Effects of Scaffolding in Tilted Planes on Evolvable Robot Morphologies

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Abstract

We evolve modular robots in various environments with the objective to show that the environment affects the morphology and behavior of the robots. We use the system designed by the Evolutionary Robotics group at VU. The phenotype of the robots consists of attachable components and the genotype is represented by an indirect encoding framework called an L-system. The Evolutionary Robotics group has run experiments using various selection preferences and plain terrains, resulting in the same traits or diverse robots performing poorly. We seek to build on this research, by running experiments with non-flat terrain environments that vary in difficulty and using directed locomotion fitness functions. We experiment with a water world and friction world, and eventually pursue a tilted world because it is the most feasible and promising. Our experimental setup involves two environments increasing in three difficulties: (1) a staircase world, (2) a tilted plane. We used two fitness functions: (1) upwards speed, (2) horizontal speed. Our results demonstrate that the three scaffolding levels affects dominant morphologies and morphological descriptors. We suggest further lines of research into simulations with fine-grained scaffolding.

Introduction

The goal of our research is to show that the environment affects the morphology and behavior of robots. Though the evidence of evolution that surrounds us gives us the intuition to form such a hypothesis, it is not easy to prove. The Evolutionary Robotics group at VU has been pursuing this research goal by simulating the evolution of modular robots under various fitness functions and comparing evolved morphologies and behaviors. The phenotype of the modular robots consists of attachable components (core, brick, and active joint) and the genotype is represented using an indirect encoding framework (L-system, ANN controller, grammar production rule). In the experiments, robots are selected based on a fitness function and their morphologies are analyzed using quantitative morphological descriptors. Despite these representations and methods, results have shown that different fitness functions lead to the same traits with robots performing poorly. In particular, there is a bias towards snakes as dominant morphologies when the task is locomotion and the environment is a flat terrain. The Evolutionary Robotics groups believes there are several reasons that may contribute to improper conditions for the robots to differentiate. First, the task environments (fitness functions) may have been too challenging, which inhibited the robots from developing. Second, the wrong methods (i.e. fitness functions, operators, parameters) may have been used. Third, there were no incremental changes in the environment. Natural evolution typically involves dynamic interactions between an organism and an environment, so it is intuitive that a dynamic environment may be necessary to trigger a change in evolved traits.

Why do we want to evolve robots? Currently, industrial robots are designed for very specific purposes that are known in advance. Their designs are fixed. However, there are problems that require robotic systems to be adaptable, on the controller level and the morphological level. Evolutionary Robotics can find solutions for optimization and design when there are uncertainties about the problem or when the problem is dynamic. The field also has great potential for solving design problems in environments that are unknown or inaccessible. For example, autonomous robots can be evolved to explore new planets or unknown parts of the ocean. Moreover, Evolutionary Robotics can be used to model and study natural evolution. The Evolutionary Robotics group at VU has demonstrated that artificially evolved systems can solve natural tasks in natural ways. For the task of locomotion, they demonstrated that robots can develop gaits that are similar to those of animals such as worms, salamanders, and penguins.

Objectives

How does the complexity of the environment affect the traits of the robot? In previous research, we have seen that using speed as a fitness function on a flat terrain leads to dominant morphologies that lack limbs and resemble snakes with one long limb. We further saw that introducing morphological preferences in the fitness functions increased diversity but decreased performance. Our goal is to attain diverse morphologies across diverse environments that do not perform poorly. To do this, we aim to extend the research by making the simulations more natural and nuanced. By this, we mean evolving the robots in more complex environments, and studying the impacts of these environment differences on their morphology, similar to natural evolution. Furthermore, we use fitness functions that do not incorporate morphological preferences but reward certain behaviours (e.g. moving upwards, moving horizontally). Finally, we seek to study the effect of scaffolding on the evolved traits by gradually updating the difficulty of the environment throughout the simulation.

Related work

Karine et al. define eight morphological descriptors to assess the morphological search space. In their paper, they isolate the properties of the search space defined by representation and reproduction operators from those defined by behavior by using a purely morphological novelty search algorithm. Results show that both indirect and direct encoding systems produce high levels of diversity but that there is no significant difference between the two systems. Both systems share common morphological traits, suggesting a bias in the design space (Miras et al., 2018a).

