-DOF mechanism, shaped after the octopus arm, comprising 20 rigid segments. Figure 10.4 below demonstrates the obtained results for controlled motions of the mechanism, obtained by prescribing travelling-wave joint trajectory profiles.

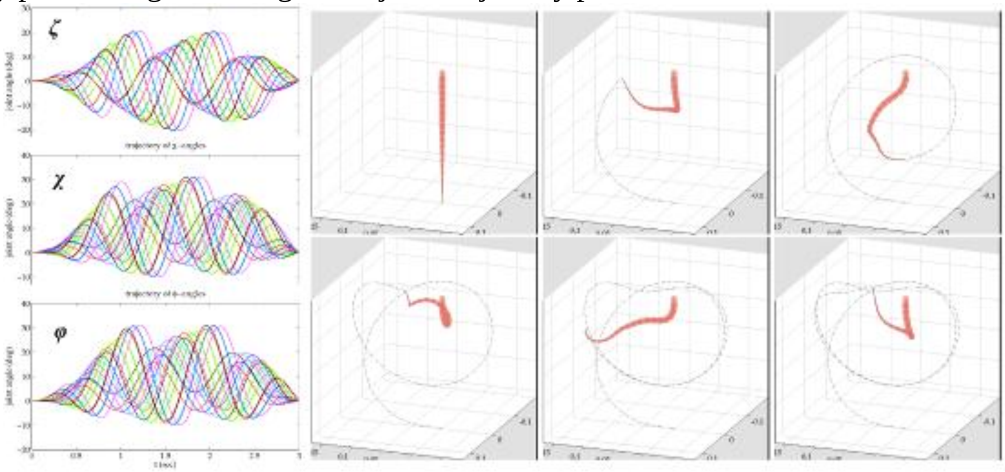


Figure 10. 4 A 3D movement of the 20-segment mechanism (right), obtained by activating the three rotational degrees of freedom (χ,φ,ζ), in each of the mechanism's joints, with travelling-wave joint trajectory profiles (left).

The robotic system of Figure 10.4 may be implemented by parallel manipulator modules (similar to the 6 DoF Stewart-Gough platform), arranged in a truss.

After having developed sufficiently accurate kinematic model control issues were investigated. The contributions of UZH is within this context. Work was carried out in the following areas:

1. development of single arm test-setup for simulation and control validation,
2. development of a simulation environment for control testing,
3. simple control models for simplified trajectory targets.

Although the contribution in this stage to WP10 mainly on lower level control, the approach was also based on identifying methods and techniques for our primary contribution on the sensory-motor behaviour control architecture which is WP11.

Single Arm test-setup

A test setup to study control problems was constructed as shown in Figure 10.5. The platform consists of a tendon driven silicone robotic octopus arm in a fresh water tank, the actuation and sensor system with interface to PC. The arm system is driven by an actuation strategy based on regulation of extension and tension of the tendons using winch servos and tension sensors. It is currently being used in tests to validate simulations and control techniques.

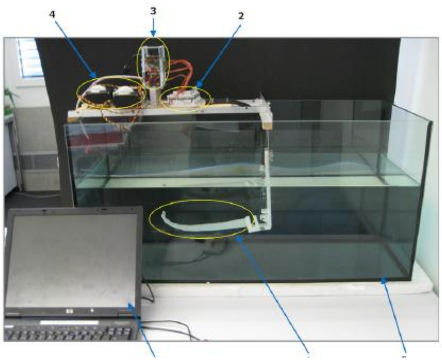


Figure 10. 5Single Arm test-setup

Simulation Environment for Control Testing

Three kinds of Simplified Simulation were created to test techniques for both low-level and high level control. The simulators were built on GNU Octave and utilized lumped parameter models. The simulators were as follows:

1D Array of elements moving in 2 Dimensions: This utilised a 1D array of elements (springs and masses with uniform damping) moving in a 2D space region.

2D Matrix of elements moving in 2 Dimensions: This utilised a dynamic model of 2D matrix of elements (Springs, masses and uniform damping) moving in a 2D

1 Dimensional Dynamic Control: A 1D simplified model was created to test various control strategies.

Simple Control Models: In order to test techniques for low-level control, Simulator 3 was used to come up with feedback and feedforward control strategies for position, and force based control of actuators. A technique for feedforward force control of the elements for step and sinusoidal trajectories was demonstrated. This is currently undergoing testing and tuning and a demonstration for a "Reach" like behaviour on the single-arm test setup is underway.

Task 10.2 Whole arm grasping and compliance control - Month 9-16 (Weizmann, IIT, UZH, FORTH)

The problem of controlling both the manipulator position and its force interactions with the environment is referred to as compliant motion control. Because of the flexible nature of the arm it is capable of grasping and manipulating objects by curling part of its structure. Essentially, the arm becomes its own highly adaptable end-effectors. For the purpose of compliance control, different control approaches have been proposed such as hybrid position/force control or impedance control on redundant manipulators.

Evolution of modularly composed arm configuration using Genetic Algorithm

A theoretical framework was developed which examines the ability to control the octopus/robotic arm using a set of elemental control primitives. We are interested in finding modular configurations which allow efficient reconfiguration of the arm. We consider such modular configurations as a set of primitives, which may suggest a simplifying strategy for selecting and easily adapting arm configuration to different target points and different geometries of the grasped objects. The first case for testing this algorithm involved configuring a hyper-redundant arm to be positioned at a particular target. Configuration primitives were then generated in an evolutionary process and the tip of the arm was controlled to reach a target point. Simple static model of the octopus arm was used for simulations. The model is made of 10 consecutive segments.–The results showed that following relatively few evolutionary iterations, a reduced set of modular arm configurations are generated.

Model-based Control

The control of the bend and the amount of bending achieved is highly dependent on the shape of the segments. This calls for a rigorous understanding of the control – shape – movement relationships. We started an analytical investigation of these relations (see report for WP6) based on the potential energy of a single segment (Figure 10.6). In this project, a model similar to the 2D model in Yekutieli et al. (2005) and referred to in WP6 was used. The first issue examined was, given a backbone curve, what the shape of each segment of the muscle hydrostat should be.

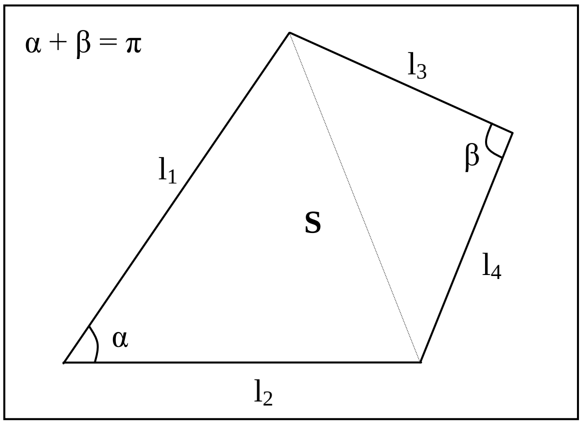


Figure 10. 6 Model of a segment of the arm in the MBCA (model based control algorithm).

After the determination of the shape of each segment, one determines the forces that each one of the 4 muscles should exert in order to achieve a minimal potential energy. For a segment in steady state, the force each muscle exerts is related to the size and shape of the segment and to its stiffness (see the report for WP6).

Another important development based on these forward equations is the *forward analytical model*. This line of research combines the *model based control* with the *genetic algorithm* control described above to develop a control scheme for the 2D dynamic model. This approach is currently used to investigate modular control both for motion and grasping tasks.

Activation-from kinematics: active versus passive control

Using the activation from kinematics control scheme (see WP6), we can determine which muscles are actively controlled and which muscles are passive at each instant, for a given motion. This technique is currently applied to various recorded motions to determine how the octopus is controlling its position and velocity during different motion tasks. This algorithm allows us to better understand the technique of passive-active control used by the octopus, by allowing to determine which sections of the arm need to be activated, and which sections simply move passively as a result of the system's passive dynamics. By understanding the control schemes that the octopus uses, one can also obtain better insight into designing advanced control technique for the flexible octopus-inspired robot.

Because in our model, in which we extracted activations from kinematics (see WP6), the octopus is represented as an under-actuated system. Other control techniques are also being currently investigated. One control technique which we started investigating is passivity-based control, using port-controlled Hamiltonian system with dissipation.

Octopus arm simulator

Work has began in combining the idea of the control of complex motions by constructing them from motion primitives (see WP6) with the idea of developing learning algorithms and learning networks that lead to a modular control architectures while taking into account the robot kinematic and dynamic models. Because of the kinematically hyper-redundant nature of the octopus arm, we found that the GA randomly converged to one of many possible solutions, often giving configurations that are irregular and unsmooth.

In this model the activation input to the muscles was simplistic and only the static positioning task was considered. Hence we began also to combine this work with the dynamic modelling work and extending it to the movement generation case. We are planning to use the GA to find the best activation code needed for the arm to reach a given target while minimizing potential energy. Then input this code into the dynamic model, thereby allowing for the examination of the resulting arm trajectories. This work was initiated by developing a forward control problem for the static case. The results from the forward model are then inserted into the GA to find the optimal static solution. Work was conducted that indicated the feasibility of this approach giving realistic-like arm configurations for an arm made of ten segments that both satisfy the constant area constraint and minimize potential energy. This GA will be used to study whether modularity indeed emerges when the arm learns to be positioned at multiple rather only several targets. At present this model is strictly 2D but can be also extended to the 3D.

3.10 WP11 – Design and development of the robotic octopus behavioural architecture

WP Leader: UZH

WP Member: FORTH

Progress summary

The deliverable of this WP is scheduled at month 18, but several works have been achieved. Here the most relevant results obtained till now are recalled.

Significant results

The most important results of WPs have been published in the papers:

- Kuppuswamy N.S, Li T., Nakajima K., Cianchetti M. and Pferifer R. (2009) A biologically inspired approach to the control of octopus-like soft robot arms *J Mol Neurosci* 39 (Suppl 1):S1–S132.

Task 11.1 Specification and design of the sensory-motor behavioural control architecture – month 7-18 (UZH, Weizmann, IIT, FORTH)

The objective of this task is to develop the sensory-motor behavioural control architecture for tasks involving the synergetic action of multiple limbs of the robotic octopus. We have taken dynamical systems approach to the control system, which is called the Dynamical Systems architecture. This approach allows us to take into account the interaction between the central and peripheral nervous systems in the octopus.

In embodied robotics, it is well known that to realize a cognitive behaviour in a robot, it is important to consider the effect of the body on the control system (Pfeifer et al. 2007). If we consider body, the various interactions accompanied with body are needed to be considered. Figure 11.1 is a schematic diagram which shows these interactions. When the robot behaves in the task environment, its behaviour affects its environment, and the mechanical system of the robot receives the mechanical feedbacks and the sensory system receives the external physical stimuli from the environment. Moreover, the mechanical system directly influences the sensory system. Based on these lower level dynamics, the control system receives the sensory feedbacks from the sensory system and then returns the motor commands to the mechanical system.

