Evolving Childhood's Length and Learning Parameters in an Intrinsically Motivated Reinforcement Learning Robot

Massimiliano Schembri **Marco Mirolli** **Gianluca Baldassarre**
Laboratory of Autonomous Robotics and Artificial Life,
Istituto di Scienze e Tecnologie della Cognizione,
Consiglio Nazionale delle Ricerche (LARAL-ISTC-CNR),
Via San Martino della Battaglia 44, I-00185 Roma, Italy
{massimiliano.schembri, marco.mirolli, gianluca.baldassare}@istc.cnr.it

Abstract

The capacity of re-using previously acquired skills can greatly enhance robots' learning speed and behavioral complexity. 'Intrinsically Motivated Reinforcement Learning (IMRL)' is a framework that exploits this idea and proposes to build agents capable of solving several specific tasks by assembling general-purpose building-block behaviors ('skills') previously acquired on the basis of 'intrinsic motivations'. This paper proposes a novel neural-network hierarchical reinforcement-learning architecture which exploits 'evolutionary robotics (ER)' techniques that not only allow tackling important limits of IMRL, as shown in previous papers, but they also allow investigating two other important issues, namely: (1) the optimization of the parameters that regulate the architecture's learning processes; (2) the optimization of the time the architecture dedicates to the acquisition of the skills' repertoire. These two issues are investigated here through a simulated robot engaged in solving compositional path-following navigation tasks. The results obtained indicate that the proposed approach allows obtaining a remarkable improvement of performance of the architecture, while at the same time decreasing the time the system needs to learn the skills, with respect to cases where hand-tuned parameters are used.

1. Introduction

Current robots are typically directly programmed to solve just one task at a time in one environment. This makes them severely limited in that they cannot cope with any other task nor with other kinds of environments. Recently, in both the machine learning and the developmental/epigenetic robotics communities, a number of proposals have been put forward for solving such limitations by relying on autonomous robot development (Kaplan and Oudeyer, 2003; Schmidhuber, 1991; Weng et al., 2001; Huang and Weng, 2002; Marshall et al., 2004; Oudeyer et al., 2007). The basic idea behind such proposals is endowing robots with developmental programs which allow them to learn, through an autonomous interaction with the environment, general-purpose building-block behaviors which might successively be 'assembled' to tackle several specific tasks.

One of the most promising frameworks that has been proposed to this purpose is 'Intrinsically Motivated Reinforcement Learning (IMRL; see Barto et al., 2003; Stout et al., 2005). IMRL is based on the idea that natural organisms, especially the most sophisticated ones like humans and primates, are not driven only by basic *extrinsic* motivations directly related to survival (e.g. for eating, drinking, avoiding predation and mating), but also by *intrinsic* motivations which drive them to accomplish exploratory behaviors directed to acquire skills and knowledge (White, 1959; Berlyne, 1960). The adaptive value of these behaviors — and of the motivations behind them — resides in that they permit the acquisition of general-purpose skills which can be used, when needed, for accomplishing a number of different tasks directly related to survival and reproduction.

Notwithstanding its undeniable appeal, at present the IMRL framework has two important drawbacks. First, as they rely on the reinforcement learning framework of 'options' (Sutton and Singh, 1999), current implementations of IMRL assume high-level abstract representations of states and actions, and hence they can be applied only to agents acting in abstract simple grid-world environments. As also recognized by Barto and coworkers (Stout et al., 2005), this is a serious limit and it is not clear whether and how IMRL might be used in robotic scenarios. Second, the 'salient events' which initiate and drive the development of basic skills must be explicitly specified by the programmer: this requires the introduction of a significant amount of assumptions about the tasks at hand and their possible solutions, thus considerably reducing both the generality of the approach (for each problem the appropriate salient events must be specified) and agents' autonomy.

Recently, Schembri et al. (2007b) proposed an architecture, based on a hierarchical actor-critic reinforcement-learning model (Sutton and Barto, 1998), which overcomes both these limits of IMRL by integrating it with 'Evolutionary Robotics (ER)' framework (Nolfi and Floreano, 1999). The architecture, described in detail in Sec. 2.2, is formed by a number of 'experts', which learn basic skills, and a 'selector', which learns to select the expert which is most appropriate for the current situation (cf. Baldassarre, 2002). In contrast to the IMRL implementations proposed so far, the use of neural-networks allows the architecture to be applicable to continuous and noisy environments typical of robotic tasks. Furthermore, the architecture acquires basic skills on the basis of evolved 'reinforcers', that is neural networks that assign a reward value to explored states, instead of hardwired salient events, thus enhancing both the generality of the approach and the overall autonomy of the system. The model is able to acquire general-purpose skills on the basis of intrinsic *evolved* motivations during a 'childhood' phase, and to solve several different robotic tasks by combining such sills during a successive 'adulthood' phase.