In a following paper, Karine et al. add a locomotion task and investigate the effects of selection preferences (fitness functions) on evolved robot morphologies and behaviors. They use four fitness functions: (1) novelty, (2) speed of locomotion, (3) speed and novelty, (4) speed and novelty and a penalty for length of limbs. Results show how the fitness functions affect what proportions of the search space are sampled and what dominant morphologies and behaviors appear. Novelty samples fewer possible morphologies than a combination of speed and novelty, which is surprising. The morphologies of the final populations of the fitness functions differ and all morphological descriptors are affected. Finally, speed results in the fastest robots, which resemble snakes and exhibit rolling, while penalized fitness functions result in slower robots that are more diverse (Miras et al., 2018b).

Milan et al. address on-line gait learning in modular robots. They use the RL PoWER algorithm and change two search operators: two parent crossover and mutation with self-adaptive step-sizes. Results show that robots before perform better with the new algorithm. They conclude that learning a good gait quickly after birth is important for evolution (Jelisavcic et al., 2016).

The lack of incremental challenge is a problem motivated by the work of Bongard and Auerbach, who managed to show that an environment with scaffolding can drive changes in the morphologies of machines. In particular, they demonstrate that an increase in environmental complexity can increase the morphological complexity of robots by starting with a high-friction control environment and gradually increasing the number of low-friction icy obstacles into the environment (Auerbach and Bongard, 2014). In another paper, Bongard suggests there can be synergy of morphological and environmental scaffolding for robots (Bongard, 2011).

System

Genotype

The genotype is represented by an indirect encoding framework called Lindenmayer-System (Jacob, 1994). The L-System uses a grammar G = (V, w, P), where

- V is the alphabet
- w is the axiom
- P is the set of production-rules

The alphabet consists of morphology modules and commands for attaching the modules and updating the corresponding controller. The system starts with the axiom, a symbol from the alphabet. Then, production-rules are applied to build the morphology.

Phenotype

The phenotype of the robots consists of a morphology and a controller. The morphology is made up of attachable 3D printable components called modules. There are five modules C, B, A1, A2, T, where

- C is the core-component containing the controller board
- B is a structural brick
- A1 is an active hinge with servo motors in vertical axes
- A2 is an active hinge with servo motors in horizontal axes
- T is the touch sensor

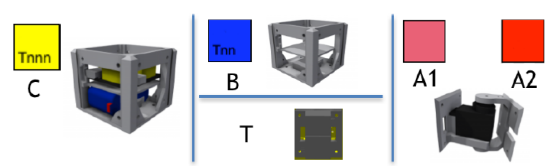


Figure 1: The components of the phenotype are referenced by color. C = yellow, B = blue, A1 = pink, A2 = red

The controller is made up of a multilayer Artificial Neural Network where active joints are represented by oscillator neurons, connections have weights between -1 and 1, and touch sensors provide input to the network.

Mapping

The genotype string is decoded element by element to construct the morphology and the controller of the phenotype. A module following a command is attached to the module preceding the command. A sequence of letters (T or n) in the core component C and structural brick B indicates where the sensor should be located. The core component C is only included once and the other blocks have no limit unless specified otherwise in experiments.

Descriptors

We use the nine morphological descriptors outlined by Miras et al. (2018a,b) to assess the morphology of the robots: Number of limbs, Length of limbs, Symmetry, Proportion, Joints, Coverage, Size, Branching, and Sensors. Our focus is on morphology, but we also consider behavioral descriptors such as Speed (shortest vs total distance), Head movements (roll, pitch, yaw), and Locomotion styles (rolling, sidewinding, undulating worm, walking, crawling).

Baseline experiments

Before we can run experiments with new environments and fitness functions, we have to study baseline experiments to get acquainted with the search space. We want to know that the evolved morphologies and behaviors are influenced by our environments and fitness functions and not just because they are ”more likely to be generated...” by the ”random initialization and mutations that the system performs” (Miras et al., 2018a). We study baseline experiments that are run in flat terrains using novelty search and speed, and combinations of these fitness functions.

In their paper ”Search Space Analysis”, Karine et al. conduct a baseline experiment with novelty search. This allows them to isolate the properties of the search space defined by representation and reproduction operators from those defined by behavior. Results show that both indirect and direct encoding systems share common morphological traits, suggesting a bias in the design space. They observe that both systems have a ”tendency in discovering certain morphologies”, that certain morphologies ”are more likely to be found”, and that the dominant morphologies across all runs are small with ”one to four [modules] ” and ”one or two limbs” which make use of ”extra modules” (Miras et al., 2018a).