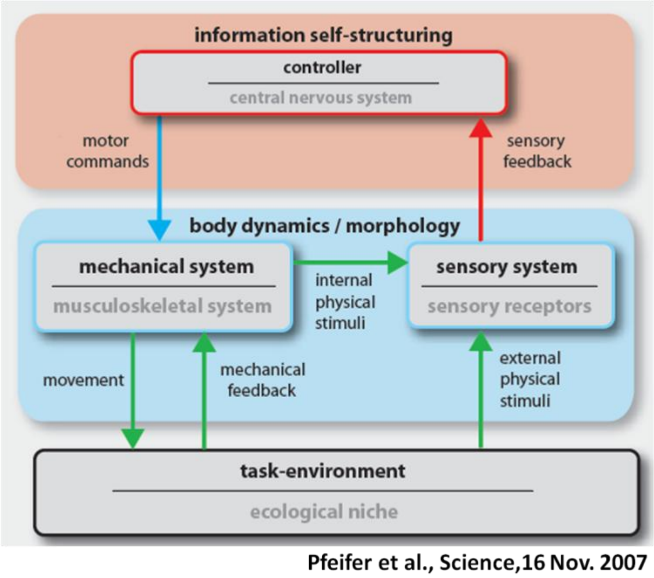


Figure 11.1 Schematic diagram of the coupling regime in the embodied robot.

When we consider these situations in octopus robot, the interactions can be summarized as Figure 11. 2. Because of the soft and flexible body, its dynamics show high diversity. To control such kind of dynamics of the body, dynamical systems approach is highly efficient. Additionally, what is important in embodied robot is that its body dynamics and its control systems are closely related to each other. In this case, if we pre-define the control system in a top down manner, we often tend to miss the important material property of the body. Dynamical systems approach allows us to take both the body dynamics and the control system into account simultaneously and allows us to generate the control system with an appropriate functionality in a bottom up manner.

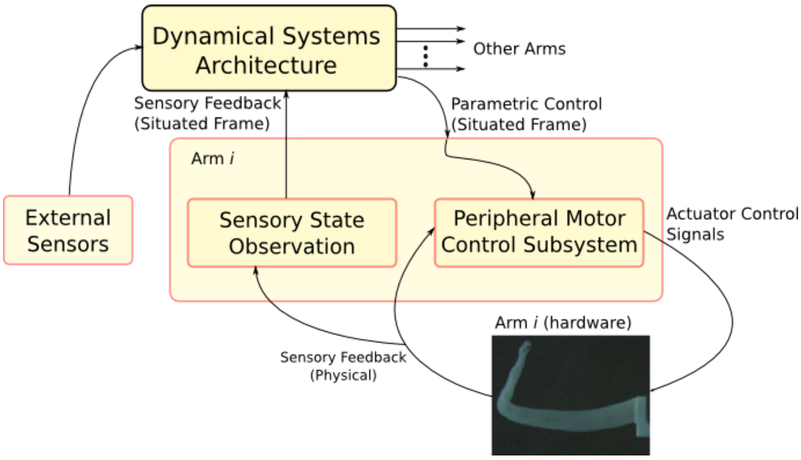


Figure 11. 2 Schematic diagram of octopus arm coupling regime

In order to realize controls via dynamical system, recurrent neural network (RNN) is generally used. It is usually governed by a huge number of control parameters such as the weight of the connections, biases, and the threshold function for each neuron, and thus is capable of obtaining and adjusting a suitable functionality. It is expressed as follows:

$$y_k(t) = g(net_k(t))$$

$$net_k(t) = \sum_{j}^{m} y_j(t) w_{kj} + \theta_k$$

where y is a state of neuron, g is a sigmoid function, w is a connection weight, and θ is a bias.
When a RNN is utilised as the control system, the RNN is formally described as a dynamical system with external perturbations (inputs) or a dynamical system with a switching map system. It is useful to achieve the sequential control which is expected to constitute the octopus behaviour.
Taking an evolutionary robotics approach, we have attempted to draw an overall view of the high-level control architecture required in the octopus behaviour. The primary focus is to reveal, in a theoretical sense, the appropriate and requisite interaction regime between the peripheral and central nervous systems for multi-limb control. By adopting the genetic algorithm (GA), it is possible to choose an appropriate set of control parameters that use body dynamics effectively to achieve the required task. Figure 11.3(a) is the example of the network topology of the RNN for octopus control and Figure 11.3 (b) shows the attractors of recurrent dynamics. The parameter optimization for the required tasks is now under construction.

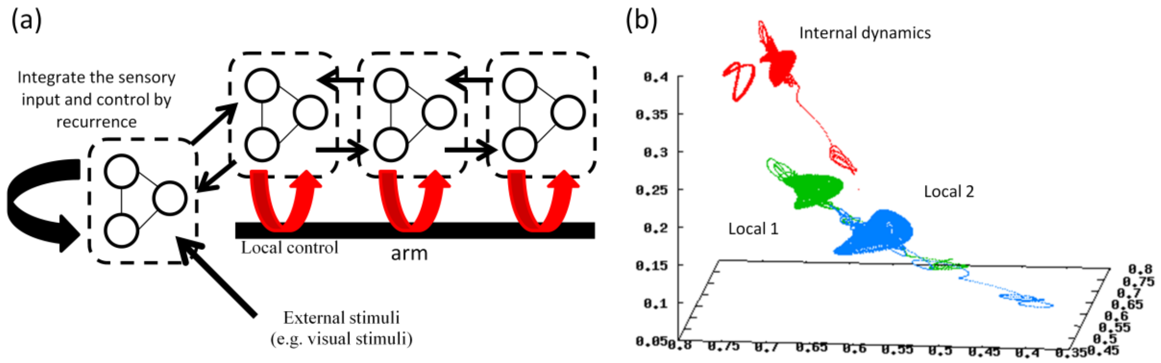


Figure 11.3 (a) Schematic diagram of network topology. (b) Example of several attractors in the RNN.

FORTH has proposed the distributed motion control architecture which could be applied. The software environment, based on the SimMechanics toolbox of Matlab/Simulink, being developed to allow modelling and control design for hyper-redundant multi-link mechanisms, whose morphology and functionality is inspired from the octopus, is outlined in the WP10 section. Related, more detailed, modelling efforts are outlined in the WP6 section.
The distributed motion control architecture (Figure 11.4), which is currently in the process of being designed and implemented for the modular parallel manipulator-based robotic prototype described in the WP10 section, is inspired from animals using body undulations to move and to swim. Bio-inspired motion control schemes, like Central Pattern Generators (CPGs) for binding various groups of DoFs of the system, and sensor-based reactive behaviours, may be implemented on such architecture (Sfakiotakis et al. 2007a, Sfakiotakis et al. 2007b).

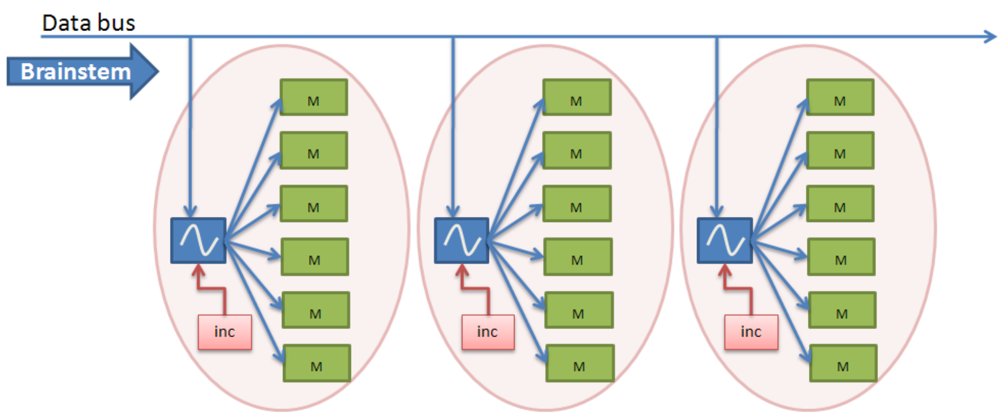


Figure 11. 4 Distributed motion control architecture.

A possible implementation of this control architecture is shown in Figure 11. 5: each module is controlled by a microprocessor (currently ATMEL mega 328), which receives guidelines from a master controller and controls the actuation of several motors. In addition, it receives and processes input from various sensors placed on the module. In the current preliminary implementation, we consider only nearest-neighbour coupling between modules, but the hardware could support other forms of coupling. The master controller (analogous to brain centres like e.g. the brainstem in living organisms) will provide high-level control guidelines, like the "gait" type, the direction and speed of locomotion, etc., while the module controllers will specify the details of the required control actions.

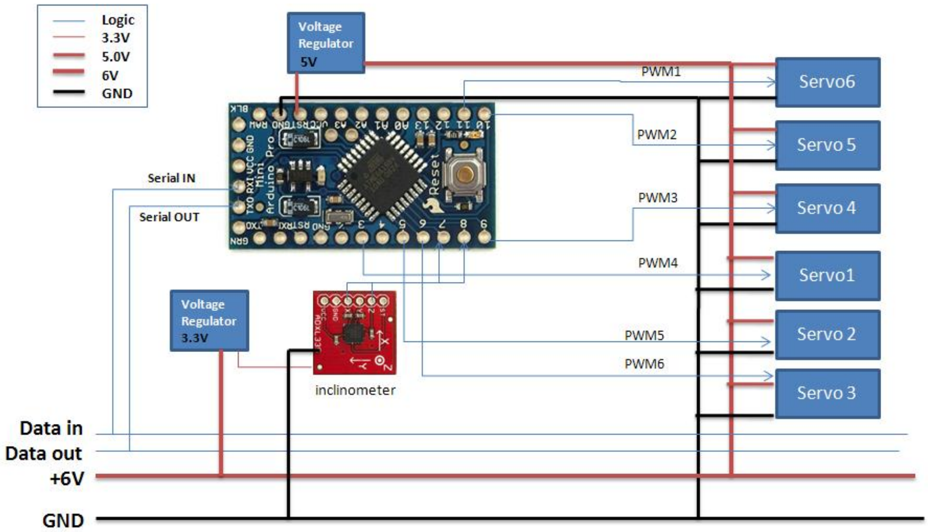


Figure 11. 5 Module motion control system.

Task 11.2 Integration of learning techniques for tasks involving multiple arms – month 7-18 (UZH, Weizmann, IIT, FORTH)

The objective of this task is to investigate strategies for incorporating learning techniques into the robot's behavioural architecture. We considered implementing hebbian learning to work on the RNN locally. It is expressed as follows;

$$\triangle w_{ij}(t) = \mu(s_i(t) - y_i(t))\, y_j(t-1),$$

where μ is the learning rate, s_i is the signal sent by the central network.

This hebbian learning technique was introduced to the peripheral network. As can be seen from the equation, connection weights in the peripheral network vary to reduce the deviation from the signal sent from the central recurrent network. This construction is expected to activate the interaction between the central and peripheral network and enables to enhance the robustness and adaptability of the control system to the external perturbation and noise. We can find a similar work in (Morimoto et al. 2004). This methodology could be effectively applied to the required tasks.

Task 11.3 Design and implementation of the input and output interface – month 11-16 (UZH)

A schematic diagram, Figure 11.2, shows the design of the interface between the sensory-motor control system and its inputs (the robot's sensors) and outputs (actuators). The sensory state observation module will collect sensory feedback from the physical robot system, meanwhile, the peripheral motor control subsystem module will send actuator control signals to the robot's actuators.

