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To cite this version:
Jean-Baptiste Mouret, Stéphane Doncieux. Overcoming the bootstrap problem in evolutionary robotics using behavioral diversity. Eleventh conference on Congress on Evolutionary Computation (CEC’09), 2009, Trondheim, Norway. IEEE Press, pp.1161–1168, 2009. <hal-00473147>

HAL Id: hal-00473147
https://hal.archives-ouvertes.fr/hal-00473147
Submitted on 14 Apr 2010

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Overcoming the bootstrap problem in evolutionary robotics using behavioral diversity

Jean-Baptiste Mouret

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Abstract—The bootstrap problem is often recognized as one of the main challenges of evolutionary robotics: if all individuals from the first randomly generated population perform equally poorly, the evolutionary process won’t generate any interesting solution. To overcome this lack of fitness gradient, we propose to efficiently explore behaviors until the evolutionary process finds an individual with a non-minimal fitness. To that aim, we introduce an original diversity-preservation mechanism, called behavioral diversity, that relies on a distance between behaviors (instead of genotypes or phenotypes) and multi-objective evolutionary optimization.

This approach has been successfully tested and compared to a recently published incremental evolution method (multi-subgoal evolution) on the evolution of a neuro-controller for a light-seeking mobile robot. Results obtained with these two approaches are qualitatively similar although the introduced one is less directed than multi-subgoal evolution.

I. INTRODUCTION

Evolutionary algorithms have been widely used to design controllers, and especially neuro-controllers, for robots (see [1], [2] and [3] for an overview). Compared to other learning methods, one of their main strength is their ability to evolve both the structure and the parameters of complex architectures using a high-level reward function. However, this huge amount of work hides many unsuccessful attempts to evolve complex behaviors by only rewarding the performance of the global behavior. The bootstrap problem is often viewed as the main cause of this difficulty, and consequently as one of the main challenges of evolutionary robotics: if the objective is so hard that all the individuals in the first generation perform equally poorly, evolution cannot start and no functioning controllers will be found. For instance, it has been found hard to evolve a light-seeking behavior for a robot in a complex arena without having first evolved an obstacle-avoidance reflex [4].

In consequence, many researchers added some kind of rewards for intermediate steps, leading to successful incremental evolution processes [4]–[9]. Nonetheless, these evolutionary approaches rely on some assumptions that require an accurate knowledge of the problem to solve and can lead the evolutionary algorithm to a local extremum. Most of them, for instance, require to precisely order the different sub-tasks or to determine when to switch from a sub-task to another one. These biases prevent them from scaling up well to more complex or more open tasks; remarkably, most of them have been tried with only two or three sub-tasks.

Another idea to bootstrap an evolutionary process is to efficiently explore the neighborhood of current candidate solutions to find one with a non-minimal fitness. This concept is close to diversity-preserving mechanisms, widely investigated in evolutionary computation (e.g [10]–[12]), which typically rely on a distance between the genotypes or the phenotypes. However, such distances are conceptually and computationally difficult to employ with complex structures as neural networks.

Drawing inspiration from these diversity-preserving mechanisms and adapting them to evolutionary robotics, we introduce in this paper the behavioral diversity, an original method to maintain the diversity in a population that relies on a distance between behaviors and a multi-objective evolutionary algorithm (MOEA, see [13]). We then show how such a diversity preservation mechanism can efficiently overcome the bootstrap problem in an evolutionary robotics experiment in which a simulated robot that has to successively reach some lights in an arena. As a reference point, we compare the results obtained using this new approach with the ones obtained with multi-subgoal evolution [9], a recently published incremental method based on multiobjective evolution.

The remainder of this paper is organized into four parts. In section II, we briefly review the related literature about multi-objective evolutionary algorithms, incremental evolution and diversity preservation. The proposed method is detailed in section III. Section IV describes an evolutionary robotics experiment and reports the results of both methods. A short discussion concludes this paper.
II. PREVIOUS WORK

A. Multi-objective evolutionary algorithms

Most problems tackled in evolutionary robotics involve trade-offs between numerous objectives, such as energy versus efficiency (see e.g. [14]). The classical approach is to aggregate objectives using a weighted sum or a product to define a composite fitness. Hence, a particular set of weights defines a particular trade-off. Despite its experimental success, this method has several substantial drawbacks. First, it can be theoretically shown that some trade-offs cannot be found (see [13]), thus silently constraining the study to a subset of possible trade-offs. Second, weights have usually to be inferred from a time-consuming trial-and-error approach because no theoretical methods to define them are available. Last, the exploration of each trade-off requires launching a new evolutionary process. These different implications generally limit analysis and discussions of results to one or two particular trade-offs, associated to a particular set of weight parameters that may be difficult to explain.