In Miras paper Effects of Selection Preferences, we are given four baseline experiments: (1) novelty, (2) speed, (3) speed and novelty, (4) speed and novelty and a penalty for long limbs. The fourth fitness function specifically addresses the bias for long limbs.First we learn that the fitness functions explore the search space in distinct ways. Novelty samples fewer possible morphologies than a combination of speed and novelty. This is surprising as we expect speed and novelty to have the exploration of forms be limited by the pressure to be speed. Second, we learn that the morphologies of the final populations differ across the fitness functions. Third, we learn that all morphological descriptors are affected by the four fitness functions. Finally, we learn that selection pressure can overcome the bias of long limbs but it comes at a cost to performance. Speed results in the fastest robots, which resemble snakes and exhibit rolling, while penalized fitness functions result in slower robots that are more diverse. If the environment can affect the evolved morphology and behavior of the robot, then these results suggest it is possible to overcome the bias using a strong environment.

Experimental setup

The study conducted three final experiments using two environments, a staircase world and a tilted world, and two fitness functions, upwards speed and horizontal speed. Scaffolding was applied by using three levels of each environment: easy, medium, hard. The easy level was used for generations 1 to 50, the medium level for generations 51 to 75, and the hard level for generations 76 to 100.

Table 1: Experiment Parameters

Population size	50
Generations	100
Runs	1
Evaluation time	240 seconds
Initialization	50 random robots
Terminal condition	100th generation

Experiment 1: Step World (Upwards speed)

The first environment is a staircase world, with step height increasing from 0.05 to 0.10 to 0.20. The fitness function was upwards speed. This was implemented by changing the speed fitness function to f=z (vertical axes).

Figure 2: Environment for Gen 1 - 50 (Step height = 0.05 cm)

(a) Front view (b) Side view

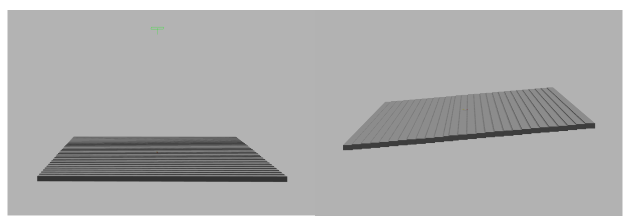


Figure 3: Environment for Gen 51 - 75 (Step height = 0.10 cm)

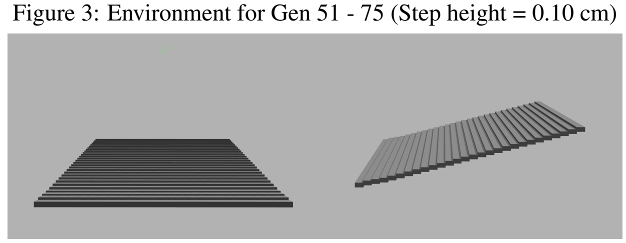
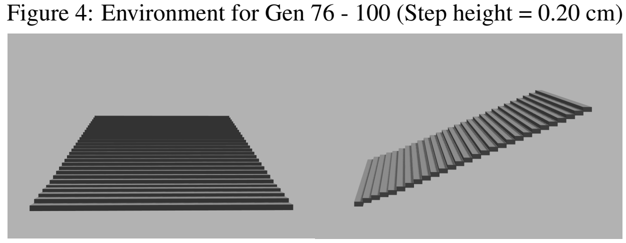


Figure 4: Environment for Gen 76 - 100 (Step height = 0.20 cm)



Experiment 2: Tilted World (Horizontal speed)

The second environment is a flat tilted world, with the angle of the tilt increasing from 20 degrees to 30 degrees to 40 degrees. The fitness function was horizontal speed. This was implemented by changing the speed fitness function to f=y-x^2 (horizontal axes).

Figure 5: Environment for Gen 1 - 50 (Tilt = 20 Degrees)

(a) Front view (b) Side view

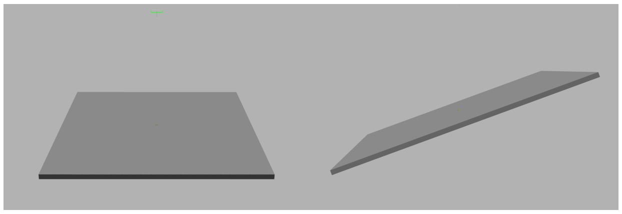


Figure 6: Environment for Gen 51 - 75 (Tilt = 30 Degrees)