In a second work, Schembri et al. (2007a) compared the performance of the architecture with other systems in which various components of the architecture are either trained during lifetime or evolved through a genetic algorithm. The results were quite encouraging: the versions of the architecture using both evolution and learning significantly outperformed the versions using either one of the two. Furthermore, among the systems using both evolution and learning, the one evolving internal reinforcers driving the acquisition of building-block skills had a higher evolvability than those directly evolving the related behaviors.

The present work tries to push the idea of exploiting ER techniques for optimizing the learning capabilities of an intrinsically motivated robot even further. Any reinforcement learning architecture has a number of parameters that regulate its learning processes. Typically, the values of these parameters are decided by the programmer according to intuitive heuristics and non-systematic trial-and-error optimization processes. The use of ER opens up the possibility of using a genetic algorithm for finding optimal sets of the parameters regulating reinforcement learning processes (to the best of the authors' knowledge, the only work that exploited this idea is Eriksson et al., 2003).

Furthermore, as the architecture studied here assumes that the robot's life is divided in a childhood and an adulthood phase, there is another fundamental parameter which in the previous two works (Schembri et al., 2007a,b) was set by trial-and-error processes and hence which could be optimized through the genetic algorithm: the length of childhood, that is the number of steps during which the robot trains its experts on the basis of intrinsic motivations. Both for robots and for real organisms, there is clearly a trade-off between short and long childhood phases. If childhood is too short, an agent cannot learn enough, and all of its basic abilities can only be genetically inherited. On the other hand, childhood has clear costs: for an organism, it is time during which the organism is not autonomous and must be fed and protected by its parents; for a robot, it is time which is not spent for solving the tasks the robot has been designed for. In order to test whether our system could be further optimized, in this paper we use the genetic algorithm not only to evolve the reinforcers driving the acquisition of basic skills, but also the length of childhood and the learning parameters of the reinforcement learning algorithm.

The rest of the paper is organized as follows. Sec. 2.1 describes the robotic setup and the simulated experiment used to test the model. Sec. 2.2 contains a detailed description of the model. Sec. 2.3 describes the used genetic algorithm. Sec. 3. reports the main results. Finally, Sec. 4. concludes the paper.

2. The setup

2.1 The simulated environment and robot

The simulated robot is a 'wheelchair' mobile robot with a 30 cm diameter equipped with a camera assumed to look at a portion of the ground measuring $24 \times 8cm$ located just in front of the robot. In each cycle the robot's input is furnished by a vector $\mathbf{x}$ of $12 \times 3 = 36$ binary values that corresponds to the activation of the RGB receptors sampling the camera's image on the vertex of a 6×2 regular grid (see Fig. 2). The robot's motor system is driven by setting the orientation variation within $[-30, +30]\, deg$, and the translation speed within $[0, 2]\, cm$.

The environment is a square walled arena with a regularly textured floor (Fig. 1). The robot's life is divided into two phases: 'childhood' and 'adulthood'. During childhood the robot learns a set of basic sensorimotor skills based on its intrinsic motivational system. Childhood's length is particularly important in this work as in some experiments its length was evolved and how this affected the parameters was studied (see Sec. 2.3). During adulthood,

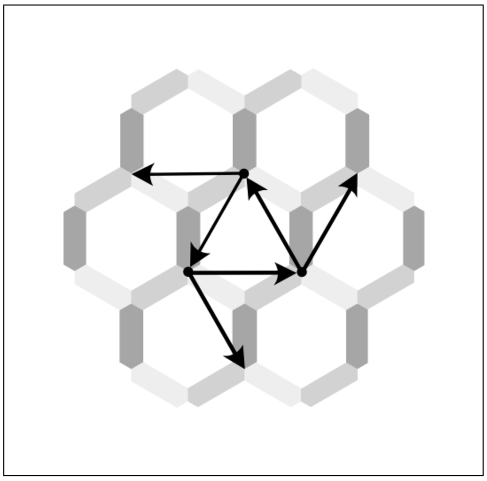

Figure 1: The walled arena and adulthood tasks. Hexagons with colored edges are drawn on the black ground (dark gray: blue; gray: red; light gray: green; white: black). Arrows represent the six adulthood different tasks: each arrow's tail and head indicate, respectively, the starting and the target position of a task.

the robot learns to combine the acquired skills in order to accomplish six different tasks. In each of these tasks the robot has to reach a given target location (having a 26*cm* diameter) starting from a particular initial position (Fig. 1). During each task, every time the robot reaches the target it receives a reward and is set back to the initial position.