Task 11.4 Implementation of the sensory-motor behavioural control architecture – month 13-18 (UZH, Weizmann, IIT, FORTH)

In order to implement and validate the control architecture mentioned, mock-up systems and simulators are needed as test beds. We have constructed an octopus arm mock-up system based on the silicone arm provided by the SSSA. IIT also has constructed a fluidic hydrostatic structure. And Weizmann has designed a simulation model. These systems would be used as test beds for the final control system of WP11.

A tapered silicone based tendon-driven robot arm, was built by SSSA to closely match the dimensions as well as the material properties of the natural octopus arm. The robotic arm, shown in Figure 11. 6 has 4 embedded nylon cables along the arm and are arranged equally in circular direction to mimic the 4 groups of longitudinal muscle bundles in octopus arm.

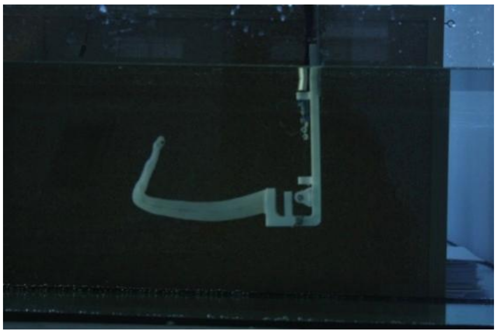


Figure 11. 6 A silicone arm constructed by silicone, nylon cables, and a ABS block at the tip.

Platform Setup

Our platform consists of the silicone robotic octopus arm, the actuation and sensor system with interface to PC and a water tank with fresh water as the underwater environment. The arm system is driven by an actuation strategy based on regulation of tension of the muscle like member using winch servos and tension sensors. It includes a silicon arm with four cables embedded inside, cables guiding mechanism, four servos to provide cable tensions, four force sensors to measure cable tensions and provide feedback, interface boards to connect motors and sensors, and control program running in a PC, The platform setup is shown in Figure 11. 7.

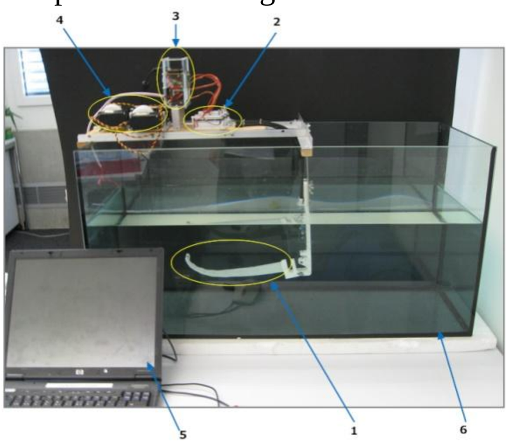


Figure 11. 7 Silicone robot arm platform including (1) octopus robot-arm, (2) tension sensors, (3) control boards, (4) winch servos, (5) control program running in a PC, and (6) a water tank

In the prototype, each tension sensor is connected serially to measure the tension on one cable to provide feedback for the force control program.

Control Algorithm for tension regulation

The test setup utilizes winch-servo motors for regulating tension on the string. The linear potentiometer based tension sensors measure the tension on the strings. The tension is then controlled by setting an appropriate angle on the winch servos. In order to develop the control algorithm for this task, the dynamics of the system need to be described. As a first approximation a simple feed forward controller assuming linear spring-damper dynamics was designed. Experiments have shown that a more detailed study on modelling the material properties is needed in order to regulate tension, since silicone is a nonlinear elastomer.

3.11 WP12 – Design and development of the sensorized skin

WP Leader: UREAD

WP Members: SSSA

Progress summary

Skin artefacts have been designed, manufactured and tested. Compared with octopus skin, the skin artefact is softer and tougher for a given crack length. It fulfils the specification of the OCTOPUS arm. This time period for this task is 18 months. Sensors will be chosen added to the artificial skin in the next few months.

Significant results

Task 12.1 Identification of candidate materials

The hydrostats specified in WP9 include diameter changes from 20mm to 16mm and thus the elongation is about 60%. For this purpose, silicone gel is selected as matrix material and knitted nylon has been selected as reinforcing material for the composite material of the artificial skin. Static testing results have shown this material can be elongated over 100% without failure. Compared with the octopus skin, the artefact has lower Young’s moduli, higher strength and higher fracture toughness for unit length of crack.
Results from the measurement of the octopus skin show that the Poisson’s ratio of the skin is a function of the strain. The Poisson’s ratio decreases as strain increases and the measured values are higher than 0.5 in most cases. The Poisson’s ratio of the composite is also changing with strain level. Theoretical calculation shows that the Poisson’s ratio needs to change with strain to keep constant volume for materials under plane stress tensile load.

Task12.2. Fabrication of skin structures – month 10-18 (<u>UREAD</u>, SSSA)

Knitted nylon reinforced silicone tubes have been made. The tubes are 160mm long and 20mm in diameter. The wall thickness of the tubes is 1.4mm. Tubes filled with vegetable oil have been tested up to 100% elongation. Testing results show that tubes filled with oil maintain constant volume under uniaxial tension. Finite element analysis using MARC has been carried out and the model represents the tests very well.
An undergraduate research project studying the properties of squid suckers has been going on for a few months. Rigid annulus is found inside each suck. The mechanical support of the annulus to the suck is measured by compression tests in both length and radial directions. The adhering force generated by suckers is limited by the strength of the skin connecting suckers to the arm. Thus the maximum suction is obtained by measuring the tensile strength of the connecting tissue.
Tensile tests have been conducted using Instron 5564 machine. Forced and displacement were recorded by the machine. Two types of specimen of silicone gel have been tested. Straight specimens have been tested for elastic properties and waisted specimens for strength tests. No specimens were loaded to failure as a result of losing griping at the clamps. Shown in Figure 12. 1 is set-up for the tensile tests. Maximum strains are up to 500%. It needs to point out that tests ended due to lose of grip instead of material failure. In the compression test, Teflon film and zinc stearate

powder have been used at the interfaces of the specimen and loading components to reduce friction. The stress level is lower than 0.1 MPa for compressive strains at 40%.

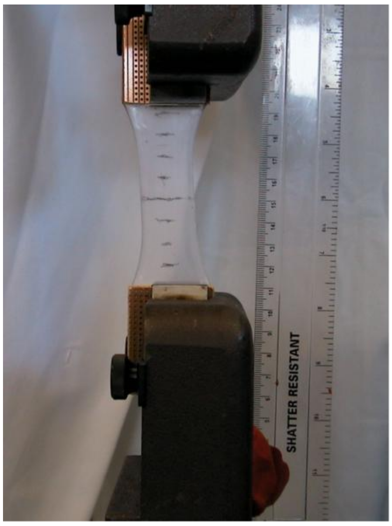


Figure 12. 1 Set up of tensile tests.

Knitted Nylon has been chosen as reinforcement for the artefact of skin. The structure of this material is shown in Figure 12. 2. The loops of nylon thread allow high level of deformations.

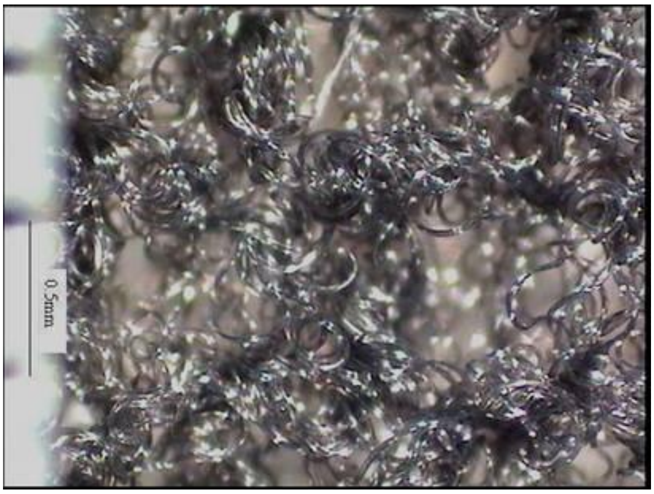


Figure 12. 2 Microstructure of the knitted nylon sheet.

Testing results show that the artefact of the skin is much softer compared with octopus skin. But at the same time the artefact is much thicker than the real skin. So the structural stiffness of these two materials may be quite close to each other. In addition, the stiffness of the composite can be adjusted according to requirement by changing the number of layer of the nylon sheet.

The fracture toughness of the artefact is lower than the real skin. As the thickness of the artefact is about 10 times that of the real skin, work needed for a give crack length is higher for the artefact than that for the real skin.

Nylon/silicone cylindrical tubes have been made using a moulder consisting of two cylinders with a difference in diameter of 2.8mm. Figure 12. 3 shows the tensile test set-up of the tubes filled with vegetable oil.

Figure 12. 3 Set-up of the tensile tests of the tubes filled with oil.

Shown in Figure 12. 4 is the measured diameter changing with elongation of tubes. The dotted line in Figure 12. 4 is the theoretical relation between the length and the diameter when the volume is kept constant.

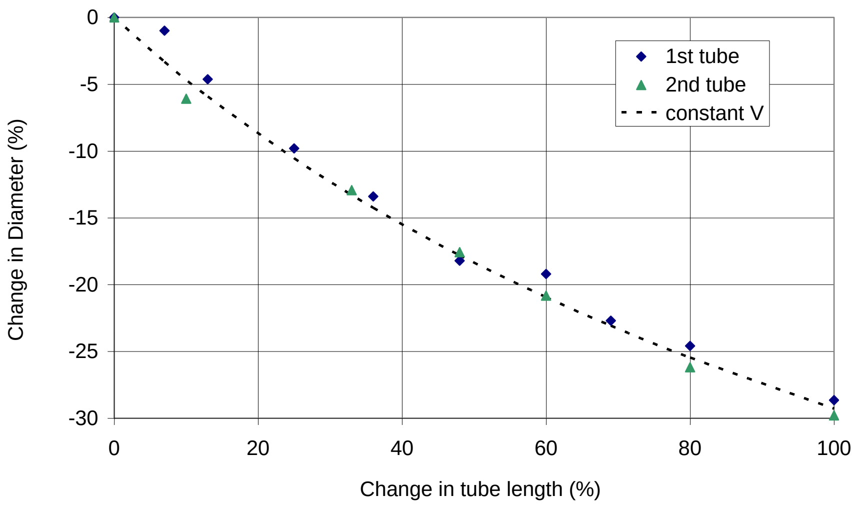


Figure 12. 4 Change of diameter as a function of changing length of the tubes filled with vegetable oil.

To help design and save time in the future, finite element analysis has been carried out to simulate the tensile test of silicon tubes. 3D solid elements have been used in the model. The material model for the nylon/silicon composite is Mooney. The material constants have been obtained from experimental curve fitting of testing data. Oil is simulated by Mooney material with very low values of constants. Both of the materials have been given very high bulk modulus to ensure constant volume. Figure 12. 5 shows the compression of load-strain curves from measurement and FEA simulation. They agree very well for strain levels below 80%. The specified elongation of the tentacle of octopus robot is not higher than 60%.