Recent research in evolutionary computation proposed numerous algorithms to simultaneously optimize several objectives without aggregating them [13]; most of them rely on numerous algorithms to simultaneously optimize several objectives that may be difficult to explain. Application of particular trade-offs, associated to a particular set of weight parameters that may be difficult to explain. Application of a particular trade-off. These different implications generally limit analysis and discussions of results to one or two particular trade-offs, associated to a particular set of weight parameters that may be difficult to explain.

Definition 1: A solution \( x^{(1)} \) is said to dominate another solution \( x^{(2)} \), if both conditions 1 and 2 are true:

1) the solution \( x^{(1)} \) is not worse than \( x^{(2)} \) with respect to all objectives;

2) the solution \( x^{(1)} \) is strictly better than \( x^{(2)} \) with respect to at least one objective.

The non-dominated set of the entire feasible search space is the globally Pareto-optimal set (Pareto front).

Multi-objective evolutionary algorithms are designed to find the Pareto-front, i.e. the set of all the Pareto-optimal trade-offs. Most of them rely on two mechanisms:

- a selection procedure that ensures that non-dominated individuals have a selective advantage;
- a diversity-preservation method designed to spread non-dominated individuals along the whole Pareto front, i.e. that as many different trade-offs as possible are explored.

A typical MOEA sorts individuals with respect to domination. Non-dominated individuals may, for instance, be ranked 1, making them the most suitable for reproduction. Individuals which are only dominated by non-dominated ones may be ranked 2, and so on. The diversity on the Pareto front can be maintained using several ways such as fitness sharing [15] or clustering methods [16].

Despite their considerable success in the optimization field (see [17]), MOEAs deserved little attention in the evolutionary robotic literature (notable exceptions being [14], [18]–[21]). One of the ambitions of this paper is to highlight how they can be useful in evolutionary robotics, in particular to solve the bootstrap problem.

B. Incremental evolution

Four main approaches emerge from the different attempts to tackle the bootstrap problem in evolutionary robotics: staged evolution, environmental complexification, fitness shaping and behavioral decomposition.

Staged evolution is probably the most intuitive – and most used – incremental process. The main task is split into ordered sub-tasks, each with a corresponding fitness function. During each stage, individuals are selected only using the associated fitness. The process is switched from each stage to the next one once a convergence criterion is reached, for instance when a “good enough” fitness is obtained by the best individual or when the best fitness doesn’t change for some generations. This technique has first been successfully employed by Harvey et al. [5] to evolve a vision-based target location task. Three stages were used, from locating a large immobile target to tracking a moving smaller one. Many other examples of staged evolution can be found in the literature (e.g. [7], [8], [14], [22]–[24]).

Following the same idea, environmental complexification aims at more continuously changing the complexity of the task through the tuning of dedicated parameters. Gomez and Miikkulainen [6] thus worked on a prey-capture task parameterized with the prey speed and the delay before starting the pursuit. Ten ordered sub-tasks were thus defined by specific values of these parameters and their use proved to lead to more efficient solutions.

In behavioral decomposition, each sub-task is solved by a sub-controller evolved using a dedicated fitness, different from the main goal. Another evolutionary process is then used to combine all the sub-controllers together. This approach has been recently used to evolve a position controller for an autonomous helicopter [25].

Fitness shaping is sometimes used to help to bootstrap an evolutionary process, though it is not often seen as an incremental evolution scheme. The fitness is defined as an aggregation (a weighted sum or a product) of different evaluation criteria in order to create a fitness gradient. For example, Nolfi and Parisi [26] successfully evolved a feed-forward neuro-controller for a robot to locate, recognize, and grasp a target object. The fitness was increased if the individual was close to the target object, if the target was in front of the robot, if the robot tried to pick-up the object, if the robot had the object in the gripper and if the robot released the object outside the area.