2.2 The model

The controller of the robot is a hierarchical modular neural network (Fig. 2) formed by a selector and a number of experts. The selector and each expert are formed by a neural-network implementation of the actor-critic model (Sutton and Barto, 1998). This model is composed of two neural components, an 'actor' and a 'critic', and it is capable of learning to select appropriate actions in order to maximize the sum of the future discounted rewards ('discounted' means that the same reward is given less importance if received later in time, see below). The actor learns to associate suitable actions with the perceived states of the environment on the basis of the critic's evaluation. The critic learns to associate evaluations with single visited states on the basis of the rewards experienced after these visits, and produces a one-step judgment of the actor's actions on the basis of the evaluations of couples of states visited in sequence.

The experts are now described in detail. Each expert e is formed by three components: a 'reinforcer', an 'actor' and a 'critic' . The reinforcer is a 2-layer neural network that with its 1×36 vector of weights $\mathbf{w}_e^r$ maps the retina activation $\mathbf{x_t}$ at time t to the activation of a sigmoid unit that ranges in $[-1, +1]$ and encodes the expert's reward r_{et} (note that in the paper the symbols at the exponent do not represent indexes but qualify the main symbol):

$$r_{et} = 2 \cdot \sigma \left[\mathbf{w}_e^r \mathbf{x_t}\right] - 1 \tag{1}$$

where $\sigma[.]$ is the standard sigmoid function. Note that $\mathbf{w}_e^r$ are evolved, as illustrated in Sec. 2.3.

An expert's actor is a 2-layer neural network that with its 2×36 matrix of weights $\mathbf{w}_e^a$ maps the retina activation to two sigmoid units $\mathbf{m}_e$:

$$\mathbf{m}_{et} = \sigma \left[\mathbf{w}_e^a \mathbf{x_t}\right] \tag{2}$$

In order to obtain the performed actions (cf. Mannella and Baldassarre, 2007), the activation of the two units is added a Gaussian noise to obtain two values $\mathbf{a}_{et}$ ranging within $[0, +1]$ (noise values are redrawn until the values respect this range):

$$\mathbf{a}_{et} = \mathbf{m}_{et} + \epsilon\left[0, \rho\right] \tag{3}$$

where $\epsilon\left[0, \rho\right]$ is a Gaussian noise with zero mean and standard deviation ρ initially set to 0.3 and linearly reduced to zero during childhood. The values $\mathbf{a}_{et}$ are then mapped onto the orientation-variation and translation commands issued to the motor system.

The weights of the actor are updated using the following formula:

$$\Delta \mathbf{w}_e^a = \eta^{ae} \cdot s_{et} \cdot (\mathbf{a}_{et-1} - \mathbf{m}_{et-1}) \cdot \\ \cdot \sigma' \left[\mathbf{w}_e^a \mathbf{x_{t-1}}\right] \cdot \mathbf{x}_{t-1} \tag{4}$$

where η^{ae} is the learning rate of the experts' actors, s_{et} is the expert's critic surprise (see below) and $\sigma'[.]$ is the derivative of the sigmoid function. The effect of this learning rule is to lead the means $\mathbf{m}_{et-1}$ of actions toward their noisy values $\mathbf{a}_{et-1}$ if $s_{et} > 0$ and away from them if $s_{et} < 0$.

Note that the experts' actor and critic are trained only during childhood, while in adulthood the experts skills are fixed and are recombined by the selector in order to achieve 'externally' rewarded goals.

The experts' critic is mainly formed by an 'evaluator' which is a 2-layer neural network that with its 1×36 vector of weights $\mathbf{w}_e^v$ maps the retina activation to a linear output unit encoding the expert's evaluation v_{et} of the perceived state:

$$v_{et} = \mathbf{w}_e^v \mathbf{x_t} \tag{5}$$

The critic uses the evaluator's evaluations, together with the reward provided by the expert's reinforcer, to compute the expert's surprise s_{et} as follows:

$$s_{et} = (r_{et} + \gamma^e \cdot v_{et}) - v_{et-1} \tag{6}$$

where γ^e is the experts' discount coefficient used to weight the future rewards.

