ADAPT

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Artificial Development Approach to Presence Technologies

Deliverable Item 3.1
Definition and implementation of a human-like robotic setup

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Short Description: This deliverable describes the robotic setup where most of the artificial development experiments will be carried out. It includes definition of the hardware with particular emphasis to the robotic hand, which was realized as a part of the project. This document contains also a description of the low-level software layer, a behavior based componentized software structure that provides robot control functionalities and communication within a distributed architecture based on Pentium class processors and running a variety of operating systems. Further, this document includes the description of a learning model that to some extent has been used within the architecture. Additional material on the system's architecture as it relates to D2.1 (a theory of intentionality) could be found on D5.1.

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Content list

1. Introduction

This deliverable describes one of the characterizing foundations of Adapt, i.e. the robotic setup. For reasons of coherence of this presentation and completeness of the deliverable, we included a depiction of the complete architecture of the robot from the hardware composition to various software layers. Clearly, not all what is described here has been specifically developed for Adapt, and in particular the distributed control architecture is the result of previous work. Also, Section 7 is only the very first sketch of one of the component of the learning architecture that is due to be developed in workpackage 5.

For explanatory purpose the complete model has been divided in two parts covered by this document (which stresses the implementation aspects) together with D5.1 (system's architecture, which focuses on the learning aspects) and, to some extent, to D2.1 (theory of intentionality). In particular D5.1 bridges the gap between the theory of intentionality (a theory on the phenomenal aspects of Presence) as formulated in D2.1 and this document by describing the system's architecture in terms of learning and modularization. D5.1 is intended as the first document of a series of three (together with D5.2, D5.3) which will provide exhaustive description of the implementation.

Therefore, this document only describes the robot architecture in terms of hardware and supporting software. It includes definition of the hardware with particular emphasis to the robotic hand, which is crucial to the project. It contains also a description of the low-level software layer, a behavior based componentized software structure that provides robot control functionalities and communication within a distributed architecture based on Pentium class processors and running on a variety of operating systems. Further, this document includes the description of a learning model that to some extent has been repeatedly used within our architecture (which will be analyzed in details in D5.1).

Overall, the robot architecture can be seen as a layered system as shown in Figure 1. It is worth stressing here that layering involves only the "engineering" of the robotic artifact. It does not constrain what specific learning schema is employed or how the different developmental modules interact one with another. In this sense this is not in contrast with the main philosophical underpinning of the project: that is, certain cognitive skills have to be acquired through a prolonged developmental period. Although modularity (and layering in this case) is perhaps the only tool we have in face of complexity, we previously suggested that we need to carefully take into account how interrelationships between modules evolve as artificial adaptation unfolds if we are to properly characterize learning and development. It was important thus not to commit too early into the decision of which learning schema or control structure had to be used.

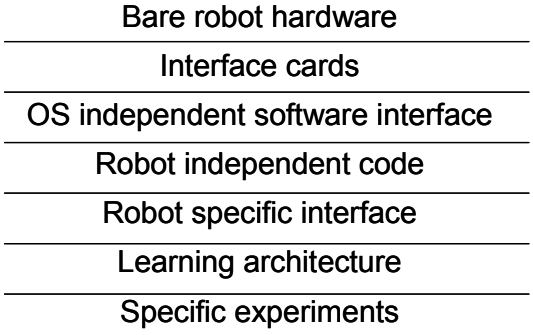


Figure 1 Organization of the hardware and software layers of the robotic artifact

The seven layers in Figure 1 span the conceptual space from the "bare metal" to the "experimental level". All what we have designed in between is sort of "supportive" structure. These middle layers might condition, to a certain extent, whether a particular type of experimentation could be actually carried out, and consequently they represented a delicate design decision.