C. Multi-subgoal evolution

The previously mentioned approaches allowed to generate non trivial behaviors, but they require an important help from the human designer: intermediate steps have to be defined, ordered and their combination also requires the intervention of the human designer, may it be to trigger the switch between these steps or to gather all the elementary solutions in a wider controller. The method introduced in [9], called multi-subgoal evolution, intends to relax some of the constraints of these incremental approaches.
In multi-subgoal optimization, intermediate steps still have to be defined, but once this is done, the evolutionary process will do the rest, without the need to order them or to choose when to switch between the goals. Another interesting aspect with this approach is that all those intermediate steps are optional. We can therefore provide more information than what is actually necessary without endangering the convergence of the evolutionary run. This feature also differentiates it from fitness shaping in which the fitness pushes towards the tendency of the evolutionary run. This idea, which can be seen as a push in favor of diversity, is formulated for multiobjective evolution while the interest of using these methods in evolutionary robotics is growing (see [14], [35], [36], for instance). Hence, maintaining the diversity of genotypes with fitness sharing when evolving evolutionary robotics experiments offers some other possibilities: the behavior can be used to distinguish individuals. Fitness values are based on an observation of the behavior, in unexplored regions. More precisely, if $d_{ij}$ is the distance between the genotype of $i$ and $j$, the sharing function $sh(d_{ij})$ is defined as follows:

$$
sh(d_{ij}) = \begin{cases} 
1 - \left( \frac{d_{ij}}{\sigma_{\text{share}}} \right)^{\alpha}, & \text{if } d \leq \sigma_{\text{share}} \\
0, & \text{otherwise} 
\end{cases}
$$

(1)

where $\sigma_{\text{share}}$ is a user-defined parameter. The fitness of individual $i$ is then divided by the niche count $c_i$:

$$
F_i = \frac{F(x_i)}{c_i} \quad \text{where} \quad c_i = \sum_{j=1}^{N} sh(d_{ij})
$$

(2)

Dividing the fitness by the niche count can be seen as an aggregation of two objectives, the fitness and the diversity. Given the recent progress of Pareto-based multiobjective evolutionary algorithms, some researchers suggested to use a multiobjective approach instead of the aggregation. This explicitly models the classic trade-off between exploration and exploitation [29] and let the evolutionary algorithm automatically tune it. Different ways to improve the diversity by adding an objective have been investigated and compared, from the distance to the nearest neighbor to a simple random value [20], [30], [31]. All the available studies conclude that (1) multiobjective methods to preserve the diversity are more efficient than their single-objective counterparts and (2) the mean distance between the individual and the remaining of the population leads to the best results.

III. Behavioral Diversity

Computing a distance between individuals is, however, difficult in evolutionary robotics, especially when evolving the topology of neuro-controllers. The distance between genotypes is often hard to compute because typical distances between two graphs, thereby two neural networks, are NP-complete [32]. The permutation problem [33] prevents the definition of simple metrics on neural-networks with a fixed topology. Although some methods have been published to allow the fitness sharing of neural networks [34], an infinity of very different neural-networks can lead to a similar behavior. This is especially striking with degenerate individuals as those observed when the evolutionary process is unable to start: any neural network not linked to the motors will lead to an immobile robot, thus fitness sharing won’t help here. Moreover, fitness sharing has not originally been formulated for multiobjective evolution while the interest of using these methods in evolutionary robotics is growing.
but they are focused on a small set of behavior consequences, not on behaviors on their own. As an alternative approach to fitness sharing, we propose to compute a distance between behaviors instead of genotypes, thus explicitly promoting new behaviors. This distance could be used to modulate the fitness, as in fitness sharing. However, using a multiobjective evolutionary algorithm allows to rely on the good results obtained with multiobjective approaches to preserve the diversity and to explicitly model the exploration/exploitation trade-off.

Let us denote by $D_{ij}$ the distance between the behaviors of individuals $i$ and $j$. In its simplest form, the behavior sharing function $B(i)$ can be formulated as the mean distance between the behavior of $i$ and the one of each individual of the population. Instead of maximizing the fitness $F(i)$ only, we have to maximize two objectives:

$$\begin{align*}
F(i) = & \\
B(i) = & \frac{1}{N} \sum_{j=1}^{N} D_{ij}
\end{align*}$$