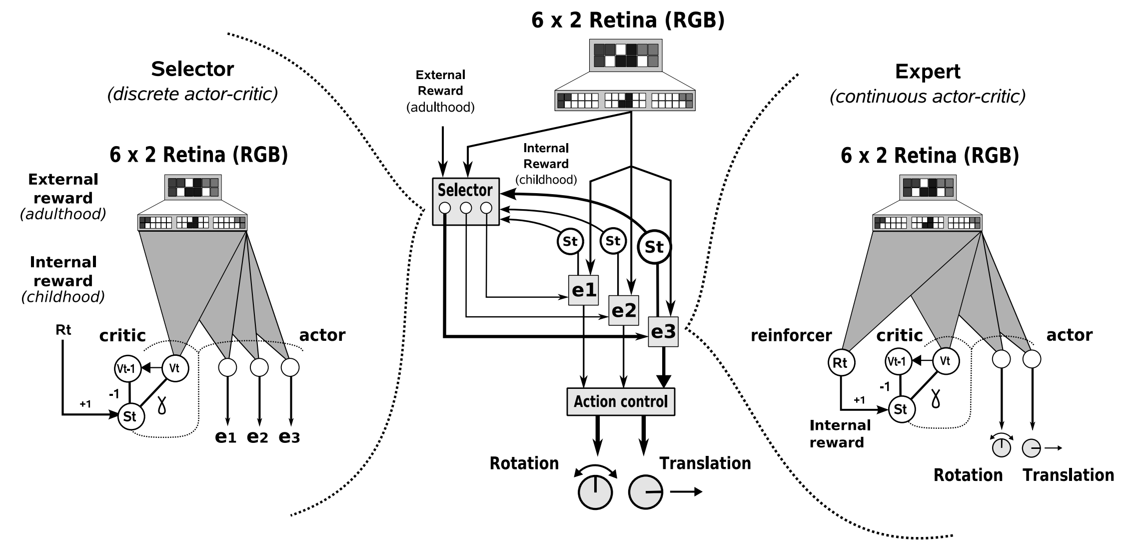

Figure 2: Center: the whole architecture. Left: the selector's architecture. Right: one expert's architecture.

The weights of the evaluator are updated, on the basis of the surprise signal, using a Temporal Difference (TD) learning rule (Sutton and Barto, 1998):

$$\Delta \mathbf{w}^{v}_{e} = \eta^{ve} \cdot s_{et} \cdot \mathbf{x}_{t-1} \tag{7}$$

where η^{ve} is the learning rate of the experts' evaluators.

The selector is now described in detail. The selector is formed by two components, the 'actor' and the 'critic'. At each time the actor selects the expert that has the control and trains its actor and evaluator (only during childhood). The actor is a 2-layer neural network that with its 3×36 matrix of weights $\mathbf{w}^{a}$ maps the retina activation to three (as many as the number of experts) sigmoid output units $\mathbf{m}$:

$$\mathbf{m}_{t} = \sigma \left[\mathbf{w}^{a} \mathbf{x_{t}} \right] \tag{8}$$

These activations are used as pseudo-probabilities to compute the probabilities $\mathbf{p}_{t}$ used to randomly select the expert that takes control:

$$\mathbf{p}_{t} = \mathbf{m}_{t} / \left(\mathbf{u}^{T} \mathbf{m}_{t} \right) \tag{9}$$

where $\mathbf{u}$ is a 3-element unit vector.

The weights of the actor, in particular only those related to the 'winning' (selected) expert, denoted with the 1×36 vector $\mathbf{w}^{aw}$, are updated as follows:

$$\Delta \mathbf{w}^{aw} = \eta^{as} \cdot s^{s}_{t} \cdot \sigma' \left[\mathbf{w}^{aw} \mathbf{x_{t-1}} \right] \cdot \mathbf{x}_{t-1} \tag{10}$$

where η^{as} is the learning rate of the selector's actor and s_{t} is the surprise of the selector's critic (see below). The effect of this learning rule is an increase of the selected expert's m_{wt-1} if $s_{t} > 0$ and a decrease of it if $s_{t} < 0$.

The selector's critic is mainly formed by an 'evaluator' which is a 2-layer neural network that with its 1×36 vector of weights $\mathbf{w}^{v}$ maps the retina activation to a linear output unit encoding the selector's evaluation v_{t} of the perceived state:

$$v_{t} = \mathbf{w}^{v} \mathbf{x_{t}} \tag{11}$$

The critic uses the evaluator's evaluations, together with the reward r_{t} (given its importance, r_{t} is discussed in detail below), to compute the selector's surprise s_{t} as follows:

$$s_{t} = (r_{t} + \gamma^{s} \cdot v_{t}) - v_{t-1} \tag{12}$$

where γ^{s} is the selector's discount coefficient.

The weights of the evaluator are updated, on the basis of the surprise signal, using a TD learning rule (Sutton and Barto, 1998):

$$\Delta \mathbf{w}^{v} = \eta^{vs} \cdot s_{t} \cdot \mathbf{x}_{t-1} \tag{13}$$

where η^{vs} is the selector evaluator's learning rate.

The reinforcement signal r_{t} used by the selector is very important for the topic of intrinsic motivations, and is computed in different ways during childhood and adulthood. During childhood $r_{t} = s_{wt}$, that is the reward is equal to the surprise of the selected expert. This implies that the selector uses an *intrinsic* reward not directly related to the achievement of specific *pragmatic goals* but to the acquisition of knowledge and skills, that is to *epistemic goals*. Indeed, as *the surprise of an actor-critic model is a good indicator of its learning progress*, it can be used to train the selector to give control to the expert which is expected to learn at the maximum rate in a certain state (this might be an important insight that will be further investigated in the future). During adulthood r_{t} is set to 1 when the robot achieves the target location of the task and to 0 otherwise. This implies that this is a standard goal-related *extrinsic* reward.