The first layer contains the robot hardware. It includes a simplified description of the mechanics and the limitations of the current implementation. The robot's sensors and actuators are interfaced to a set of computers through interface cards. Layer number 2 is made of these cards. Layer 3 is the first software interface with the hardware. It is written with portability in mind since many different cards might be connected to the same setup [or, on the contrary, the same card might be used in another setup], the controlling computers could be possibly running different operating systems, and different subparts might be running on different machines connected through an IP-based network. Using a publicly available portable library (ACE), we designed a communication system and general purpose computation environment. Our guiding criterion was "try not to be monolithic". In this sense our system does not force the use of any particular library or set of libraries and in fact it was easily interfaced to Intel IPL (for efficient image processing), and Matlab (because of the many available toolboxes). The core system runs seamlessly on Windows (NT series), QNX (a real-time OS), and Linux.
In general, code directly controlling the robot tends to have a nasty organization and often contain details of the specific locale even when the controlling cards are the same. We wanted to decouple the "robot" part of our software from the more general purpose OS interface. Consequently, layer 4 is meant as an interface between the robot-independent code built on a generic "device driver" definition ["device driver" here is a user-level software component]. The goal of the latter is of shielding the nasty details from the higher level where unspecific code could be produced. This allows interfacing to any different hardware at the price of rewriting a relatively small virtual device driver module. Layer 5 allows customization of the robot control code to the specific locale. This is required in order to "tune" the control code to the details of the actual robot. It allows reusing the same code on two not-too-dissimilar setups. It consists mainly on specific software and configuration files.
Layer 6 contains a general description of the organization of the learning modules of the system. These components are simply a tentative formalization of the implementation of the sensorimotor coordination behaviors of the robot. At this stage they are not necessarily innovative in any respect and in fact we pretty much relied on standard function approximation methods and traditional neural network algorithms (e.g. backpropagation). The system's

architecture as described in D5.1 will either integrate or replace this layer with "something" more innovative along the guidelines provided by the developmental psychology and philosophical insights of the project.
Finally, layer 7 represents the level where specific experiments are conducted. It is worth noting that none of this organizational structure is strictly imposed. From the outside the architecture consists of a set of libraries and executable modules. The remainder of this document is divided into sections describing each layer to a reasonable level of detail.

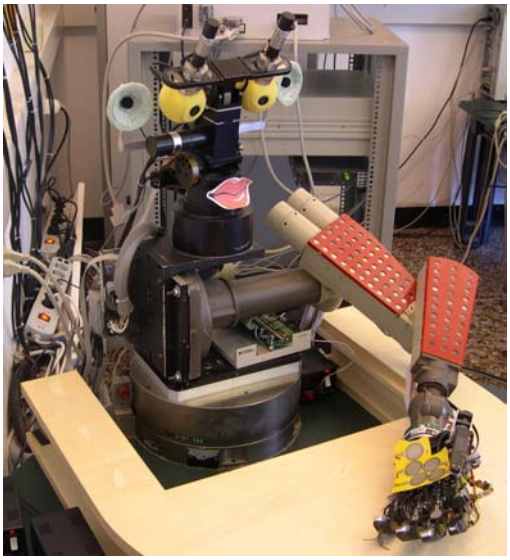
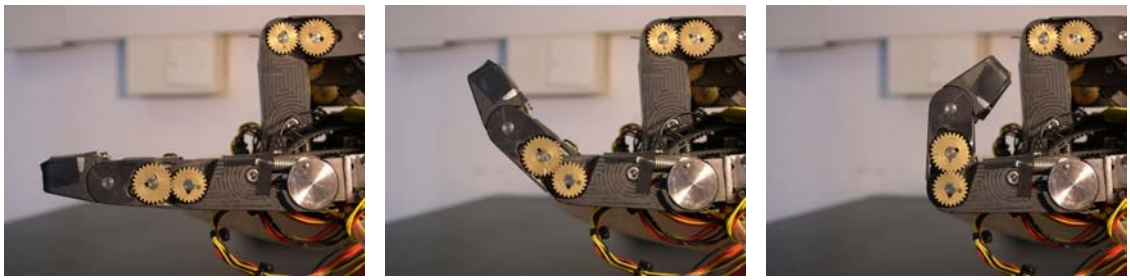


Figure 2: The robotic setup, the Babybot.