Designing a distance between behaviors of robots may seem to be a challenging task. However, we have found that in many cases a distance built on basic features tied to robot behavior was sufficient to bootstrap the evolutionary process and avoid many local minima. A simple and efficient approach for mobile robotics is to associate to each individual $i$ a vector $\mathbf{v}^{(i)}$ describing the state of the environment at the end of the experiment. $D_{ij}$ can then be defined as the Euclidean distance between $\mathbf{v}^{(i)}$ and $\mathbf{v}^{(j)}$. For instance, if the robot has to move objects in an arena, a $\mathbf{v}^{(i)}$ may contain the positions of the objects. If the robot has to explore a maze, the final positions can also be used. As a last example, when evolving a $n$ inputs logic function, e.g. XOR, the output for each of the $2^n$ set of inputs can be stored in a $2^n$-dimensional vector.

The behavioral diversity approach shares some similarities with the recently published novelty search [37]. In this paper, Lehman and Stanley proposed to maximize the novelty of behaviors instead of fitness to define an open-ended evolutionary process. Using a distance between behaviors $D(i, j)$, similar to the one discussed here, they defined the sparseness $\rho$ at a point $x$: $\rho(x) = \frac{1}{\sum_{i=0}^{k} D(x, \mu_i)}$ where $\mu_i$ is the $i$-th nearest neighbor of $x$ with respect to the distance $D$. The neighbors are computed using the current population and an archive of all the previously explored behaviors. Three main points differentiate the two approaches:

- they optimize only novelty whereas we propose to use a multiobjective algorithm that does not ignore the main goal;
- they use an archive of all the previously explored behaviors;
- since the distance is computed using the archive and the current population, they mixed a diversity measure with a novelty one.

Despite the substantially high computational cost induced by the growing archive, novelty search could avoid evolutionary cycles that could occur with behavioral diversity. Nonetheless, we will see in the next section that some intuitive behavior distance can not be employed with novelty search while they can be used with behavioral diversity.

IV. LIGHT-SEEKING ROBOT

A. Main task

To benchmark the proposed approach on a typical incremental task, we designed a variant of the light-seeking task which involves seven sub-tasks with complex dependencies. A similar but simple version of this task has, for example, been studied in [38]. A simulated wheeled robot is placed in an arena with seven different colored lights (figure 2). Each light is mounted on a button switch which, when pressed, turns on one or more lights in the arena. Once a light is on, it remains in the same state during the whole experiment. The main goal is to turn on a particular light. The connection between lights and switches, a simple explicit dependency between tasks, is to be discovered by the evolutionary algorithm. To benchmark future incremental algorithms, the task can be easily complexified by adding lights or changing the dependencies between lights. This task has been chosen because it does not require nor complex genotypes nor complex fitness functions to be solved: its main challenge is its incremental nature.

The underlying structure of this incremental task is depicted on figure 2. Each lights turn on only if the previous related light is on, following the relations depicted on figure 2. The first light turns on two other lights, creating two paths to solve the goal-task. A part of the population may choose to learn to turn on lights $\{0, 1, 2, 3, 4, 5, 6\}$ and another one may learn sequence $\{0, 4, 5, 6\}$. This task can therefore be learned in different ways. Despite the simplicity of this problem and of the different sub-tasks, it involves at least four sub-tasks (turn on each of the lights belonging to the shortest path to the goal light), making it one of the most complex composite tasks explored with incremental evolution at this time.

The simulated robot (figure 3) is equipped with seven pairs of light-sensors, each one sensing a different light color. Light sensors have a 90 degrees field of view and a binary output (1 if the light is in the field of view, 0 otherwise).
Fig. 3. The simulated robot is equipped with seven pairs of binary light sensors, each one sensing a different light. The controller is an evolved neural-network with 14 inputs and 2 outputs (the speed of the motors).

A robot is controlled by an evolved neural network with 14 inputs and 2 outputs whose topology and synaptic weights are encoded by a simple direct encoding [1]: the network is represented by a weighted directed graph in which neurons and connections can be randomly added or removed. Two kinds of mutations are possible:

- structural mutation: addition/removal of a neuron or a connection;
- parametric mutation: change of a randomly chosen synaptic weight or a neuronal bias; we used here a change in a set of 15 possible values (similar results were obtained using real-valued weights and Gaussian mutation).

The mutation rates of each operator are detailed in appendix.