2.3 The genetic algorithm

The genetic algorithm uses a population of 50 individuals, each encoding the connection weights of the three experts' reinforcers as real variables (the initial values are randomly drawn in $[-1.0, +1.0]$). In a first condition of the experiment, the parameters are set as indicated in the last column of Tab. 1 (cl denotes the childhood's length). This parameters have been 'manually optimized' by running some pilot experiments, and were also used in Schembri et al. (2007a) to compare the version of the architecture presented here with other versions of the architecture in which some other system's components were evolved together with the reinforcers. In a second condition of the experiment such parameters are evolved as values ranging in $[0, 1]$ (cl was then mapped onto 600,000). For each of these two conditions the experiment is run 20 times with different seeds of the random number generator and each time evolution lasts 100 generations. In a third condition the same parameters of the second conditions are evolved with the exception of cl that is set at 14 different fixed values, namely $100 \cdot 2^i, i = 0, 1, 2, ..., 13$. For each of these values, five runs of 100 generations each are run using different 'seeds'. The adulthood's length al is set to 600,000 in all three conditions.

The fitness f is computed as the number of times that the robot reaches the target divided by the theoretical maximum achievable if the robot follows the straight lines indicated in Fig. 1 at maximum speed. In the second condition a cost linearly related to the childhood's length is introduced to have a 'penalized' fitness pf and induce the algorithm to optimize cl:

$$pf = f - (cl/al) \tag{14}$$

At the end of each generation the best 10 individuals are selected and each generates 5 offspring. Each weight of the five offspring of each parent (with the exception of the first one to have 'elitism') is mutated with a probability of 10% by *adding* to it a random value uniformly drawn in $[-1.0, +1.0]$. In the second and third condition also the aforementioned evolved parameters are mutated, with a probability of 10%, by *substituting* to them a random value uniformly drawn in $[0, +1.0]$.

3. Results

Fig. 3 reports the fitness along the generations of the evolution of the best individual in each generation and the average fitness of whole population, for both the first and second condition of the experiment. The figure shows that the best individuals of the condition with evolved parameters reach a level (about 0.78) that is remarkably higher (40%) than the level of the condition with hand-tuned parameters (about 0.55). On the other side the average fitness of such condition is only slightly higher than the other condition. The reason of this is that the mutations of the parameters can easily have catastrophic effects. Since the mutation of each of the seven parameters is 10%, and so the chances that an individual is mutated is quite high, this have a strong effect on the average fitness. Another interesting fact emerging from these simulations is that, as indicated in Schembri et al. (2007a), they confirm that the architecture has a high evolvability when the parameters are set to fixed values (notice how in this condition the 'best' and 'average' fitness increase in few generations). On the contrary, evolution is rather slower when the parameters are evolved, indicating that the search in their space is not easy.

Fig. 4 shows three examples of the behavior of the robot during adulthood. In general the robot solves each navigation task by composing the basic skills learned in childhood. Sometimes evolution produces a set of reinforcers which lead experts to specialize in following a specific color trail (as in fig. 4a). More frequently the set of emerged basic skills is not as intuitive as expected and the resulting compositional strategy is difficult to interpret (fig. 4b). In some other cases a single expert is able to accomplish the whole navigation task (fig. 4c). An extensive behavior analysis is currently being carried out to clarify and quantify these aspects.

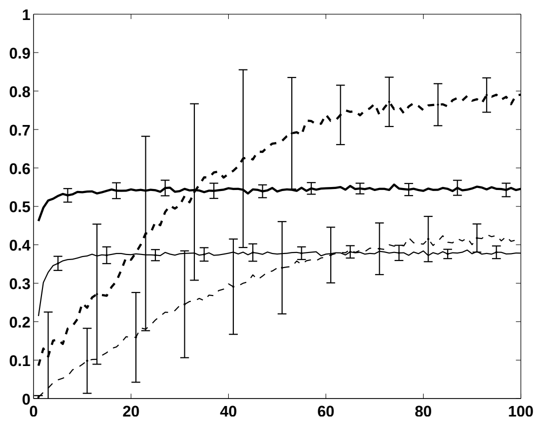

Figure 3: Fitness curves (y-axis) related to the best individuals (bold lines) and the average of populations (thin lines) during evolution's generations (x-axis) of the simulations run with evolved parameters (dashed lines) and hand-tuned parameters (continuous lines). Each curve is the average of 20 different simulation runs. Note that the fitness' measures of the condition with evolved parameters are related to f and not pf to ease comparisons.