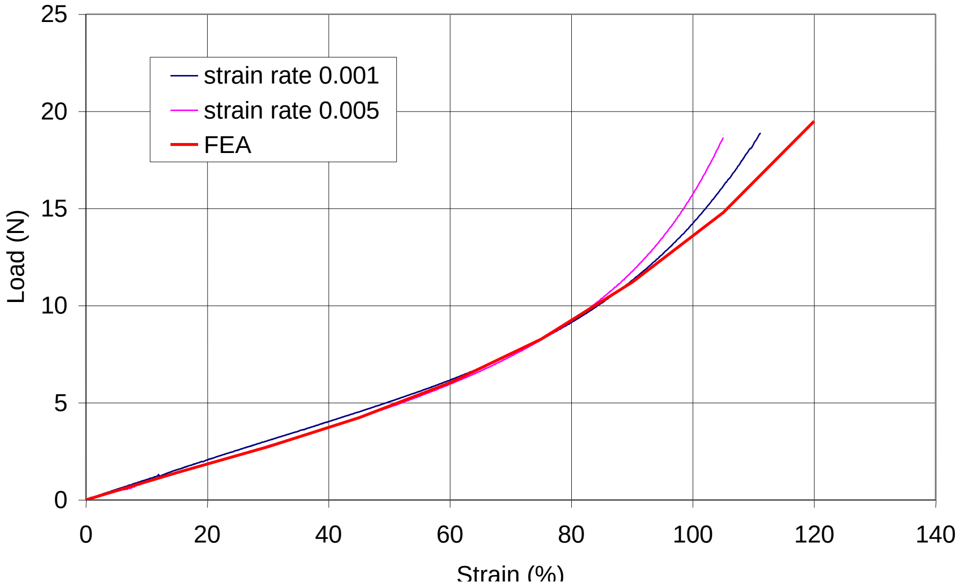


Figure 12. 5 ***FEA result compared with testing of tube filled with vegetable oil.***

3.12 WP18 –Dissemination, Training, Collaboration and Exploitation

WP Leader: SSSA

WP Members: All partners

Progress summary

During the first year of the project, the consortium carried out many dissemination activities, such as publication of research results in the best scientific journals, the organisation of sessions to ensure the visibility in the scientific community, and the setting up of a web site (www.octopusproject.eu), in which all the material of the project is collected and presented to the consortium and to the research communities. During the reporting period, training and collaboration activities were also carried out. In particular, a large number of PhD students are educated and trained in the different Institutions involved in the project, including their participation in Summer Schools and Workshops.

Significant results

Task 18.1 Dissemination – month 1-48 (SSSA, All)

The **internal dissemination** activities are carried out with the goal to create a joint community of researcher within the consortium, closing the gap between biologists and robotics.

The tutorials (D2.1 and D3.1) resulting from the activities carried out within WP2 and WP3, and the brainstorming meeting in Crete (April 27-28, 2009) have represented the first actions to share the knowledge from one side and the other.

During the first year, the consortium has created several internal research lines and activities, including collaborations with the exchange of researcher between the partners:

- UZH-SSSA: for the integration of the control system in a preliminary mock up platform for the simulation of the arm bending;
- UZH-HUJI: for the design of the octopus behavioural architecture;
- Weizmann-FORTH: for the exchange and comparison between the two different approaches in the modelling of the octopus arm, both for the biological and the robotic arm modelling;
- UREAD-SSSA: for the modelling and simulation of the first arm prototypes and the first integration of the actuators with the smart skin.

Many of the collaborations have involved biologists and robotics to solve a common issue under different viewpoints and with different methods.

The **external dissemination** activities were carried out to assure the diffusion of the project progress to the biologists and roboticists communities, as well as to the generic audience.

A total of 4 scientific papers have been published during the first year of the OCTOPUS activities. The publication of the OCTOPUS results on ISI Journals will be pursued for all the project lifetime, as one of the most important indicator of quality of the scientific and technological achievements.

The third OCTOPUS meeting was organized in occasion of the ISFN - Israel Society for Neuroscience - Annual Meeting (November 22 – 24, 2009, Eilat, Israel). All the OCTOPUS partners submitted works to the Conference and participated in the poster session. A special oral session on "Bioinspired Robotics" was organised in the context of this ISFN event.

A Web-based project presentation was developed by SSSA at the start of the project and published at the following address: http://www.octopus-project.eu. The website is continuously updated with new information, documents, reports, and additional material related to the project.

External dissemination activities were also carried out with the promotion on scientific television channels and scientific press.

Task 18.2 Training – month 1-48 (SSSA, All)

The training activities have the special role of creating a new scientific discipline on the base of the interaction between the communities of biologists and roboticists.

The interdisciplinary origin of the partners and the exchanging of young researchers, as happen in these months, is a perfect chance for their education to different sciences and/or different research methods.

Also the exchanging of professors among partners have a key role for the training of young researchers: an example is the seminar that Prof. Rolf Pfeifer (UZH) held at the SSSA in March and April 2009 (*How the body shapes the way we think: implications of the embodiment for a theory of intelligence*), as part of the PhD in Biorobotics program.

As planned in the OCTOPUS DoW, a one-week Summer School will be held by teachers from the groups of the consortium and external specialized invited speakers (mainly from other FET-Proactive EMBODYi Projects). The first planned Summer School, with the "Embodied Intelligence" theme, will be organized in late June 2010.

Task 18.3 Collaboration – month 1-48 (SSSA, All)

a) Joint Publications and Events

- Special sessions have been organized both with the partners of the OCTOPUS IP and with the STREP Projects of the EMBODYi initiative. During the FET Conference (April 21 - 23, 2009, Prague) a session on EMBODIED INTELLIGENCE (*New technologies and design approaches for building physically embodied intelligent agents* *and artefacts*) was organized by the OCTOPUS coordinator, Cecilia Laschi, with the participation of the following speakers: Rolf Pfeifer, University of Zurich, Switzerland, Paolo Dario, Scuola Superiore Sant'Anna, Pisa, Italy, Kenji Suzuki, University of Tsukuba, Japan, Eugenio Guglielmelli, University Campus Bio-Medico, Rome, Italy, Chiara Bartolozzi, Italian Institute of Technology, Lijin Aryananda, University of Zurich, Switzerland, Alin Albu-Schaeffer, DLR, Germany, Frederic Boyer, Ecole des Mines de Nantes, France.

- The next workshop will be held in Livorno, Italy, on March 17th, 2010, in occasion of the OCTOPUS and STREP EMBODYi Projects First Annual Cluster Review, which will involve the FET-Proactive EMBODYi Projects representatives.

b) Strategy and Roadmapping

- OCTOPUS supported the FET Consultation on Embodied Intelligence and Robotics.

c) Web portal

- www.embodiedintelligence.eu

OCTOPUS have also carried on a series of **International Co-Operation** activities with international partners, already part of the network of scientific collaborations of the OCTOPUS partners also for the training of young researchers. A Summer School titled “From Communication to Collaboration” (WSK-TNg’09) was organised by Waseda-SSSA-KIST-Tsukuba-Nagoya University and held in November 2009, in Tokyo, Japan, involving students from the SSSA to collaborate in research activities with Japanese and Korean university students.

A PhD student from SSSA, Laura Margheri, spent 6 weeks for training and research activities in the laboratory of Dr. Graziano Fiorito at the Stazione Zoologica Anton Dohrn. The activities focused on the measurement of the octopus arms mechanical properties and the study of the morphology using histology and ultrasound methods.

Task 18.4 Exploitation – month 1-48 (SSSA, All)

No significant exploitation activities were carried out during the first year of the project lifetime. Nevertheless, many contacts have been already established with Italian companies working on sea technologies in order to evaluate possibilities of further exploitation of some selected results achieved within OCTOPUS.

3.13 Deliverables and milestones tables

Deliverables (excluding the periodic and final reports)- The deliverables due in this period, as indicated in Annex I of the Grant Agreement, are reported in the following table.

TABLE 1. DELIVERABLES[4]

Del. no.	Deliverable name	WP no.	Lead beneficiary	Nature	Dissemination level	Delivery date from Annex I (proj month)	Delivered Yes/No	Actual / Forecast delivery date	Comments
D2.1	Fundamentals of inspirations from octopus biology to flexible robotics	2	HUJI	R	PU	M3	Yes	April 30, 2009	-
D2.2	Tutorial on fundamentals of octopus biology	2	HUJI	O	PU	M3	Yes	April 27, 2009	-
D3.1	Fundamentals of robotic technologies relevant to octopus biology	3	UZH	R	PU	M3	Yes	April 30, 2009	-
D3.2	Tutorial on technologies for biomimetic ICT and robotics	3	UZH	O	PU	M3	Yes	April 27, 2009	-
D18.1	IP website and dissemination materials	18	SSSA	O	PU	M3	Yes	TBC	-
D8.1	Biomechatronic specifications of the robotic octopus	8	SSSA	R	CO	M6	Yes	July 31, 2009	-

4 For Security Projects the template for the deliverables list in Annex A1 has to be used.

Milestones - Milestones in the reporting period are reported in the following table, together with corresponding means of verification, as specified in Annex I of the Grant Agreement.

TABLE 2. MILESTONES							
Milestone no.	**Milestone name**	**Work package no**	**Lead beneficiary**	**Delivery date from Annex I**	**Achieved Yes/No**	**Actual / Forecast achievement date**	**Comments**
M1	Biomimetics Workshop	WP2, WP3, WP4, WP5, WP6, WP7, WP8, WP18	HUJI	M3	Yes	April 27, 2009	-
M2	Biomechatronic specifications	WP8	SSSA	M6	Yes	July 31, 2009	-

4 Project management

This section summarises the management of the consortium activities carried out during the period.

4.1 Consortium management tasks and achievements

Task 1.1 Scientific and Technical Management – month 1-48 (SSSA, All Partners)

SSSA has duly kept contacts with the European Commission throughout the 12-month reporting period, and specifically Cecilia Laschi, the project coordinator, and Barbara Mazzolai, the project manager, has been in contact with the Project Officer David Guedj.

For the first Review Meeting, SSSA has led the coordination of the activities of the beneficiaries for delivering the progress report and for preparing the presentations of the work done in the IP. Furthermore, SSSA has significantly contributed to the organization of the Cluster Review event in Livorno, gathering the review meetings of the all 6 EMBODYi projects, including the scientific workshop due as one of the OCTOPUS deliverables.

During the first 12 months of the project, SSSA has coordinated the preparation and delivery of the 7 planned deliverables, as well as the accomplishment of the 2 milestones.

SSSA has organized periodic plenary meetings and reviewed the work done by the beneficiaries, with respect to the organization of WPs reported in the DoW and with respect to their time schedule, supporting the beneficiaries coordinating their activities within same WPs. At the plenary meetings, SMB meetings have been held, too, for discussions and decisions on general matters concerning the IP. Where relevant, the Advisory Board was also involved in the meetings for proper evaluation, advise, and steering.

The SMB has been appointed at the kick-off meeting, on February 17, 2009, in Pontedera. It includes representatives for all beneficiaries, as follows:

- SSSA: Cecilia Laschi
- HUJI: Benny Hochner
- Weizmann: Tamar Flash
- UZH: Rolf Pfeifer
- IIT: Darwin Caldwell
- UREAD: Richard Bonser
- FORTH: Dimitris Tsakiris

The Advisory Board is composed of Paolo Dario (chair) and Graziano Fiorito, from the Stazione Zoologica in Naples (Italy).