2. Babybot – the bare robot hardware

Babybot is an upper torso humanoid robot with a head, a manipulator arm and a hand. The head has five degrees of freedom (DoF). Three of them are associated with the two cameras to achieve independent panning and coupled tilting. The two remaining DoF allow panning and tilting at the level of the neck respectively. The manipulator is a 6 DoF Unimation PUMA 260, mounted with the shoulder horizontal to better resemble a human like arm (see Figure 2). In practice since it lacks a degree of freedom in the shoulder it often requires awkward configurations to reach a point in space.
Attached to the arm end point is a 5 fingered robot hand. Each finger has 3 phalanges; the thumb can also rotate toward the palm. Overall the number of degrees of freedom is hence 16. Since for reasons of size and space it is practically impossible to actuate the 16 joints independently, only six motors were mounted in the palm. Two motors control the rotation and the flexion of the thumb. The first and the second phalanx of the index finger can be controlled independently. Medium, ring and little finger are linked mechanically thus to form a single virtual finger controlled by the two remaining motors. No motor is connected to the fingertips; they are mechanically coupled to the preceding phalanges in order to bend in a natural way as explained in Figure 3.
The mechanical coupling between gears and links is realized with springs. This has the following advantages:

- The mechanical coupling between medium, ring, and small finger is not rigid. The action of the external environment (the object the hand is grasping) can result in different hand postures (see Figure 5).
- Low impedance, intrinsic elasticity. Same motor position results in different hand postures depending on the object being grasped.
- Force control: by measuring the spring displacement it is possible to gauge the force exerted by each joint.



a) b) c)

Figure 3: Mechanical coupling between the second and the third phalanges. The second phalanx of the index finger is directly actuated by a motor. Two gears transmit the motion to the third phalange. The movement is respectively of 90 and 45 degrees.

The robot's sensory systems include vision, audition, touch, proprioception, and inertial sensing. Proprioceptive feedback is achieved by means of the motor optical encoders. Two cameras rotating with the eyes and two microphones attached to the head respectively provide visual and auditory feedback. During the acquisition, images are sampled non-uniformly to mimic the distribution of receptors of the human retina. More pixels are acquired in the central part of the image (fovea) and less in the periphery (mathematically the distribution is approximated by a log-polar function).
The head mounts a three axis gyroscope that provides the robot with an artificial equivalent of the human vestibular system (in Figure 4). This sensor measures inertial information consisting of angular velocity along three orthogonal axes. It can be used for stabilizing the visual world efficiently and in coordinating the movement of the head with that of the eyes.

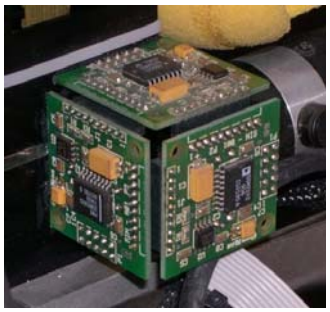
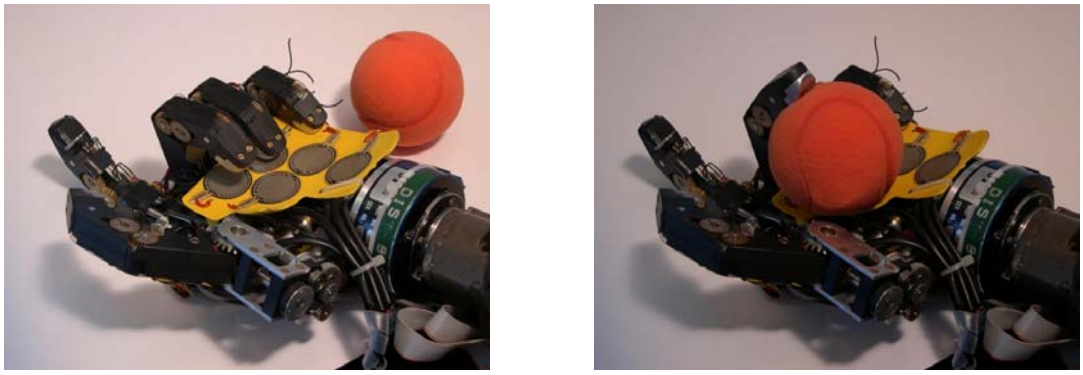


Figure 4: The inertial sensor of the Babybot developed at LIRA-Lab. It consists of three mono-axial sensors arranged along three orthogonal axes.