Cross-over is not used. Neurons use the following activation function, based on tanh(x), to easily allow the inhibition of a neuron in the case of negative inputs:

\[
f(x) = \begin{cases} 
\tanh(x) & \text{if } x > 0 \\
0 & \text{otherwise}
\end{cases}
\]

**B. Experimental setup**

Behavioral diversity and multi-subgoal evolution have been tested on this problem to compare them.

To use the multi-subgoal approach, one objective for each light \( F_{m}^{i} \), \( i \in \{0, 1, \ldots, 6\} \) was defined. To avoid over-learning and check the robustness of the evolved behaviors, each objective is the minimal score for three experiments in which the robot starts from different positions:

\[
F_{m}^{i}(x) = \min_{n=1,2,3} \frac{-\varphi(n,i)}{T} \quad (4)
\]

where \( i \in \{0, 1, \ldots, 6\} \) is the identifier of the light, \( T \) is the length (in time-steps) of each experiment and \( \varphi(n,i) \) denotes the number of time-steps spent before reaching light \( i \), for experiment \( n \).

The behavioral diversity approach first requires to define a classic fitness \( F_{bd} \) corresponding to the goal to be reached. Here we used the number of time-steps to reach the last light:

\[
F_{bd}(x) = F_{6}^{m}(x) = \min_{n=1,2,3} \frac{-\varphi(n,i)}{T} \quad (5)
\]

We then have to define a distance \( D_{ij} \) between the behavior of \( i \) and \( j \). We choose to describe the behavior of \( i \) by a Boolean vector \( v^{(i)} \) such that:

\[
v^{(i)}_k = \begin{cases} 
1 & \text{if the } k\text{-th switch has been pressed} \\
0 & \text{otherwise}
\end{cases}
\]

\( D_{ij} \) can be computed using an Euclidean distance between \( v^{(i)} \) and \( v^{(j)} \):

\[
D_{ij} = \|v^{(i)} - v^{(j)}\| \quad (7)
\]

This distance lead to surprising results if we use it with novelty search. To distinguish novelty and diversity, we only consider here the archive when computing \( \rho \). Thus, we will not mix the diversity with the novelty. At the end of the random generation, the archive typically contains the following behaviors, due to the incremental structure of the task: 0000000, 10000000, 1000100 and 1100000. We are clearly more interested in 1000100 and 1100000 because the corresponding robot reaches more lights. Since the archive contains only 4 entries, only 4 kinds of behaviors are present in the population. Let’s compute their novelty score to know which ones will be selected for the reproduction:

\[
\begin{align*}
0000000 & : \rho = 0.957 \\
1000000 & : \rho = 0.75 \\
1000100 & : \rho = 0.957 \\
1100000 & : \rho = 0.957
\end{align*}
\]

The most interesting individuals have the same fitness than individuals with the 0000000 behavior. Since the latter is the least interesting and easiest to obtain, we can predict that the evolutionary process will never start. This prediction has been confirmed by some preliminary experiments.

We used NSGA-2 [39], a state-of-the-art MOEA, to maximize the objectives in the multi-subgoal case and in the behavioral diversity case, with a population of 200 individuals, 30 runs of 1000 generations for each of the proposed methods have been launched.

**V. Results**

Runs of a direct evolution algorithm designed to minimize the number of time-steps to turn-on the last light, did not find any working controller, all individuals obtaining the minimum fitness. This contrasts with the results obtained with the two presented methods, summarized in table I. In both cases, all the runs converged to very similar values of the goal fitness. The bootstrap generation (the generation where at least one individual reach a main fitness greater than \(-0.8\)) was significantly lower with multi-subgoal evolution than with the behavioral diversity (138 versus 218) but both values

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<td>Goal objective</td>
<td>-0.27(0.04)</td>
<td>-0.27(0.05)</td>
<td>( p &lt; 0.001 )</td>
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<th>Goal objective</th>
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<td>T-test</td>
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shows a clear staircase structure. Almost 50 generations are required to obtain the first individuals to reach the light 0 but after 100 generations, the whole population reaches it. Individuals can then switch the next lights, 1 and 4. These new skills are shared by the whole population in a few generations, allowing some individuals to reach light 6 in less than 150 generations. This incremental structure gives support to our assumptions about the effect of the multi-objective evolutionary pressure: the first attainable objectives are first optimized and the process automatically switches to new ones as soon as possible; the two hypothesis – the two available paths to solve the task – are explored simultaneously; and solved objectives apply almost no pressure once they are solved.