SSSA has promoted dissemination actions, as reported in WP18, at the level of the overall IP.

Task 1.2 Administrative and financial management – month 1-48 (<u>SSSA</u>, All Partners)

The following activities have been performed:

- At the end of October 2008 negotiations have been closed and the final version of the GPFs (together with A2.5 and A2.6 duly signed Forms) has been sent to the Commission Project Officer.
- Upon receipt of the Grant Agreement draft (email dated November, 27 2008), SSSA has signed two originals and on December, 2 2008 has sent them to the European Commission; on December 15 the Project Officer has returned to the Coordinator the original of the Grant Agreement, signed by the EC. The Octopus GA has entered into force on 12.12.2008, while the project start date has been fixed on February, 1 2009. Each beneficiary has received a paper copy of the core contract and related annexes, duly signed by the EC and the coordinator (letter dated 20.02.2009).

- As per GA, art. 1.2 Accession Forms have been gathered from all partners and have been countersigned. On December, 30 2008 one copy of Form A from each Partner has been sent back to the Commission.
- During the first 2009 months, the Consortium Agreement has been finalised. In May 2009 the CA has been signed and each beneficiary has entered into it. SSSA has sent each beneficiary a signed original of the CA (04.06.2009);
- On 17-18 February, 2009 held successfully the Kick-off Meeting
- The Advisory Board (AB) members (prof. Paolo Dario and prof. Graziano Fiorito – from Stazione Zoologica, Naples) as well as WP Leaders have been appointed by the Scientific and Management Board (SMB);
- On January 20, 2009 SSSA has received the EC pre-financing (after 5% guarantee fund retention) which amounts to EUR 2.660.000,00 and in May the 75% of it has been transferred to the Consortium on the basis of the specific partner share. As agreed in the CA, art. 7.3 the remaining 25% will be distributed to the beneficiaries at the beginning of the second reporting period, provided that the reports and deliverables due at the end of period 1 have been submitted;
- On occasion of the end of the first reporting period, the coordinator has designed templates for collecting inputs to the required EC documents; contribution form each beneficiary have been collected and integrated into a more coherent document, the current periodic report.
- Management of the consortium activities during the first reporting period has been efficient, thanks to the close interaction among all the components of the foreseen management structure (Scientific and Management Board, Advisory Board, Project Manager, Financial and administrative coordinator, Responsible for Intellectual Property, Use and Dissemination, WP Leaders);

SSSA has monitored the compliance of the Consortium activities with the obligations under the Grant Agreement.

4.2 Problems which have occurred and how they were solved or envisaged solutions

No major problems have occurred in the first 12-month period of the OCTOPUS IP.

4.3 Changes in the consortium

Beneficiary n°	Short name	Changes occurred	Status (JANUARY, 31 2010)
1	SSSA	NONE	-
3	HUJI	NONE	-
4	WEIZMANN	NONE	-
5	UZH	NONE	-
6	IIT	NONE	-
7	UREAD	NONE	-
8	FORTH	The legal representative of FORTH is Prof.V.Dougalis	The legal representative of FORTH is Prof.V.Dougalis

4.4 Changes to the legal status of any of the beneficiaries

Beneficiary N°	Short name	Legal Status / Indirect costs method (01 OCT 2008)	Legal Status changes (30 MARCH 2010)

Beneficiary N°	Short name	Legal Status / Indirect costs method (01 OCT 2008)	Legal Status changes (30 MARCH 2010)
1	SSSA	• non profit public body • higher education establishments • research organisation • Special transitional flat rate	NONE
2	HUJI	• non profit public body • higher education establishments • Special transitional flat rate	NONE
3	WEIZMANN	• non profit public body • higher education establishments • research organisation • Special transitional flat rate	NONE
4	UZH	• non profit public body • higher education establishments • Special transitional flat rate	NONE
5	IIT	• non profit • research organisation • Special transitional flat rate	NONE
6	UREAD	• non profit public body • higher education establishments • research organisation • Special transitional flat rate	NONE
7	FORTH	• non profit public body • research organisation • Actual indirect costs	• non profit public body • research organisation • Actual indirect costs • no more public body

4.5 List of project meetings, dates and venues

During the period, the following **project meetings** have been held:

OCTOPUS PROJECT MEETINGS IN THE FIRST PERIOD (01.02.2009 - 31.01.10).				
Meeting no.	Meeting	Participants	Date	Venue
1	Kick-off Meeting	All	17-18/02/2009	Pontedera (Pisa), Livorno (Italy)
2	Project restricted Meeting, at UZH	SSSA, UZH	01-03/04/2009	Zurich (CH)
3	Brainstorming and Tutorial Meeting	All	27-28/04/2009	Heraklion, Crete, Greece
4	Project restricted Meeting, at IIT	IIT	25/05/2009	Genova (Italy)
5	Project restricted Meeting, at UZH	UZH, HUJI	12/08/2009	Zurich (CH)
6	Project restricted Meeting, at UREAD	SSSA, UREAD	22-24/07/2009	Reading (UK)
7	Project restricted Meeting, at SSSA	SSSA, Advisory Board	15/09/2009	Pisa (Italy)
8	Project restricted Meeting, at SSSA	SSSA, UZH	05/10/2009	Pontedera (Pisa, Italy)
9	Project restricted Meeting, at SSSA	SSSA, IIT	14/10/2009	Pontedera (Pisa, Italy)
10	Project Meeting, Eliat (Israel)	All	25-26/11/2009	Eilat (Israel)

11	Project restricted meeting,at HUJI	HUJI, IIT	29/11/2009	Jerusalem (Israel)
12	Project restricted meeting, at SSSA	SSSA, IIT, FORTH	4/02/2010	Livorno (Italy)

4.6 Project planning and status

WP2

This WP has been duly accomplished and delivered its results on schedule, i.e. the document on relevant biology D2.1 and the tutorial by biologists to roboticists D2.2.

WP3

This WP has been duly accomplished and delivered its results on schedule, i.e. the document on relevant technological state of the art D3.1 and the tutorial by roboticists to biologists D3.2.

WP4

Task 4.1 and 4.2 officially concluded on month 7. As planned in the Dow, during the CryoSEM analysis useful pictures of the arm skin and suckers were captured to observe the samples in their hydrated state.
Task 4.2 was planned to investigate arm structures mechanical passive properties: a preliminary arm mechanical investigation has been carried out and a deep study of the skin mechanical behaviour has been completed.
Task 4.3 officially concluded on month 9. No particular useful results have been reached, because of the ability of the octopus to finely manipulate objects with no applied pressure. A further investigation on this ability is necessary on a larger number of animals, and with the use of different sensors, measuring both traction and pressure.
As planned in the task 4.4, the in-vivo measurement gave specifications on the elongation and force capability of the arm. The instrumental setup and the data have been validated on a large number of animals. Biomechanical data will be used and validated in the modelling of the arm, also for a next study of the arms stiffening.
Task 4.5 results include the description of the arm muscles and nerve organization in the arm.
In WP4.5 have been using basic histological techniques to clarify the structure and ratio between muscle and nerve cells at different length along the arm. As originally planned we have been doing an anatomical characterization of the octopus arm which is important for the understanding of its function as a biomechanical device.
We showed that the area occupied by ganglia (expressed as a percentage of the total area of the sections) decreases from the base to the tip of the arm while the area of the axial nerve cord increases dramatically from the base to the tip.
A tri-dimensional reconstruction of the anatomy of the arm is planned for the next period.

WP5

HUJI acts as coordinator and main laboratory in this WP. We do collaborate now and in the future with our partners in Weizmann and IIT. All tasks are currently within the timeframe laid out in the OCTOPUS project proposal.

WP6

All partners were involved in this WP with the main work being conducted by the Weizmann, HUJI, Forth and IIT teams. Wp6 consisted of four tasks. The objective of Task 6.1 was to develop advanced techniques for motion analysis, segmentation and modeling. Work on task 6.1 involved further developments and advancing of the motion measuring systems, methods and computational algorithms for near-automatic motion tracking and construction of 3D backbone curves and their kinematic analysis. The developed system a achieved satisfactory level of performance that expands the range of analyzable octopus movements. The objective of task 6.2 was to apply the methods developed in task 6.1 to study more complicated movements and to develop various motion decomposition schemes into motion primitives. Several different decomposition schemes were examined and the most successful scheme was chosen and further developed leading to a successful scheme and computational algorithms for decomposing 3D motions and clustering the resulting elementary motions into a reduced number of primitives. Task 6.3 was aimed at developing arm dynamic models and using these models both to study the neural control strategies used by the octopus arm to control its movements and interacting with the environment as a basis for the development of the robotic arm. Several complementary models were included in this WP. One model involved the building of a 3D model by the Weizmann and HUJI teams which generalize the available 2D model (Yekutieli et al., 2005) to the 3D case. This model proved useful in simulating 3D movements and investigating the control strategies underlying reaching and fetching movements. Extensive work was also conducted on investigating what neural activation schemes are used to create bends in different 3D arms as a function of theirs and the arm's morphology. The IIT team studied the real morphology of the arm in the octopus to augment the Weizmann and HUJI studies and used their findings as a basis for the design of the robotic arm. The Forth team developed detailed computational models of the octopus arm elastodynamics and hydrodynamics which complemented the work of the other teams and will also be useful in modelling arm impedance. To develop control strategies in the octopus a computational algorithm was developed by the Weizmann team that allows the inference of muscle activation from kinematics. This was further developed to analyze real recorded octopus motion data from the Weizmann team. The forth task in WP6 was task 6.4 aimed at investigating interactive behaviour and the control of compliant tasks such as object grasping. A mode-based control scheme for inferring the forces needed for the arm to follow a prescribed shape while minimizing potential energy was developed. This model will be used to develop and test various control strategies for controlling arm stiffness in the static case. Finally modifications to the muscle models were introduced that represent the control of muscle rest lengths in hydrostats. This modification will enable the project to investigate control strategies for arm elongation and the selection and control of arm impedance.

WP7

HUJI acts as coordinator and main laboratory in this WP. We do collaborate now and in the future with our partners in UZH. Further collaborations are planed with SSSA. All tasks are currently within the timeframe laid out in the OCTOPUS project proposal.

WP8

This WP has been duly accomplished and delivered its results on schedule.
The Work Package has been finished at the due date and led to a document (deliverable D8.1) that outlines the biomechatronic specifications of the robotic platform. This document has been produced with the involvement of all the partners and will serve as a reference for every technical decision.

WP9

The main features on the design of the artificial muscular hydrostat (planned for months 7-9) has been decided and followed for the development of the hydrostatic structure. Many mock-ups have been developed since the very early stage of the project. But even if the scheduled timing is extended to month 10-11, many others will be probably manufactured. This is because this technique allows for a very efficient and quick way of visualizing and evaluating new ideas. Many materials have been evaluated and at this stage the most probable candidates have been selected for their role in generating octopus-like performances in combination with the actuation system. During the last months of the WP very few changes will probably be necessary. Several actuating technologies have been evaluated and tested and some of these first prototypes have already been implemented following the arrangement inspired by the octopus anatomy. Some optimizations are necessary so the remaining time of the WP will be mainly dedicated to these. For specific actuating solutions a mechanical interface has been used and in future (till month 18) deeper studies and manufacturing optimization will focus on it. Recently a solution for integrated stretch sensors based on optoelectronic and silicones has been adopted and first mock-ups will be shortly ready for evaluation. Within month 14 it will be integrated with rest of the structure. It is clear that the progress of the Work Package is going on in parallel ways as every Task affects the development of the others, but this also the way to obtain a well integrated system and this is not delaying the fulfilment of the aim.