For the hand, Hall-effect encoders at each joint measure the strain of the hand's joint coupling spring. This information jointly with that provided by the motor optical encoders allows, at least in theory, estimating the posture of the hand and the tension at each joint. In addition, force sensing resistor (FSRs) sensors are mounted on the hand to give the robot tactile feedback. These commercially available sensors exhibit a change in conductance in response to a change of pressure. Although not suitable for precise measurements, their response can be used to detect contact and measure to some extent the force exerted to the object surface. Five sensors have been placed in the palm and three in each finger [apart from the little finger] (see Figure 4).



a) b)

Figure 5: Elastic coupling. a) and b) show two different postures of the hand. Note however that in both cases the position of the motor shafts is the same. In b) the intrinsic compliance of the medium finger allow the hand to adapt to the shape of the object.

Further proprioceptive information is provided to the robot by a strain gauge torque/force sensor mounted at the link between the hand and the manipulator's wrist. This device is a standard JR3 sensor designed specifically for the PUMA flange. It can measure forces and torques along three orthogonal axes (see Figure 5).

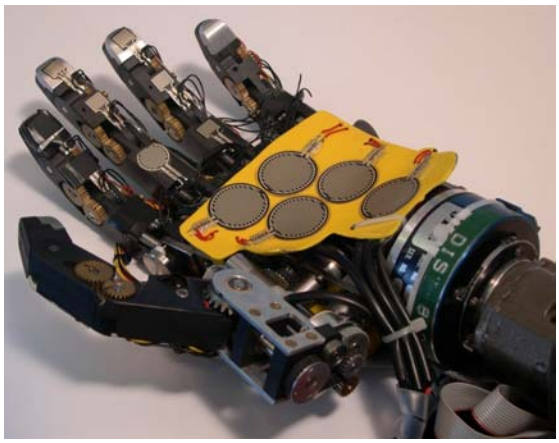


Figure 6: Tactile sensors. 17 Sensors have been placed: five in the palm, three on each finger apart the little finger. In this picture the sensors in the thumb are hidden. The short blue cylinder that links the PUMA wrist to the hand is the J3R force sensor.

3. Interface cards

The robot sensing includes some digitizing interfaces and special signal conversion and conditioning modules. The link between the hardware and the robot is provided through standard PCI/ISA cards, serial ports, etc.

Motor control also requires special hardware to generate the appropriate signal driving the motors. At this level the Babybot follows a very traditional electric motor control approach. The robot is actuated by DC motors. All of them have their specific control card and power amplifier. In the case of the PUMA [the arm] the original (the one provided by Unimation) linear amplifier was modified and interfaced to the standard control card on board a PC. The head and hand joints are controlled through a bank of switching amplifiers (PWM). Each control card has a DSP on board and to some extent they can be programmed to generate the desired control strategies. For example the head is controlled with a high gain controller while for the arm we employed a low-stiffness control schema. Encoder signals are collected by the same control cards. In some cases also analog data is read directly from the motor control boards.

Images are provided by standard CCD color cameras and they are sampled at full frame rate by frame grabbers sporting the common BT848 chipset. The original images are sub-sampled as early into the processing as possible to the desired resolution and format (within the Babybot always in log-polar format). Auditory signals are sampled at up to 44 KHz by a standard sound card. The signal coming from the microphones is amplified and conditioned appropriately before sampling. Tactile sensors have their own microcontroller and AD converter. Digital values are sent to a PC though a serial line. Hall-effect analog signals are sampled by yet another card with a bank of AD converters.