The parameters evolved are indicated in Tab. 1. The most important fact is that life is sensibly shorter (34,993 cycles) than the value that was manually optimized (150,000 cycles). The reason is likely that the combination of parameter found by the genetic algorithm are particularly well suited to allow

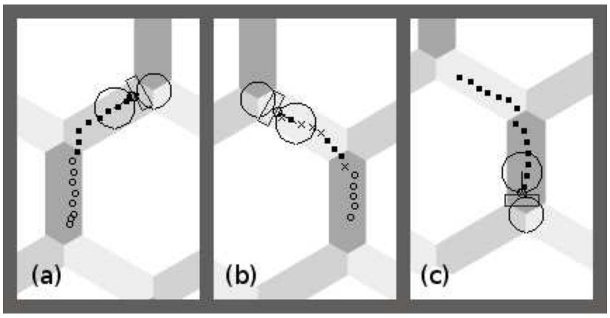

Figure 4: Examples of strategies emerged in evolution. Small symbols indicate which expert is selected in a particular time step (sampled every five simulation steps). (a) Example of a compositional strategy in which each expert is specialized in following a single color trail. (b) Compositional strategy based on less-clearly specialized experts. (c) Strategy based on one expert specialized in avoiding one color trail.

a fast learning.

Passing to analyze the differences between the evolved and the hand-tuned parameters, the most interesting result is the imbalance between the learning rates of the actor and the critic of both the selector and the experts. These were manually set at the same values whereas the genetic algorithm found quite different values, namely values from ten to twenty times lower for the critic than for the actor. The reason of this unexpected outcome is probably the fact that the evaluators' neural networks have linear output units whereas the actors' neural networks have sigmoidal output units. Since this implies that the derivative of the output units' used in the learning rules (cf. Eq. 4 and Eq. 10) is respectively equal to 1 or ranges within $[0, 0.25]$, the genetic algorithm found suitable learning rates to compensate this difference. This result is quite general as in neural-network implementations of actor-critic reinforcement learning system it is quite common to use neural networks with linear units to implement evaluators and neural networks with non-linear units to implement actors (included the popular 'soft-max function', see Sutton and Barto, 1998).

Another interesting fact is that the γ of the selector is higher (implying a lower discount of future events) than that of the experts. This reflects the intuition we had when we manually tuned the parameters for which the assemblage of experts takes place at a bigger spatial and temporal granularity with respect to the assemblage of primitive actions composing the experts' behaviors. However, also in this case the genetic algorithm found different (lower) and probably more effective levels of the parameters with respect to those we found by trial-and-error.

The length of childhood is particularly important as it constraints the possibilities of the system to acquire accurate building-block behaviors. Given a particular setup and typology of tasks as those considered here, it is useful to have a technique that allows drawing a quantitative picture of the relation existing between such length and accuracy of skills. In the third condition of the experiment the architecture's parameters were evolved while systematically setting the childhood's length to fixed values. Fig. 5, which reports the values of the fitness obtained at fixed childhood lengths, indicates that beyond a childhood's length of about 6,400 the system reaches a rather high level of fitness indicating that this is a minimal childhood's length beyond which the system succeed to develop a repertoire of quite reliable skills thanks to the evolved parameters (note that this implies that the system takes only about 1,050 cycles, on average, to train each of the six experts). The figure also shows that the system achieves a steady-state fitness with a childhood's length ranging between 25,600 and 51,200. This is a notable result as the optimized childhood's length emerged in the second condition of the experiment is equal to 34,993 (see Tab. 1).

Table 1: The mean and standard deviation of evolved parameters, and the hand-tuned parameters.

Parameter	*Mean*	*Std*	Hand-tuned
cl	34,993	13,708	150,000
γ^s	0.9522	0.0630	0.99
η^{as}	0.7016	0.1811	0.05
η^{vs}	0.0351	0.0156	0.05
γ^e	0.6184	0.1945	0.90
η^{ae}	0.6214	0.1827	0.01
η^{ve}	0.0402	0.0296	0.01

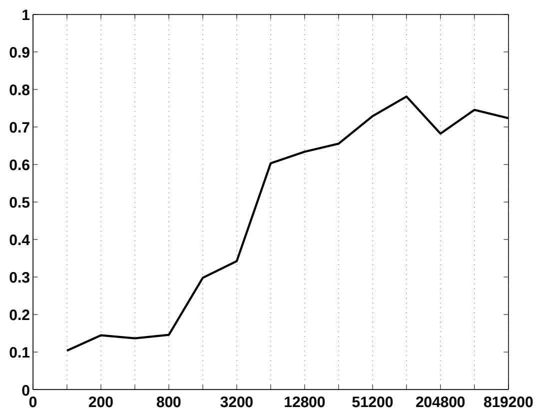

Figure 5: The fitness (y-axis) with different childhood lengths (x-axis). Each value of fitness is an average of 5 different simulation runs.