WP10

Activities are proceeding as scheduled. After defining the system on which the control will be implemented kinematic models of increasing complications have been developed and control algorithms developed.

WP11

Activities are proceeding almost as scheduled. We are going to continue defining a control architecture in detail according to the required tasks. We are also planning to devote our effort further to the survey of learning techniques and to the development of the interface to implement the proposed control architecture.

WP12

WP 12 proceeding as scheduled.

WP18

Activities for dissemination, training, collaboration and exploitation are daily carried out, to improve the project visibility, the collaboration and exchanging among the partners and the international community. All the activities are proceeding as scheduled: the IP website and the dissemination materials, as the joint events among all the FET-EMBODY[i] Projects have been successfully delivered. The one-week Summer School is in preparation, and will be held next September, 2010.

4.7 Impact of possible deviations from the planned milestones and deliverables

Formally, a deviation occurred during the first year concerns the change of the date of release of the Deliverable D4.1 “New insights on the octopus anatomy and biomechanics relevant to robotics” with respect to the original version of the OCTOPUS Description of Work. In fact, originally D4.1 was set to be released at month 12. Nevertheless, in line with the end of the other biological workpackages (WP5 and WP6), the end of WP4 and, consequently, the release of D4.1 has been changed at month 16. Deviations occurred in the section related to the morphological examination of the arm and suckers. Immunohistochemical assays were performed where necessary. A better identification of different cell type and their connection will result from this study.

4.8 Development of the Project website

The official OCTOPUS web site (www.octopusproject.eu) has been set up during the first 3 months of the project.

The homepage (Figure 4.8. 1 OCTOPUS home page) reports the following main information:

- ✓ The project information.
- ✓ Objectives of the project.
- ✓ A brief description of the partnership.
- ✓ Dissemination activities, including downloadable presentations of the project (press, brochure and poster).
- ✓ Results of the project, including a list of the publications.
- ✓ An updated list of training, courses, conferences and events interesting for the OCTOPUS project.
- ✓ Some links to official sites of the European Commission.
- ✓ A section "Pictures & Video", which is linked to the *Octopus channel* on YouTube.
- ✓ A section "News" reports meetings and workshops organised and related to the project, including links to the events and pictures.
- ✓ Links to the European Commission initiatives.

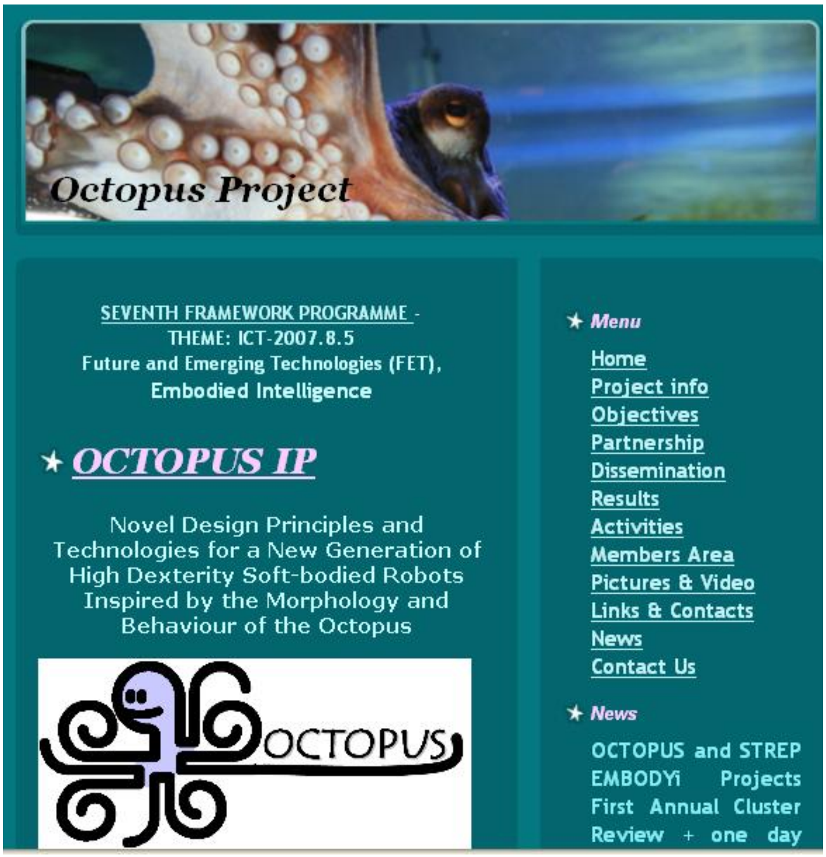


Figure 4.8. 1 OCTOPUS home page

A link to the Embodied Intelligence Projects Portal (www.embodiedintelligence.eu) is also present on the OCTOPUS home page (Figure 4.8. 2).

Figure 4.8. 2 The Embodied Intelligence projects home page

A OCTOPUS members' area has been set up and updated (Figure 4.8. 3), including all the documents (minutes of meetings, tutorials, deliverables, research results) produced during the first year of the project activity. The access to this area is protected by private credentials (i.e. username and password), assigned to all the partners of the project and to the Project Officer.

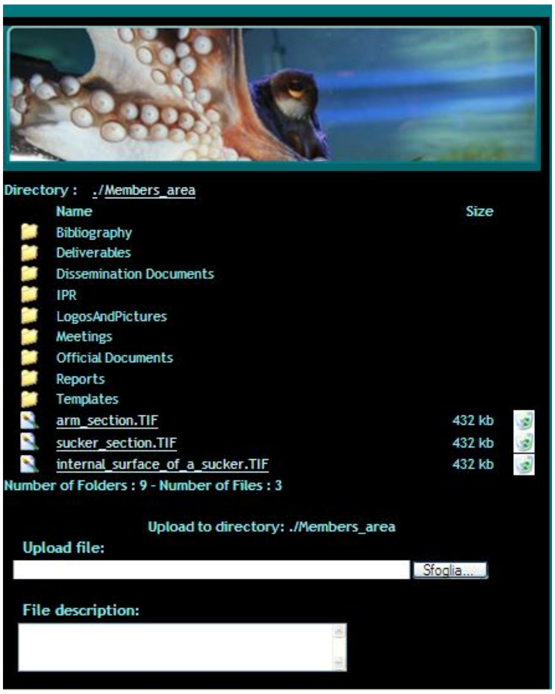


Figure 4.8. 3 OCTOPUS members' area

The "Dissemination" area is dedicated to the dissemination material, such as the OCTOPUS official brochure, the poster and the official presentations. All these documents are downloadable from the web page. In the same session press releases presenting the project activities and publications for a generic audience are also available.

The project meetings, the scientific workshops and the summer schools are presented in the "Activities" area. All the events are linkable to a dedicated page, in which pictures of the event and public documents are available.

4.9 Use of foreground and dissemination activities during this period

List of publications (Journals, Books, and Conferences)

M. Cianchetti, V. Mattoli, B. Mazzolai, C. Laschi, P. Dario (2009) A new design methodology of electrostrictive actuators for bio-inspired robotics, *Sensors and Actuators B: Chemical* 142 (1) 288-297. (SSSA)

C. Laschi, B. Mazzolai, V. Mattoli, M. Cianchetti and P. Dario (2009) Design of a biomimetic robotic octopus arm, *Bioinspir. Biomim*. Vol.4, No.1. (SSSA)

C. Laschi, B. Mazzolai, V. Mattoli, M. Cianchetti and P. Dario (2009) Design and Development of a Soft Actuator for A Robot Inspired by the Octopus Arm, in Experimental Robotics, The 11th International Symposium, O. Khatib, V. Kumar, G. Pappas (Ed.s), Springer Tracts in Advanced Robotics (STAR Series), Springer, pp.25-33. (SSSA)

I. Zelman, M. Galun, A. Akselrod-Ballin, Y. Yekutieli, B. Hochner, and T. Flash (2009) Nearly automatic motion capture system for tracking octopus arm movements in 3D space, *Journal of Neuroscience Methods*, Volume 182: 97-109. (HUJI, Weizmann)

L. Zullo, G. Sumbre, C. Agnisola, T. Flash, B. Hochner (2009) Nonsomatotopic Organization of the Higher Motor Centers in Octopus, *Current Biology*, 19:1632-1636. (IIT, HUJI)

Margheri L., Mazzolai B., Cianchetti M., Dario P. and Laschi C. (2009) Tools and Methods for Experimental In-vivo Measurement and Biomechanical Characterization of an *Octopus vulgaris* Arm *Proceedings of the 31st IEEE EMBS Int. Conf*. Minneapolis, Minnesota, USA. (SSSA)

Margheri L., Ponte G., Mazzolai B., Laschi C. and Fiorito G (2009) In vivo investigation of the arm nerve cord morphology of the *Octopus vulgaris*, using ultrasound techniques *J Mol Neurosci* 39 (Suppl 1):S1–S132. (SSSA)

Margheri L., Mazzolai B., Laschi C. and Dario P. (2009) Methods and tools for the experimental in-vivo measurement and characterization of the *Octopus vulgaris* arm mechanical properties *J Mol Neurosci* 39 (Suppl 1):S1–S132. (SSSA)

Tsakiris D. Bio-inspired motion control for pedundulatory robotic locomotion *J Mol Neurosci* 39 (Suppl 1):S1–S132. (FORTH)

Zullo L., Fossati S.M., Hochner B. and Benfenati F. (2009) Physiological characterization of octopus arm and sucker *J Mol Neurosci* 39 (Suppl 1):S1–S132. (IIT)

Fossati S.M., Benfenati F., Hochner B and Zullo L. (2009) Morphological characterization of the octopus arm relevant to robotics *J Mol Neurosci* 39 (Suppl 1):S1–S132. (IIT)

Gutnik T., Byrne R.A., Hochner B. and Kuba M.J. (2009) *Octopus vulgaris* visually guides complex arm movement *J Mol Neurosci* 39 (Suppl 1):S1–S132. (HUJI)

Hanassy S., Botvinnik A. and Hochner B. (2009) Elongation and bend propagation in the reaching movement of *Octopus vulgaris J Mol Neurosci* 39 (Suppl 1):S1–S132. (HUJI)

Hochner B., Zullo L. and Subre G. (2009) The control of goal directed movements in the flexible arm of the octopus *J Mol Neurosci* 39 (Suppl 1):S1–S132. (HUJI, IIT)

Kuppuswamy N.S, Li T., Nakajima K., Cianchetti M. and Pferifer R. (2009) A biologically inspired approach to the control of octopus-like soft robot arms *J Mol Neurosci* 39 (Suppl 1):S1–S132. (UZH, SSSA)