The hardware is somewhat heterogeneous since it evolved from previous implementation of the Babybot. Control cards have different CPUs, sampling rates, DSP and software interface. The same applies to the set of PCs where the hardware is interfaced to. They range from older Pentium to the latest generation PIV. Presently the robot is controlled by 14 machines connected via two separate 100Mbit Ethernet networks. One network is totally dedicated to control signals, the other mostly to visual processing.

4. OS independent software interface

Broadly speaking, the lowest level software components should aim at encapsulating as much as possible the details of the communication and computing layer. The hardware interface should be as seamless integrated into computation as possible. And, finally, most of the code should easily run on different operating systems depending on the requirements of the specific installation. The language of choice in our case was C++. Development tools are Microsoft Visual Studio for Windows and *gcc* for QNX and Linux.

For the task of encapsulating the operating system we naturally relied on existing software. In particular we found convenient to base our implementation on ACE, an open-source library that among many things provides a tiny object-oriented OS wrapper. For more information about ACE please refer to: http://www.cs.wustl.edu/~schmidt/ACE.html.

ACE runs on Windows, Linux, and QNX that were also our target operating systems. Basing our implementation on ACE allowed clearly running all our code on any of these operating

systems. From our point of view ACE provided a common C++ class interface for the communication code and the OS wrapper. Advanced ACE functionalities were not fully exploited. We preferred to take a minimalist approach and rely on the minimum subset of ACE that allowed solving our tasks. Following the open-source philosophy, our software was made freely available on SourceForge:

http://yarp0.sourceforge.net/

The most part of the communication code is profoundly inspired [and recycled] from a previous version developed at MIT (Paul Fitzpatrick. **From First Contact to Close Encounters: A developmentally deep perceptual system for a humanoid robot**. PhD thesis at MIT, 2003) and was tested extensively on the humanoid robot Cog on QNX4.25. The latest implementation has been completely rewritten (using ACE) but it maintains the same high level interface. The distribution is not completely user friendly yet as the only way of obtaining the code is through the CVS interface provided by SourceForge. The library in its entirety has been called YARP (Yet Another Robot Platform).

The communication code is a C++ templatized set of classes contained in a specific static library. The main abstraction for inter-process communication is called a "port". A port template class can be specialized to send any data type across an IP-network relying on a set of different protocols. Depending on the protocol different behaviors can be obtained – the implemented protocols include TCP, UDP, MCAST, QNET[1], and shared memory. A port can either send to many target ports or receive simultaneously from many other ports. A port is an active object: a thread continuously services the port object. Being an active object allows responding to external events at run time, and for example it is possible to send commands to port objects to change their behavior. Commands include connecting to another remote port or receiving an incoming request for connection and since all this can be done at run-time it naturally enables connecting/disconnecting parts of the control system on the fly.

Figure 7 shows an exemplar structure of the port abstraction. Each port is, in practice, a complex object managing many communication channels of the same data type. Each port is potentially both an input and output device although for simplicity of use only one modality is actually allowed in practice. This is enforced by the class definition and the C++ type check. Each communication channel is managed by a "portlet" object within the main port. Different situations are illustrated in Figure 7: for example an MCAST port relies on the protocol itself to send to multiple targets while on the contrary a TCP port has to instantiate multiple portlets to connect to multiple targets. In cases where the code detects that two ports are running on the same machine the IP protocol is replaced by a shared memory connection. In Figure 7 a special portlet is shown: this is indicated as "command receiver". As already mentioned its function is that of receiving commands to connect, disconnect, or generically operating on the port. Further ports can run independently without blocking the calling process (if desired) or they can wake up the calling process on the occurrence of new data. In some cases synchronous communication is allowed (TCP protocol).

[1] QNET is the native QNX network protocol (message passing). It is very efficient and tuned for real-time performance.