These results raise an interesting question: do the parameters vary with increasing childhood's lengths? Fig. 6 and Tab. 2 answer this question by reporting the values of parameters that the genetic algorithm found with different childhood lengths. Limiting the analysis to the values of childhood's length that produced a high fitness (i.e. $\geq 6,400$), the results indicate that a longer childhood tends to be associated with lower learning rates of the experts' actors and evaluators and the selector's evaluator. The reason of these correlations is likely that when childhood is longer the genetic algorithm can set lower learning rates as this eventually yields more accurate behaviors. A longer childhood tends also to be associated with a lower experts' discount factor, but the reason of this is not clear.

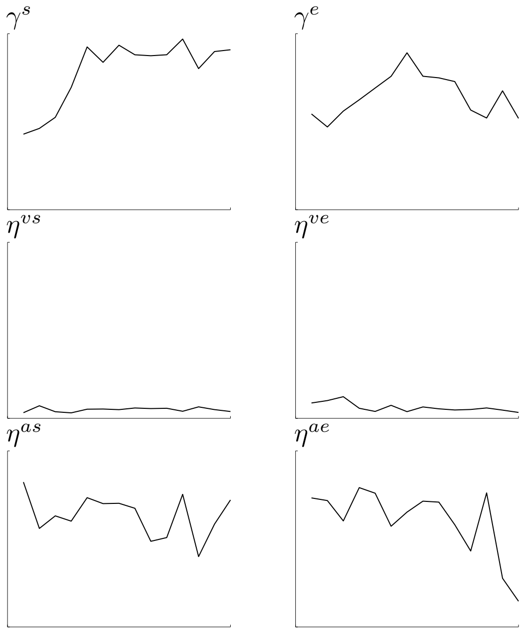

Figure 6: The evolved parameters (y-axis: this ranges in $[0, 1]$) with different childhood's lengths (x-axis). Each value of fitness is an average of 5 different simulation runs.

Table 2: Analysis of the linear correlation existing between the childhood's length (varing from 6,400 cycles to 819,200) and the evolved parameters. r: correlation coefficient; r^2: determination coefficient of linear regression; t: t-Student value on statistical significance of r; p: statistical significance.

	γ^s	η^{as}	η^{vs}	γ^e	η^{ae}	η^{ve}
r	0.012	0.110	-0.193	-0.413	-0.669	-0.194
r^2	0.000	0.012	0.037	0.170	0.448	0.034
t	0.075	0.684	-1.213	-2.792	-5.551	-1.222
p	0.940	0.637	0.232	0.008	0.000	0.229

4. Conclusions

This paper presented a neural-network two-level hierarchical reinforcement-learning architecture for Intrinsically Motivated Reinforcement Learning (IMRL) that exploits Evolutionary Robotic (ER) techniques to evolve various parameters of the learning algorithm. Two previous works (Schembri et al., 2007a,b) showed that ER and the use of neural networks allow the architecture to tackle two important limits of the models proposed so far within the Intrinsically Motivated Reinforcement Learning (IMRL) framework, namely (a) their applicability limited to problems with discrete abstract representations of states and actions, and (b) their need to be furnished 'salient events' by the programmer in order to be capable of learning the repertoire of skills. This work extended this research in two novel directions by further exploiting the ER framework, in particular it used a genetic algorithm to both optimize the learning parameters of the architecture and to optimize the time it spent in learning building-block behaviors. The viability of the proposed solutions was proved by using the architecture as the controller of a simulated robot engaged in solving different navigation path-finding tasks. In this respect, a future real robot implementation of the architecture does not seem to be particularly problematic at first sight as the use of reactive neural networks should help to tackle the usual problems of noise affecting robotics setups (e.g. the variability of the camera's luminosity). One notable exception would be the technical problem of having to set the robot back to the starting positions at each trial of the adulthood learning.

The results presented in the paper showed that the use of the genetic algorithm to evolve the learning parameters can lead to a notable increase of performance, about 40% here, with respect to the cases in which the parameters are tuned by hand. Remarkably, this increase in performance was obtained here while contemporary decreasing, through evolution, of about 75% the time that the system dedicates to learn the basic skills.

With respect to the evolution of the (costly) time spent by the system in acquiring the repertoire of skills (childhood's length), the study indicates a technique that can be used to identify: (a) the minimum amount of such time beyond which the system is capable of developing a repertoire of skills with a *satisfying* accuracy (say about 75% of the maximum one); (b) the time beyond which it achieves the *maximum* possible accuracy. The results of these experiments also showed that, if one considers childhood's lengths beyond which fitness is stable, lower learning rates tend to be associated with a longer childhood.