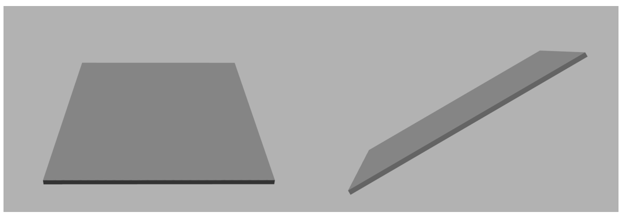
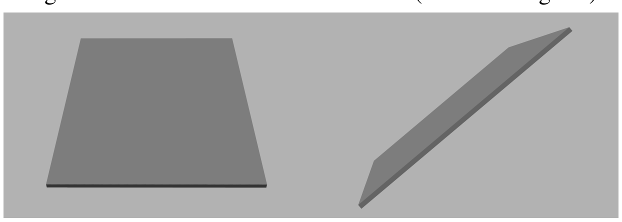


Figure 7: Environment for Gen 76 - 100 (Tilt = 40 Degrees)



Experiment 3: Tilted World (Upwards speed)

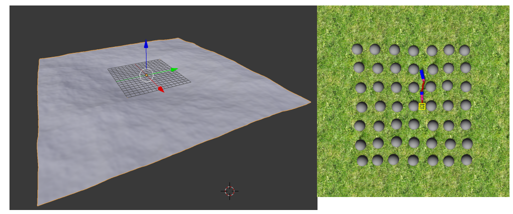
For this experiment we used the same scaffolding environment as in Experiment 2 (the tilted world) and the same fitness function as in Experiment 1 (upwards speed). This allowed us to compare the same fitness function in two different environments (Experiments 1 and 3), as well as two different fitness functions in the same environment (Experiments 2 and 3).

Results

We experimented with various environments before pursuing the tilted environment. The first environment we sought to create was a water environment in which water was slowly draining. The idea behind this environment was the ”fish out of water” concept, where modular robots would be pressured to evolve limbs to adapt to increases in gravity. Though we were able to simulate underwater dynamics with Gazebos physics engines, we were not able to simulate a low-level water environment where the robots were partially submerged. The fluid environment was also too computationally complex. We also designed environments with spherical boulders that were placed in a grid. After running simulations with population 50, generations 50, and speed as a fitness function, we observed that the dominant morphologies were snakes in the final generation. This was the case for small, medium, and large boulders, though the morphologies varied in length.

Figure 8: Failed environments

(a) Water (b) Boulders



Our most promising environments were those involving a tilted plane and fitness functions with directed speed rather than undirected speed. As described in the Experimental Setup sections, we focused our final experiments on two environments containing three levels of scaffolding. The first environment is a staircase world, with increasing step size, and the second environment is a flat tilted world, with an increasing angle.

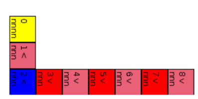
To facilitate analysis, we categorize the robot morphologies into six visually identifiable groups:

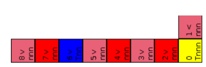
- Flexible Snake (no bricks): linear w/ only active hinges
- Stiff Snake (bricks): linear with active hinges and bricks
- L-shaped (1 limb): brick at right angle, one curved limb
- L-shaped (2 limbs): head at right angle between two limbs
- T-shaped (2 limbs): two right angles
- Other: does not fit into the above categories

Figure 9: Morphology Categories

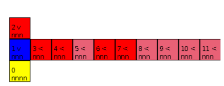
(a) Snake (no bricks) (b) Snake (bricks)

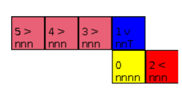
(c) L-shaped (1 limb) (d) L-shaped (2 limbs)





(e) T-shaped (2 limbs) (f) Other





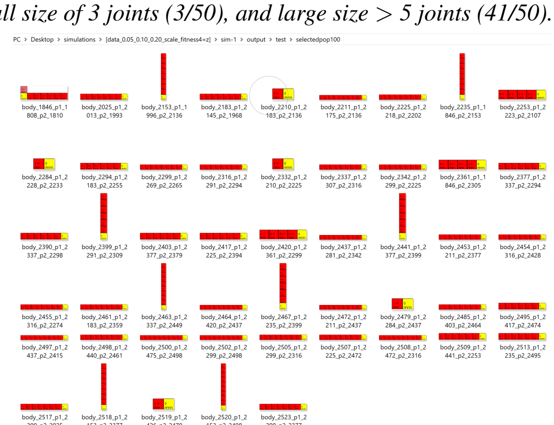
Experiment 1: Step World (Upwards speed)

After 50 generations, the morphologies are homogeneous. There are only flexible snakes composed of active hinges (see Figure 14a). After 75 generations, the morphologies diversify. The flexible snakes without bricks still dominate but the number has decreased and we see the emergence of snakes with bricks and L-shaped forms (see Figure 14b). By the final 100th generation, the diversity of the morphologies decreases to the level it was in the 50th generation, with morphologies dominated by snakes without bricks. The main difference is that there are fewer large morphologies (> five blocks) and one that is L-shaped.