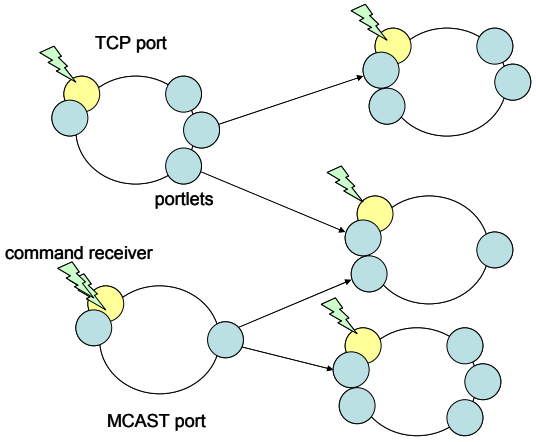


Figure 7: The YARP communication architecture.

Protocols can be intermixed following certain rules. Different operating systems can of course communicate to each other. QNET protocol is an exception and it is only valid within a QNX network.

YARP communication code leads to a componentization of the control architecture into many cooperating modules. The data sent through port can range from simple integral types to complex objects such as arrays of data (images) or vectors. Thus controlling a robot becomes something like writing a distributed network of such modules.

In addition, YARP contains supporting libraries for mathematics and robot type computation (kinematics, matrices, vectors, etc.), image processing (compatible with the Intel IPL library), and general purpose utility classes. We also designed a few modules based on existing Microsoft technology to allow remote controlling Windows machines (this support comes naturally on QNX). In short, these scriptable modules complete seamlessly the architecture allowing the design of scripts to bring up the whole control structure and connect many modules together.

As an aside lately a Matlab interface to ports has been implemented. This allows building Matlab modules (e.g. .m files) that connect to the robot to read/write data. There are basically two advantages: i) complex algorithms can be quickly implemented and tested relying on Matlab existing toolboxes, ii) an additional level of scripting can be realized within Matlab. Matlab provides a relatively efficient and easy to use display library that can be used to visualize the functioning and performance of an ongoing experiment.

In summary, Figure 8 presents schematically the link and dependences between the YARP libraries.

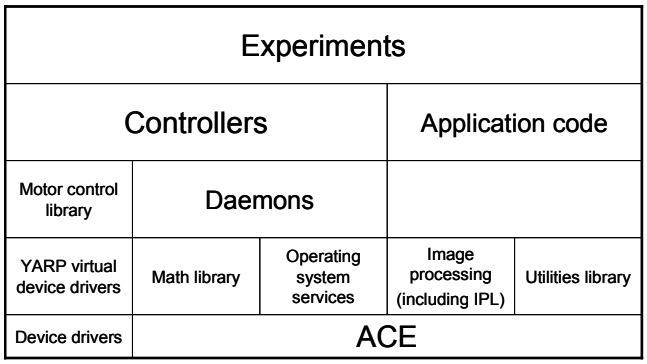


Figure 8 YARP libraries: dependence chart.

5. Robot independent code

One of the goals in writing our control architecture has been that of simplifying the programming of a complex robotic structure such as a humanoid robot. As described in section 3, control cards come in many different flavors and programming them is usually painful. It would be much better if a standardized interface were provided. It would be even better if a suitable abstraction were available.

To solve the first problem we defined a "virtual" device driver interface into YARP. To solve the second, we encapsulated the control of parts of the robot (head, arm, frame grabbers, etc.) into a standardized template class hierarchy.

In short, the virtual device drivers bear much of their structure from the UNIX device drivers. Each card's driver class contains three main methods: Open, Close, and IOCtl. The latter is the core of the interface. Each device accepts a set of messages (with parameters) through the IOCtl call. Each message accomplishes a specific function. Two different control cards supporting roughly the same commands can be easily (as it was done in our setup) mapped into exactly the same virtual device driver structure, although clearly the implementation might differ.

The next layer is a C++ hierarchy of classes which through templates includes both the specification of the controlling device driver (e.g. the head is controlled through a certain control card) and the idiosyncrasies of the particular setup (e.g. wiring of the robot might differ, or initialization might require different calibration procedures). This hierarchy is shown in Figure 9.