M. Sfakiotakis and D.P. Tsakiris (2009) Undulatory and Pedundulatory Robotic Locomotion via Direct and Retrograde Body Waves, *Proc. of the 25th IEEE Intl. Conference on Robotics and Automation (ICRA'09)*, pp. 3457-3463, Kobe, Japan. (FORTH)

G. López-Nicolás, M. Sfakiotakis, D.P. Tsakiris, A.A. Argyros, C. Sagüés and J.J. Guerrero (2009) Visual Homing for Undulatory Robotic Locomotion, *Proc. of the 25th IEEE Intl. Conference on Robotics and Automation (ICRA'09)*, pp. 2629-2636, Kobe, Japan. (FORTH)

Seminar papers

Y. Yekutieli Biomechanics and control of the octopus arm. ULTRAFEST V, 18-21 March, 2010 New Haven CT, USA (http://www.haskins.yale.edu/conferences/UltrafestV/yoram.html). (Weizmann)

C. Laschi, "The OCTOPUS project", EU-SouthKorea ICT Cooperation, Session Future & Emerging Technologies (FET), December 1, 2009. (SSSA)

"Embodied Intelligence" Session at The European Future Technologies Conference FET09 Science beyond Fiction, 21-23 April 2009, Prague. (All the partners)

"Bioinspired robotics" Session at the Israel Society for Neuroscience 18th Annual Meeting, 22-24 November 2009, Eilat, Israel. (All the partners)

OCTOPUS press releases, brochures, videos, posters, media

A section on press releases on the OCTOPUS project is available on the web site, under the "Dissemination" area. A list of the main articles published on the OCTOPUS project on magazine for a generic audience is reported below:

- "Prototipi che partono da polpi e piante", IlSole24ore, January 15, 2009.
- "Robot octopus will go where no sub has gone before", NewScientist Tech, March 21, 2009.
- "Robo-octopus wanted by EU", Planetary Gear, March 25, 2009.
- "Building a robot octopus", Sentient Developments, March 26, 2009.
- "Biomimetic robotic octopus arm designed", Robots Forum, March 27, 2009.
- Patris Newspaper, April 28, 2009.
- "Forget submarines, send in a robotic octopus instead", Israel21c, Jerusalem post, Newsletter, May 06, 2009 (http://www.israel21c.org/technology/forget-submarines-send-in-a-robotic-octopus-instead).
- "Per fare robot con le braccia d'acciaio gli scienziati copiano il molle polpo", Il Venerdì di Repubblica, May 15, 2009.
- "Acrobatic Octopus Arm Could BE Model for Flexible Robots", WIRED SCIENCE, September 17, 2009.

A brochure of the OCTOPUS project is available and downloadable from the project web site under the "Dissemination" area (www.octopusproject.eu/dissemination.html). Figure 4.9. 1 shows the structure and the contents of the OCTOPUS brochure.

Figure 4.9. 1 The OCTOPUS brochure.

A poster of the project, purposively developed for dissemination aims and at disposal of the OCTOPUS consortium, is downloadable from the "Dissemination" area. An image of this document is shown in Figure 4.9. 2.

Many videos, both technical and popular, and pictures are available on the public area of the OCTOPUS web site with a dedicated section ("Pictures & Video", http://www.octopusproject.eu/multimedia.html).

Poster session

A poster session for the presentation of the results achieved within the OCTOPUS project by the Consortium has been organised in occasion of "The Israel Society for Neuroscience 18th Annual Meeting", Eilat, November 22-24, 2009. All the abstracts submitted by the partners for the special poster session were published in the Journal of Molecular Neuroscience, Volume 39, Supplement 1 / November, 2009: http://www.springerlink.com/content.

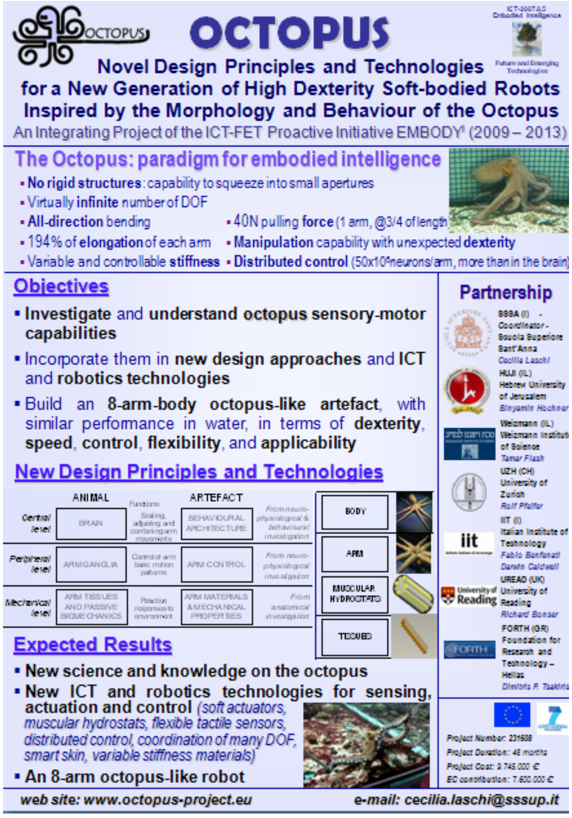


Figure 4.9. 2 The OCTOPUS poster

TV show

A demonstration of the working principles of the mock-up arm developed within the Octopus project was shown at the Swiss and German TVs in April 2010 (TV station: NZZZ Format).

4.10 Co-ordination activities

- Prof. Richard Bonser from UREAD visited UZH for Brown bag lecture and discussed.
- Mr. Matteo Cianchetti and Mr. Andrea Arienti from SSSA visited UZH for Brown bag lecture and discussed.
- Dr. Micheal Kuba and Tamar Gutnick from HUJI visited UZH to have a discussion on Octopus biology and also invited to Brown bag lecture.
- Mr. Naveen Kuppuswamy, Mr. Tao Li and Dr. Kohei Nakajima from UZH visited SSSA to bring and install a joint developed mock-up system.
- Mr. Matteo Cianchetti from SSSA visited UREAD for 5 weeks to analyze mechanical issues related to the hydrostatic structure and to integrate the work realized by UREAD with SSSA actuation system
- Mr. Matteo Cianchetti from SSSA visited IIT to coordinate and steer the first phases of the project
- Exchange of ideas, data, information and multiple meetings took place between the Weizmann and HUJI teams.

5 Explanation of the use of the resources

5.1 Planned and actual efforts for the first period

Weizmann:
The major cost item was for personnel for Postdocs, PhD, researchers and Technicians. The second major cost on the list was for travel. This was according to the planned activities.

OCTOPUS - 1st PERIOD (01/02/2009 - 31/01/2010)

WP	Activity Type		SSSA	HUJI	WIS	UNIZH	IIT	RUR	FORTH	TOT
RTD/ Innovation Activities										
WP2	Analysis of existing relevant knowledge on the octopus	Planned	0,00	1,00	4,00	0,00	8,00	0,00	0,00	13,00
		Actual	0,00	1,00	4,00	0,00	5,00	0,00	0,00	10,00
WP3	Analysis of relevant existing technologies	Planned	4,00	0,00	0,00	3,00	4,00	5,00	6,00	22,00
		Actual	4,02	0,00	0,00	5,32	3,00	5,00	5,00	22,34
WP4	Focused research on the octopus arm anatomy and biomechanics	Planned	14,00	40,00	0,00	0,00	12,00	2,00	0,00	68,00
		Actual	13,83	20,00	0,00	0,00	8,00	2,00	0,00	43,83
WP5	Focused research on the octopus neurophysiology	Planned	0,00	60,00	33,00	0,00	34,00	0,00	0,00	127,00
		Actual	0,00	30,00	10,00	0,00	18,00	0,00	0,00	58,00
WP6	Kinematics and dynamics modelling of the octopus arm	Planned	0,00	36,00	70,00	0,00	12,00	0,00	12,00	130,00
		Actual	0,00	5,00	33,00	0,00	7,00	0,00	8,00	53,00
WP7	Octopus behavioural experiments	Planned	3,00	60,00	0,00	14,00	0,00	0,00	0,00	77,00
		Actual	3,75	20,00	0,00	9,67		0,00	0,00	33,42
WP8	Biomechatronic specifications of the robotic octopus	Planned	8,00	4,00	10,00	6,00	14,00	4,00	6,00	52,00
		Actual	8,57	0,00	2,00	7,67	11,00	4,00	5,00	38,24
WP9	Design and development of the artificial muscular hydrostat	Planned	50,00	0,00	0,00	0,00	12,00	5,00	0,00	67,00
		Actual	27,88	0,00	0,00	0,00	5,00	1,00	0,00	33,88
WP10	Design and development of the robotic arm kinematic model and control system	Planned	0,00	0,00	30,00	6,00	24,00	0,00	28,00	88,00
		Actual	0,00	0,00	3,00	4,10	10,00	0,00	7,20	24,30
WP11	Design and development of the robotic octopus behavioural architecture	Planned	0,00	0,00	6,00	30,00	6,00	0,00	12,00	54,00
		Actual	0,00	0,00	2,00	16,57	1,00	0,00	2,00	21,57
WP12	Design and development of the sensorized skin	Planned	4,00	0,00	0,00	0,00	0,00	18,00	0,00	22,00
		Actual	3,34	0,00	0,00	0,00		3,00	0,00	6,34
WP13	Integration and test of one robotic arm	Planned	14,00	8,00	36,00	6,00	16,00	9,00	12,00	101,00
		Actual	0,00	0,00	0,00	0,00		0,00	0,00	0,00
WP14	Development of the robotic octopus with eight arms	Planned	46,00	0,00	0,00	0,00	16,00	16,00	0,00	78,00
		Actual	0,00	0,00	0,00	0,00		0,00	0,00	0,00
WP15	Development of the sensory-motor and behavioural schemes	Planned	0,00	18,00	24,00	44,00	10,00	0,00	30,00	126,00
		Actual	0,00	0,00	0,00	0,00		0,00	0,00	0,00
WP16	Integration of the robotic octopus final prototype	Planned	18,00	12,00	8,00	4,00	14,00	8,00	16,00	80,00
		Actual	0,00	0,00	0,00	0,00		0,00	0,00	0,00
WP17	Experimental validation of the robotic octopus	Planned	12,00	8,00	6,00	4,00	5,00	5,00	9,00	49,00
		Actual	0,00	0,00	0,00	0,00		0,00	0,00	0,00
Total RTD/ Innovation Activities		Planned	**173,00**	**247,00**	**227,00**	**117,00**	**187,00**	**72,00**	**131,00**	**1154,00**
		Actual	**61,40**	**76,00**	**54,00**	**43,33**	**68,00**	**15,00**	**27,20**	344,93
Consortium/Management Activities										
WP1	Project Management	Planned	48,00	1,00	1,00	1,00	1,00	1,00	1,00	54,00
		Actual	9,30	0,00	0,50	0,50		0,25	0,25	10,80
Total Consortium/Management Activities		**Planned**	**48,00**	**1,00**	**1,00**	**1,00**	**1,00**	**1,00**	**1,00**	**54,00**
		Actual	9,30	0,00	0,50	0,50	0,00	0,25	0,25	10,80
Other Activities										
WP18	Dissemination, Training, Collaboration and Exploitation	Planned	48,00	14,00	9,00	7,00	12,00	5,00	3,00	98,00
		Actual	2,67	0,00	1,00	2,35		1,00	0,25	7,27
Total Other Activities		**Planned**	**48,00**	**14,00**	**9,00**	**7,00**	**12,00**	**5,00**	**3,00**	**98,00**
		Actual	2,67	0,00	1,00	2,35	0,00	1,00	0,25	7,27
TOTAL PLANNED			269,00	262,00	237,00	125,00	200,00	78,00	135,00	1306,00
TOTAL ACTUAL			73,37	76,00	55,50	46,18	68,00	16,25	27,70	363,00