Table 2: **Dominant morphologies for Step World (Up. Speed)** (where L represents the number of "large" morphologies that have more than 5 blocks)
The dominant morphologies change from long brick-less snakes (Gen 50) to more varied shapes inc. bricks (Gen. 75) back to long brick-less snakes in the final generation (Gen 100).

	Gen 50	Gen 75	Gen 100
Snakes (no bricks)	50 (L=49)	40 (L=31)	49 (L=41)
Snakes (bricks)	0	6 (L=4)	0
L-shaped (1 limb)	0	1 (L=0)	0
L-shaped (2 limbs)	0	2 (L=2)	1 (L=1)
T-shaped (2 limbs)	0	0	0
Other	0	1 (L=1)	0

Figure 10: **100th Generation for Step World (Up. Speed)**
The dominant morphologies in the final generation are brick-less snakes (49/50). They vary in size with minimal size of 1 joint (5/50), small size of 3 joints (3/50), and large size > 5 joints (41/50).



In the step 0.05cm and the step 0.20cm environment, long brick-less snakes are the most successful when evaluated on upwards speed. This could be because in small steps, they outperform the other forms, and in high steps, they are the only forms that are long and flexible enough to thrust themselves over the steps. The middle level of scaffolding has the most diverse forms, some of which have bricks, suggesting that there can be more competition when the task environment is not too easy or too difficult.

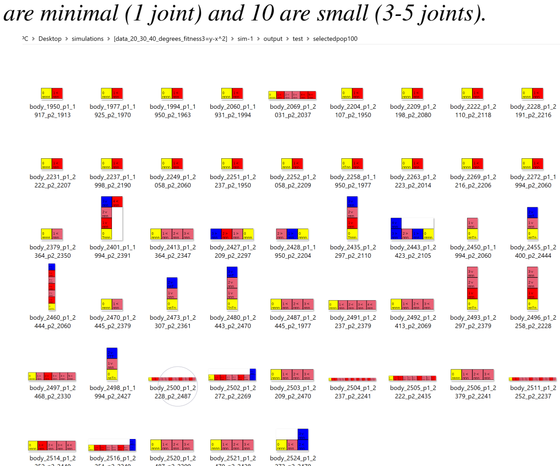
Experiment 2: Tilted World (Horizontal speed)

Similarly to the Step World, the morphologies are homogeneous after 50 generations and have diversified after 75 generations. The dominant morphologies in the 50th generation are long snakes containing bricks (see Figure 15a). After 75 generations, these morphologies still dominate, but we see an increase in the number of brick-less snakes and the number of 1-limbed L-shapes (see Figure 15b). By the 100th generation, dominance has shifted to brick-less snakes, while some bricked snakes and 1-limbed L-shapes remain. The majority of champions are small (< 5 blocks).

Table 3: **Dominant morphologies for Tilt World (Horiz. Speed)** (where L represents the number of "large" morphologies that have more than 5 blocks)
The dominant morphologies change from long bricked snakes (Gen 50) to more varied shapes (Gen 75) to mostly small brick-less snakes (Gen 100).

	Gen 50	Gen 75	Gen 100
Snakes (no bricks)	0	11 (L=6)	37 (L=3)
Snakes (bricks)	48 (L=48)	29 (L=27)	8 (L=1)
L-shaped (1 limb)	0	7 (L=6)	5 (L=2)
L-shaped (2 limbs)	2 (L=2)	3	0
T-shaped (2 limbs)	0	0	0
Other	0	0	0

Figure 11: **100th Generation for Tilt World (Horiz. Speed)**
The morphologies in the final generation are made up of mostly small brick-less snakes (37/50), followed by small bricked snakes (7/50), and 1-limbed L-shapes (5/50). Of the 50 brick-less snakes, 20 are minimal (1 joint) and 10 are small (3-5 joints).



In the smallest 20 degree tilt, long bricked snakes are successful. This may be because the length allows them to cover more distance horizontally while the bricks keep them from falling. When the tilt increases, there are more l-shapes and smaller brickless snakes, and at the maximum tilt, sizes are dramatically smaller. This suggests that the steeper the plane, the more disadvantageous it is to be long (even when there are bricks) because a robot is more likely to slide down the tilted plane than across.