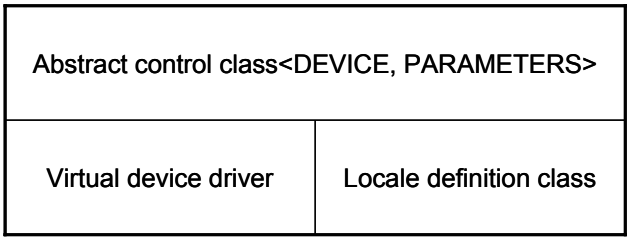


Figure 9: The structure of a control class for a generic device.

6. Robot specific interface

The real "communication" with the robot is carried out through a set of binary modules that use the device driver structure described in section 5. Module customization is at this stage accomplished through configuration files. In the YARP language these modules are called daemons (a term borrowed from UNIX). The daemons directly interact with the remainder of the robot software through YARP ports and in general they export very specialized communication channels. For example the frame grabber has an output port of type "image" and the head control daemon an input port that accepts velocity commands. There are no specific restrictions on the type of ports exported by a daemon since any type of state information about the modules might be required.

Further, some of the daemons accept or send commands of a special type that are generally used to communicate status information. A bus structure based on the MCAST protocol has been implemented to transmit and receive these special messages (called "bottles"). YARP bottles may contain any type of data or even a group of heterogeneous elements of different types. The structure contains identifiers to properly decode messages and interpret the data. YARP bottles create a network within the network of behaviors to realize a high-level control and coordinate a large number of modules.

7. Learning architecture

This layer describes an arrangement of YARP modules that tends to repeat across our robotic architecture. This is not formally into YARP proper but simply an implementation of a particular experiment relying on YARP libraries. Conceptually it forms a layer where to build more sophisticate experiments since for example it provides simple motor control and sensorimotor coordinative behaviors. Overall they could be seen as very high level commands that support positioning, gazing, reaching for visually identified objects, and grasping them.

Grossly speaking, autonomous learning requires a slightly different approach from classical supervised paradigms where data is presegmented and simply fed into a function approximator. Autonomous learning is perhaps closer to reinforcement learning in that it requires action and proper behaviors (exploratory) to gather the training set. Necessarily our architecture will require bootstrapping behaviors supporting building the training set. The question of how much explore and how to get quickly to a solution is an open one in reinforcement learning and unfortunately reinforcement learning itself tend to be difficult, requiring a very large number of samples. In addition, in the case of a real robot we shouldn't allow "spurious" or random control values to get to the low-level controllers; at the basis of any control strategy we should probably have a reasonable "safe" explorative procedure and certainly not a complete random one. Self-supervised procedures can be identified (similar in spirit to feedback error learning) and given the appropriate amount of exploration they can quickly approximate the desired sensorimotor coordination pattern.

When data samples are available in sufficient number with respect to the size of the parameter space of the function approximator of choice the system can start learning and using what has been learnt up to date; necessarily in the long run the influence of explorative behaviors should be reduced. At least two possibilities exist here: learning could be implemented either in batches or fully online. The specific strategy is mostly a function of the algorithm and specific implementation of the function approximation. Inhibition or a functional equivalent should

take care of reducing or mixing up exploration with actual "exploitation" of the acquired behavior.
Our discussion is only focused here on the function approximation problem since a good part of the sensorimotor behaviors can be actually well implemented by mapping sensory values onto motor commands or the opposite or even by a combination of the two (e.g. feedback error learning or distal learning).
Another constraint on the design of explorative behaviors is that they should mostly "explore" the space that will be used in the future. Needless to say that failure to do so might result in very poor performance.
The learning algorithm can be conceptually divided in two parts: the one providing the "learning signals" sometimes called the "critic", and the one doing the behavior called the "actor". This distinction is important in motor control problems since the actor must be extremely fast and should work in a small delay regime. On the other hand, the critic could take even seconds or minutes to process the training data and provide infrequent adjustments to the actor's parameters. We maintained as much as possible (apart from trivial cases) this distinction within our system. This division is to some extent compatible with biological mechanisms of learning being these for example the rates at which synaptic changes and growth processes develops in the brain compared to actual spikes' travel times.