5.2 Personnel, subcontracting and other major direct cost items

Period from 01/02/2009 to 31/01/2010 Beneficiary no. 1 - SSSA				
Item description	**Work Package**	**Amount**	**Activity Type**	**Explanations**
Personnel costs	*1,3,4,8*	€ 155.142,40	RTD	Salaries of researcher (61,40 months) devoted to research activities
		€ 39.046,46	MGMT	Personnel costs for management activities (9,30 months)
		€ 10.998,86	OTHER	Personnel costs for dissemination activities (2,67 months)
Travel	1,4,18,12,9	€ 31.829,30	*RTD - OTHER COSTS*	Kick-off Meeting(Pisa)17-18 February 2009
				Technical meeting Naples (Italy), Stazione Zoologica Anton Dohrn - February 10-11/2009
				BRAIN AWARENESS WEEK - Naples (Italy), Stazione Zoologica Anton Dohrn - March 18-20/2009
				Tutorials and Brainstorming Meeting Project Meeting - Heraklion (Greece) - April 26-28/2009
				Studiy activities - Naples (Italy), Stazione Zoologica Anton Dohrn - June 21/2009 and July 20/2009
				31st Annual International IEEE EMBS Conference - Minneapolis (USA) - September 2-7/2009
				Project restricted technical Meeting, University of Reading (UK) - uly 22-24/2009
				Project Meeting, Eliat (Israel), November 25-26/2009
				Summer School, "WSK-Ing 2009" Japan from October 31th 2009 to ovember 11 2009

				Project technical Meeting (on design issues), Genova (Italy) IIT May22 2009
				Project restricted Meeting, Zurich (CH) - April 1-3/2009
				Experiments on WP4 activities - Naples (Italy), Stazione Zoologica Anton Dohrn - June 30/2009 - July 1 2009
				Workshop "Biorobotics and service robotics for a better quality of life", Korea
				Workshop "Biorobotics and service robotics for a better quality of life", Korea - October 23 2009
Subcontracting	*1,7,4,18*	*€ 9.198,41*	*RTD*	Costs for project meeting organization (lunch, coffee break) Prototypies realization
			MGMT	Courier mail costs for official documents delivery
			OTHER	Designing and realization of Project web site. Printing of brochure
Equipment	*8, 17*	*€ 6.294,99*	*RTD*	Depreciation of an equipped work bank for anatomical and biomechanical studies
				Depreciation of the dedicated tank for the observation of living octopus
				Depreciation of measuring instrument, to observe and analyze the behaviour of the internal structures while the arm is inside performing the task.
				Depreciation of equipment for the fabrication of a muscular hydrostat mock-up
				Depreciation of 1 Lab VIEW Software
				Depreciation of 3 work stations for research activities
			MGMT	Depreciation of the interactive board, audiovisual equipment used in the period for the management
			OTHER	Depreciation of server for maintaining the Project web site
Consumables	*2,3,4,7,8*	*€ 12.700,82*	*RTD*	Costs for consumables related to dedicated tank; electronics, mechanicals components, sensors, cameras for the set-up of experimental environment

Remaining direct costs	*1*	€ *77,47*	MGMT	Bank charges related to EC grant transfers to the partners
Total DIRECT COSTS		**€ 265.288,71**		

Personnel,subcontracting and other major direct costs
Period from 01/02/2009 to 31/01/2010
Beneficiary no. 2 - HUJI

Item description	Work Package	Amount	Activity Type	Explanations
Personnel costs	*2, 4, 5, 6, 7, 8*	€ 94.846,00	*RTD*	*Salaries of 2 researchers and 12 students and 1 technician both full and part-time*
Travel		€ 13.303,00	RTD	Attending scientific and project meetings
		€ 2.677,00	*OTHER COSTS*	
Subcontracting		€ -		*no subcontracting in this report period*
Equipment	*5, 7*	€ 20.339,00	*RTD*	*Special computers and software, AV equipment, wet lab equipment*
Consumables	*5, 7*	€ 29.704,00	RTD	Chemicals for WP 5, Food, salt and trace elements for animal keeping, animals
		€ 14.055,00	*OTHER COSTS*	
Remaining direct costs		€ 3.848,00	RTD	
		€ 3.645,00	*OTHER COSTS*	
Total DIRECT COSTS		**€ 182.417,00**		

Personnel, subcontracting and other major direct costs

Period from 01/02/2009 to 31/01/2010

Beneficiary no. 3 - WEIZMANN

Item description	Work Package	Amount	Activity Type	Explanations
Personnel costs	2, 5, 6, 8, 10, 11, 18			
		€ 36.648,25	RTD	Salary of PI for 3.3 months
		€ 23.235,00	RTD	Salaries of 4 PhD research Students for 17.28 months
		€ 6.421,00	RTD	Salaries of 2 Researchers for 12 months
		€ 6.019,30	RTD	Salary of 1 Post Doc for 3 months
		€ 25.624,92	RTD	Salary for Assistant Staff Scientist for 6 months
		€ 35.939,96	RTD	Salaries of 1 Lab technician for 7.05 months
		€ 4.012,00	RTD	Salary of 1 research assistant for 5 months
		€ 8.797,25	OTHER	Salaries of 1 Lab technician for 1 months
		€ 4.398,62	Management costs	Salaries of 1 Administrator for 0.5 months
Travel		€ 5.527,85	RTD	Scientific Meeting(Pisa),Scientific Meeting(Forth Heraklion)
Subcontracting				
Equipment				
Consumables	11	€ 3.528,25	RTD	Lab accessories
		€ 1.588,17	OTHER	Conference
Remaining direct costs				
Total DIRECT COSTS		**€ 161.740,58**		

Personnel, subcontracting and other major direct costs

Period from 01/02/2009 to 31/01/2010

Beneficiary no. 4 - UNIVERSITAET ZUERICH

Item description	Work Package	Amount	Activity Type	Explanations
Personnel costs	3,7,8,10,11,18	€ 167.335	RTD	Salaries of 1 postdoctoral student , 6 doctoral student and 1assistent for 12 months each
	1	€ 2.881	MGMT	Personnel costs for management activities
Travel	3,11	€ 9.498	RTD	the cost of airfare, transportation and room: OCTOPUS Kick-Off Meeting (17-18 February, 2009 Pontedera (PI) & Livorno OCTOPUS Tutorials and Brainstorming Meeting 27-28 April, 2009, FORTH, Heraklion, Crete, Greece) bring a system to SSSA 2-5 Oct, 2009 Pontedera (PI) & Livorno) OCTOPUS Meeting 25-26 November, 2009, Eilat, Israel
Subcontracting				
Equipment	1,3,7,8,10,11,18	€ 3.832	RTD	
Consumables	1,3,7,8,10,11,18	€ 3.625	RTD	the cost of Electronic industry material
Remaining direct costs	1,3,7,8,10,11,18	€ 1.024	RTD	the cost of meeting
Total DIRECT COSTS		**€ 188.194,75**		

Period from 01/02/2009 to 31/01/2010 Beneficiary no. 5 - IIT				
Item description	**Work Package**	**Amount**	**Activity Type**	**Explanations**
Personnel costs	*4,9,10,11*	€ *320.078,76*	*RTD*	Salaries of :1 Fellow (10,5 months) 1 Fellow (12months) 3 Post-Doc (4 months each) 1 Post-doc (6 months) 1 Post-Doc (12 months; 1 Team Leader (6 months) 1 Senior Researcher (2 months) 3 technichians (2 months each) 1 technician (4 months) 2 Directors (2 m
Travel	4,1	€ 7.958,36		
		€ -		
Subcontracting		€ 875,00	*RTD*	Mould
		€ -		
Equipment	*4,1*	€ *2.163,96*	*RTD*	Teslameter
		€ -		Vacuum oven
		€ -		Octopus aquarium
Consumables	*11*	€ *14.157,47*	RTD	Connectors, valves and silicon tubes for prototyping Reactant and chemicals for muscolar electrophisiological and morphological test on the octopus Materials and supplies required for the welfare of the experimental animals
Total DIRECT COSTS		**€ 345.233,55**		

Period from 01/02/2009 to 31/01/2010

Beneficiary no. 6 - UNIVERSITY OF READING

Item description	Work Package	Amount	Activity Type	Explanations
Personnel costs	*2,4,8,12*	*€ 47.134,90*	*RTD*	*Postdoc for 11 months*
		€ 18.492,20	RTD	Principal invesigator (25%)
		€ 7.792,48	RTD	Co Invesigator (10%)
	1	€ 439,42	MGMT	PI
	18	€ 952,07	Dissemination	PI
Travel		€ 5.312,57		
Subcontracting		-	-	
Equipment		-	-	
Consumables		*€ 1.458,70*	RTD	Octopus and software
Remaining direct costs		-	-	
Total DIRECT COSTS		**€ 81.582,33**		

Personnel, subcontracting and other major direct costs

Period from 01/02/2009 to 31/01/2010

Beneficiary no. 7 - FORTH

Item description	Work Package	Amount	Activity Type	Explanations
Personnel costs	1, 3, 6, 8, 10, 11, 18	€ 82.747,18	RTD	Salaries of 1 researcher, 4 postdoctoral technical staff and one lab technician
Travel		€ 8.806,19	RTD and OTHER	Consortium meetings, Professional conferences and talks
Subcontracting				
Equipment				
Consumables		€ 439,34	RTD and OTHER	Experimental supplies
Remaining direct costs		€ 3.696,99	MGMT and OTHER	Hosting consortium meetings and related events
Total DIRECT COSTS		**€ 95.689,70**		

6 Financial statements – Form C and Summary financial report

Each beneficiary shall submit its Financial Statement (Form C) on the **NEF system**.
A Summary Financial report consolidating the claimed Community contribution of all the beneficiaries in an aggregate form will be automatically generated.

6.1 Certificates

List of Certificates which are due for this period, in accordance with Article II.4.4 of the Grant Agreement.

Beneficiary	Organisation short name	Certificate on the financial statements provided? yes / no	Any useful comment, in particular if a certificate is not provided
1	SSSA	no	Expenditure threshold not reached
2	HUJI	no	Expenditure threshold not reached
3	WEIZMANN	no	Expenditure threshold not reached
4	UZH	no	Expenditure threshold not reached
5	IIT	YES	-
6	UREAD	no	Expenditure threshold not reached
7	FORTH	no	Expenditure threshold not reached

Beneficiary Number	Short name	Certificate on the methodology on both personnel and indirect costs	Certificate on the methodology on average personnel costs
1	SSSA	no	no
2	HUJI	no	no
3	WEIZMANN	no	no
4	UZH	no	no
5	IIT	no	no
6	UREAD	no	no
7	FORTH	no	no

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