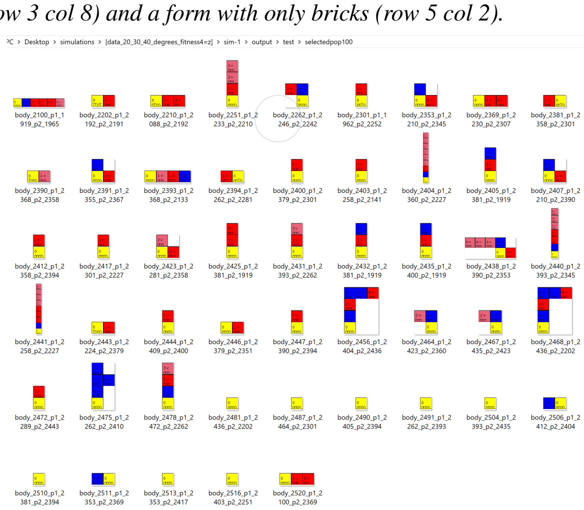
Experiment 3: Tilted World (Upward speed)

Unlike the other two experiments, the morphologies are heterogeneous after 50 generations. The dominant forms are divided between long brick-less snakes and long T-shapes (see Figure 16a). By the 75th generation, the morphologies are even more diverse, with a decrease in the previous dominant forms and an increase in all other categories, in particular L-shapes and forms that combine T-shapes and L-shapes (see Figure 15b). At generation 100, we see a complete loss of the dominant T-shapes from the 50th generation and a lead by small snakes without bricks. In the final generation there are 8 morphologies that are only core components. This could be the result of a system error so they are not included in the table.

Table 4: **Dominant morphologies for Tilt World (Up. Speed)** (where L represents the number of "large" morphologies that have more than 5 blocks)
The dominant morphologies change from long brick-less snakes and T-shapes (Gen 50) to more varied shapes (Gen 75) to small snakes and L-shaped forms (Gen 100).

	Gen 50	Gen 75	Gen 100
Snakes (no bricks)	22 (L=20)	10 (L=5)	20 (L=0)
Snakes (bricks)	2 (L=2)	4 (L=3)	11 (L=3)
L-shaped (1 limb)	1 (L=1)	11 (L=9)	5 (L=0)
L-shaped (2 limbs)	1 (L=1)	6 (L=5)	4 (L=0)
T-shaped (2 limbs)	24 (L=23)	17 (L=12)	0
Other	0	2 (L=2)	2 (L=0)

Figure 12: **100th Generation for Tilt World (Up. Speed)**
The dominant morphologies in the final generation are relatively diverse. They are split between small brick-less snakes (20/42), small bricked snakes (7/42), and small L-shapes (9/42). There are two unusual shapes: a form with a limb attached to an L-shape (row 3 col 8) and a form with only bricks (row 5 col 2).