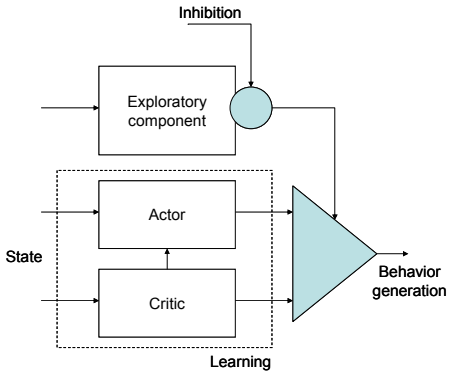


Figure 10: A module for learning sensorimotor coordination.

Figure 10 sketches the modules required for each actual behavior acquisition. At the moment of writing we have only conducted a few experiments with the combination and definition of modules presented here. Examples of explorative components are (at the moment) bounded random behaviors (used when training the hand localization map) or early muscular synergies (simulated muscles of course) connecting and generating activations of muscles spanning different joints and even different limbs. In learning reaching, these synergies can be exploited to bias the exploration space and avoid random movements. Whenever learning relies on multiple cues, such as visual and motor, having an initial coordination (although imprecise) can be advantageous. One net effect would be the reduction of the learning space that needs to be explored before getting to a reasonable behavior. This strategy was used in our previous work (see G.Metta, G.Sandini and J.Konczak. *A Developmental Approach to Visually-Guided Reaching in Artificial Systems.* Neural Networks Vol 12 No 10 pp. 1413-1427 (1999)).
The actor and critic modules in our experiment consisted of a simple batch learning backpropagation neural network. Although, not the best, it proved to be very reliable so far.

Backpropagation has been extensively tested and its behavior very well characterized in literature. Consequently, it is much easier to understand especially when things do not go as expected. The implementation maintains the separation of actor and critic to the point of having a slow batch learning method as critic, and a distinct process providing the behavior. Naturally, given the overall robot architecture, the two modules can be even running on two different machines.
Inhibition and the control of activation and coordination of many behaviors is still argument of further research and no definite implementation has been reached yet. Figure 11 shows the combination of many blocks of this type. In this case too, the realization is completely hypothetical since testing has not been performed yet.

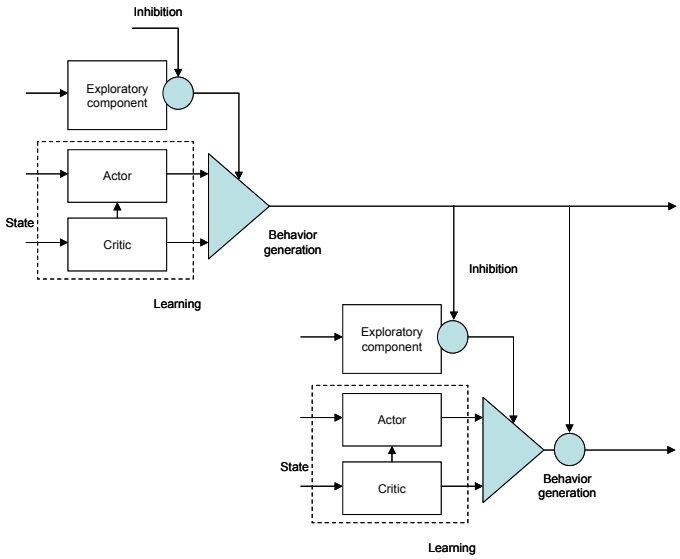


Figure 11: The combination of learning modules in a hypothetical subsumption arrangement.

8. Conclusions

The present document describes the Adapt robotic platform to some detail. However, this is only the starting point where our research of Presence begins. Relying on this platform a model of the development of the multimodal representation of objects in the brain will be implemented and tested. This document relates to the system's architecture deliverable (D5.1) which in fact elaborates further along the definition of a suitable developmental architecture. D5.1 also draws on the theory of intentionality D2.1 which represents the philosophical underpinning of our project. Please, see the technical annex to the contract and/or D2.1 and D5.1 for further information on the rationale of the approach.