The diagram corresponding to behavioral diversity shows a very similar structure in which gradients show that each sub-task is successively solved. However, the picture is noisier because the diversity approach also maintains individuals that don’t solve each task, since at a given generation, they may be different from the remaining of the population. Significantly fewer generations are required to converge with the multi-subgoal method than with the behavioral diversity.

VI. Conclusion and Discussion

We proposed a new method to solve the bootstrap problem observed in evolutionary robotics and compared it with a recently published approach. Compared to previous methods, both approaches don’t require to order sub-tasks or to specify when to switch between them since the evolutionary process automatically explores all the available orders. Moreover, the performance on the subgoals can be continuously improved and some may be ignored. We showed that both methods efficiently solved the bootstrap problem on a typical incremental robotics task although the newly introduced method is less directive than the previously published one. Hence, our contribution is twofold: (1) we propose a new way to maintain the diversity of a population, especially adapted to evolutionary robotics and (2) we show that such a diversity preservation mechanism can efficiently overcome the bootstrap problem in an evolutionary robotics experiment.

Although they seem at first glance very different, the two approaches actually share the same basic principle: their common goal is to provide a selective pressure towards exploration and they only differ by the method used to supply it. Both behavioral diversity and multi-subgoal will select individuals which are able to switch on lights that no other can\(^1\). However, the behavioral diversity ranks individuals according to an averaged Euclidean distance whereas multi-subgoal uses a Pareto sort. Consequently, behavioral diversity will also select individuals that can’t switch a single light, as long as they are the only one to do so, whereas an individual that switches any light will always dominate an individual that doesn’t switch any light at all in multi-subgoal. This

\(^1\)They would be even more similar with a binary value for the subgoals in the multi-subgoal approach: 0 light not switched on, 1 light switched on during evaluation.
doesn’t make a huge difference here, as individuals that don’t switch any light are easy to find and then won’t capture the search effort for long. More formally, the main difference lies in the fact that multi-subgoal is an oriented search. It means that the designer has to know how to sort good and bad behaviors and how to evaluate the robot’s performance for each of the subgoals. To use behavioral diversity, only a frame in which behaviors can be described needs to be provided. On the toy problem we considered here, this doesn’t make a huge difference, neither on the results, nor on the knowledge we have provided to the algorithm, but it might be more significant in other tasks.

The simplicity of behavioral diversity makes this approach appealing and easy to integrate in an existent framework. However, in particular problems, it may be hard to design a relevant distance between behaviors. A generic way to describe behaviors of mobile robots would be useful to design such distances, hence making easier the application of behavioral diversity to new tasks.

Behavioral diversity makes explicit the exploration and exploitation part of the algorithm through the behavioral diversity objective and the goal fitness. Compared to other learning algorithms like reinforcement learning, there is no need to explicit here the balance between the two objectives, it is autonomously managed by the multiobjective algorithm. The true ability of the algorithm to handle this important aspect of the search should be more carefully studied.

The cross-over operator, not used in this work for the sake of simplicity, could have an effect on the two investigated methods. Since multi-subgoal evolution and behavioral diversity maintain individuals able to solve different subtasks, each part of them could be combined to create more efficient individuals. Using this operator to evolve neurocontrollers would probably require a modular encoding of

Fig. 6. Multi-subgoal evolution. (top) Proportion of individuals which reach each light as a function the generation, in a typical run. (bottom) Best fitness for the main objective.

Fig. 7. Behavioral diversity. (top) Proportion of individuals which reach each light as a function of generation, in a typical run. (bottom) Best fitness for the main objective.
neural networks, such as MENNAG [40].

REFERENCES

APPENDIX

• population size: 200
• number of runs : 30 for each method
• weights:
  \[
  \{-5.0, -4.0, -3.0, -2.0, -1.5, -1.0, -0.5, -0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6\}
  \]
• weight mutation rate: 0.2
• number of inputs: 15
• number of outputs: 2
• min. neurons (random gen.): 10
• max. neurons (random gen.): 20
• min. connections (random gen.) : 20
• max. connections (random gen.) : 35
• rate of connection addition: 0.15
• rate of connection removal: 0.25
• rate of connection change: 0.1
• rate of neuron addition: 0.025
• rate of neuron removal: 0.025
• activation function: \(y_i = \tanh(-b + 5 \cdot \sum_j w_{ij}x_j)\)