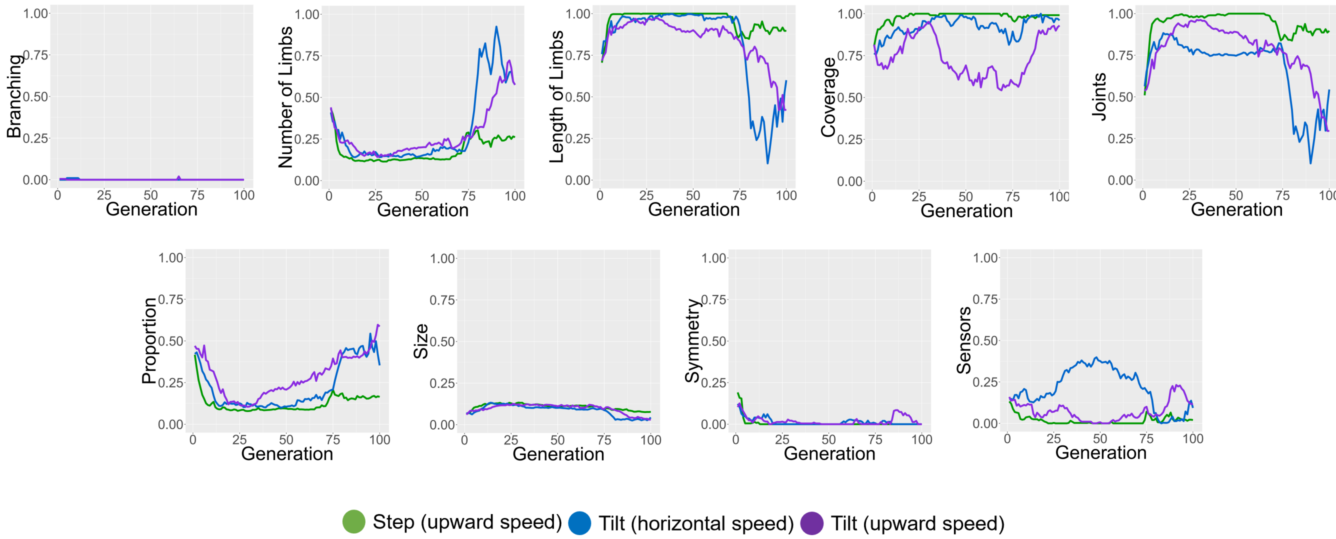


In the smallest 20 degree tilt, long brick-less snakes and long T-shapes may be successful because the angle is small enough that a long body is not disadvantageous. It can propel the robot up the plane. When the tilt increases, a decrease in robot size (to minimal of 2-5 blocks) may suggest that smaller shapes are more useful for avoiding to slide down when the angle is steep. The small sizes may be a result of a system error.

Morphological descriptors

Branching. Branching is relatively low and stable across the three scaffolding levels. For tilted world (up), there is a small spike in the middle of the second scaffolding level.
Number of Limbs. The number of limbs is relatively low until the third level of scaffolding, where there is an increase in the number of limbs. This increase is more pronounced for the tilted worlds than for the step world, suggesting that limbs are useful when tilted worlds are very steep (40 deg).
Length of Limbs. This descriptor is inversely proportional to Number of Limbs. When tilted worlds are very steep, long limbs may become less useful because it is better to use extra modules for new limbs.
Coverage. The step world (up) has the highest coverage because it has the most snake forms. The tilted world (up) has the lowest coverage because it has many long T-shapes and L-shapes in the first and second scaffolding levels. The coverage for the tilted world increases in the third scaffolding level (possibly because the size decreases).
Joints. Joints follow similar trends as Length of Limbs. One difference is that for tilted world (horiz.), joints is lower than the length of limbs in the first and second scaffolding level (possibly because there are long shapes that use bricks/sensors instead of joints).
Proportion. For tilted world (up), there is a gradual increase in proportionate shapes across all scaffolding levels (starting from the 25th generation) while for tilted world (horiz.) the increase happens suddenly after the 75th generation.
Size. Size remains constant until the third scaffolding level, where it decreases in the tilted worlds. The decrease happens quickly for tilted world (horiz.) and gradually for tilted word (up). This suggest that in tilted worlds, smaller sizes are preferred when the angle is steepest (possible explaining the increase in coverage in the final generations).
Symmetry. Symmetry remains low across the three scaffolding levels. For tilted world (up), there is a small increase in symmetry in the third scaffolding level.
Sensors. For the tilted world (horiz.), the descriptor for sensors is high in the first two scaffolding levels. As we saw in the dominant morphologies, there are long shapes with bricks in these levels, which can result in more sensors and fewer joints. As the tilt increases, the number of sensors decrease (perhaps due to decreases in size). It could be that at a small angle (20 deg), a long bricked robot can still utilize its length and bricks to cover a large horizontal distances and keep from slipping. But at steeper angles (40 deg), it is more useful to be small with more than one limb.

Figure 13: **Morphological descriptors averaged for a population of 50 along 100 generations (1 run)**



Discussion

The morphological descriptors of all experiments appear to be affected by the three scaffolding levels. The changes displayed in the tilted world experiments are gradual for upwards speed and quick for horizontal speed, while the changes diplayed in the step world experiment are less dramatic than those of the tilted worlds.

The Tilted World (Upwards Speed) has low-coverage shapes with few long limbs for 20 and 30 degree tilts. Then in the maximum tilt (40 deg), there is a decrease in low-coverage shapes in favor of smaller morphologies with more short limbs. This is supported by the dominant morphologies examined earlier in the paper, namely the occurrence of long L-shapes and T-shapes at the end of the first two scaffolding levels and small shapes in the final generation. The results suggest that when robots are tasked with moving up a tilted plane, low-coverage shapes are useful up to a certain tilt (40 degrees), after which smaller robots take over.

The Tilted World (Horizontal Speed) has morphologies with few long limbs and bricks/sensors for 20 and 30 degree tilts. In the maximum tilt (40 deg), there is a decrease in sensors in favor of smaller morphologies with more short limbs and fewer sensors. These trends are backed up by our previous observations that the dominant morphologies were long bricked snakes in the 50th generation, long bricked snakes and L-shapes in the 75th generation, and small shapes with fewer bricks in the 100th generation. These patterns may be implying that when trying to move horizontally across a tilted plane, bricks and long morphologies are useful up to a certain tilt (40 degrees), after which smaller robots take over.