To the authors' knowledge, this is the first research where childhood's length is evolved and its effects on learning are studied in a systematic fashion. This type of simulations might also be used, in future work, to investigate the emergence of childhood's length that real organisms invest in playing and in the acquisition of skills while relying on parents for protection and food.

Overall these results confirm that IMRL architectures can greatly benefit if developed within an ER framework. In fact ER allows evolving aspects of the architectures, such as the learning parameters, that might be very hard to be tuned by hand as they produce highly non-linear and unpredictable effects.

Acknowledgements

This research was supported by the EU Projects *ICEA*, contract no. FP6-IST-027819-IP, and *MindRACES*, contract no. FP6-511931-STREP.

References

Baldassarre, G. (2002). A modular neural-network model of the basal ganglia's role in learning and selecting motor behaviours. *Journal of Cognitive Systems Research*, 3:5–13.

Barto, A. G., Singh, S., and Chentanez, N. (2003). Intrinsically motivated learning of hierarchical collections of skills. In *Proceedings of the 3rd International Conference on Development and Learning.*

Berlyne, D. (1960). *Conflict, Arousal, and Curiosity.* McGraw Hill, New York.

Eriksson, A., Capi, G., and Doya, K. (2003). Evolution of meta-parameters in reinforcement learning algorithm. In *Intelligent Robots and Systems, 2003. (IROS 2003). Proceedings. 2003 IEEE/RSJ International Conference on*, volume 1, pages 412–417.

Huang, X. and Weng, J. (2002). Novelty and reinforcement learning in the value system of developmental robots. In Prince, C. G., Demiris, Y., Marom, Y., Kozima, H., and Balkenius, C., (Eds.), *Proceedings Second International Workshop on Epigenetic Robotics: Modeling Cognitive Development in Robotic Systems*, pages 47–55, Edinburgh, Scotland.

Kaplan, F. and Oudeyer, P.-Y. (2003). Motivational principles for visual know-how development. In Prince, C. G., Berthouze, L., Kozima, H., Bullock, D., Stojanov, G., and Balkenius, C., (Eds.), *Proceedings Third International Workshop on Epigenetic Robotics: Modeling Cognitive Development in Robotic Systems 101*, pages 73–80, Boston, MA, USA.

Mannella, F. and Baldassarre, G. (2007). A neural-network reinforcement-learning model of domestic chicksthatlearn to localize the centre of closed arenas. *Philos Trans R Soc Lond B Biol Sci*, 362(1479):383–401.

Marshall, J. B., Blank, D., and Meeden, L. (2004). An emergent framework for self-motivation in developmental robotics. In *Proceedings of the 3rd International Conference on Development and Learning (ICDL 2004)*, pages 104–111, Salk Institute, San Diego.

Nolfi, S. and Floreano, D. (1999). Learning and evolution. *Autonomous Robots*, 7(1):89–113.

Oudeyer, P.-Y., Kaplan, F., and Hafner, V. (2007). Intrinsic motivation systems for autonomous mental development. *IEEE Transactions on Evolutionary Computation*, 11(6).

Schembri, M., Mirolli, M., and Baldassarre, G. (2007a). Evolution and learning in an intrinsically motivated reinforcement learning robot. In *Proceedeng of the 9th European Conference on Artificial Life*. Springer.

Schembri, M., Mirolli, M., and Baldassarre, G. (2007b). Evolving internal reinforcers for an intrinsically motivated reinforcement-learning robot. In *6th IEEE International Conference on Development and Learning (ICDL2007).*

Schmidhuber, J. (1991). A possibility for implementing curiosity and boredom in model-building neural controllers. In Meyer, J. A. and Wilson, S. W., (Eds.), *Proc. of the International Conference on Simulation of Adaptive Behavior: From Animals to Animats*, pages 222–227, Cambridge, Massachusetts/London, England. MIT Press/Bradford Books.

Stout, A., Konidaris, G. D., and Barto, A. G. (2005). Intrinsically motivated reinforcement learning: a promising framework for developmental robot learning. In *Proceedings of the AAAI Spring Symposium on Developmental Robotics*, Stanford University, Stanford, CA.

Sutton, R. S. Precup, D. and Singh, S. (1999). Between mdps and semi-mdps: a framework for temporal abstraction in reinforcement learning. *Artificial Intelligence*, 112:181–211.

Sutton, R. and Barto, A. (1998). *Reinforcement learning an introduction.* MIT Press, Cambridge, MA.

Weng, J., McClelland, J., Pentland, A., Sporns, O., Stockman, I., Sur, M., and Thelen, E. (2001). Autonomous mental development by robots and animals. *Science*, 291(5504):599–600.

White, R. (1959). Motivation reconsidered: the concept of competence. *Psychological Review*, 66(5):297–333.