For the Step World (Upwards Speed), the trends remain relatively stable until the 75th generation, where there is typically a mild disruption. This makes sense because the dominant morphologies are brickless snakes in the 50th and 100th generation, but more diverse in the 75th generation. It could be that the medium scaffolding level, the 0.10 cm step size, was the only level that permitted the evolution of diverse forms because the simple level was too easy for one morphology and the hard level was too hard for most morphologies.

In conclusion, we have investigated the effect of scaffolding in environments and its impact on dominant morphologies and morphological descriptors. We suggest further lines of research into the behaviours that accompany the dominant morphologies and into the effect of fine-grained scaffolding with more than three levels.

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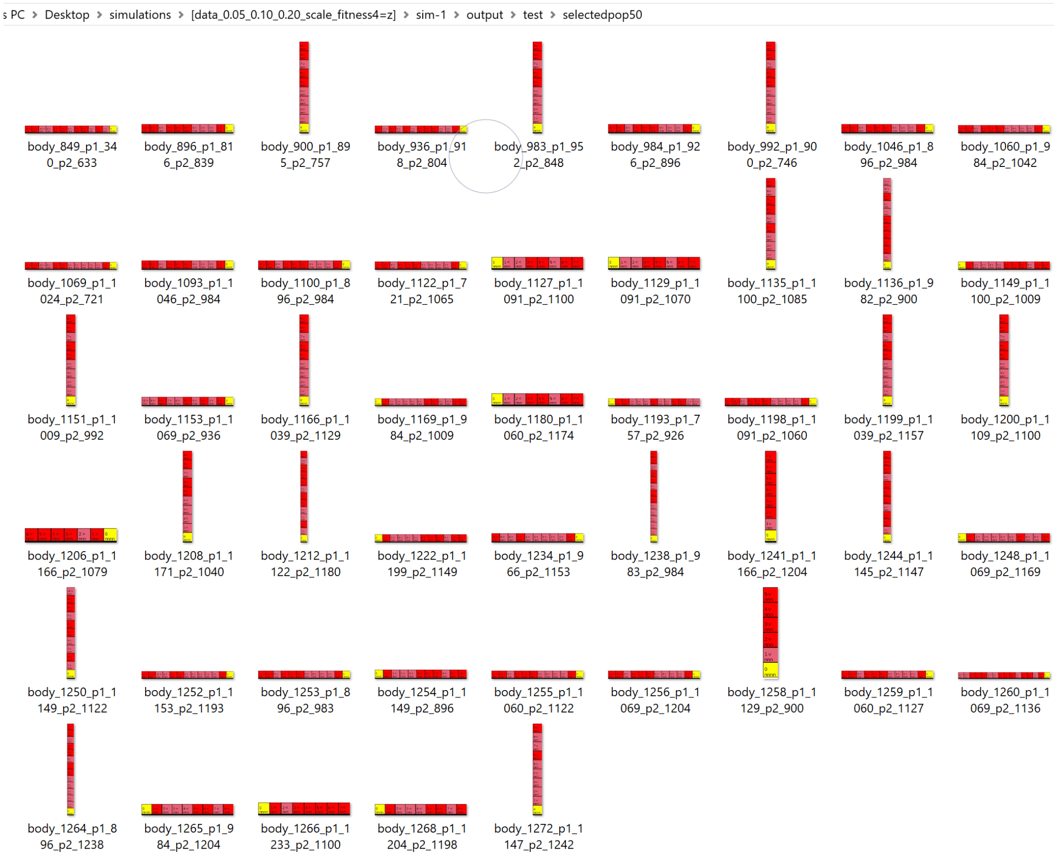
Appendix

Table 5: Elements in Alphabet representing Commands (cur.=current and dest.=destination)

	Morphology-mounting commands
addr	add the next module to the right
addf	add the next module to the front
addl	add the next module to the left
	Morphology-moving commands
moveb	move reference to the module at the back
mover	move reference to the module to the right
movef	move reference to the module to the front
movel	move reference to the module to the left
	Controller-change commands
bnode	add a new node to the neural network
bedge	add a new edge to the neural network
bperturb	perturb the weight of an edge
bloop	add a self-connection edge to the network
	Controller-moving commands
bmvFTC	move current edge origin-reference to a child
bmvFTP	move cur. edge origin-reference to a parent
bmvFTS	move cur. edge origin-reference to a sibling
bmvTTC	move cur. edge dest.-reference to a child
bmvTTP	move cur. edge dest.-reference to a parent
bmvTTS	move cur. edge dest.-reference to a sibling

Figure 14: **Morphologies in Selected Populations for Step world (Up. Speed)**

(a) Gen 50: 0.05 cm



(b) Gen 75: 0.10 cm

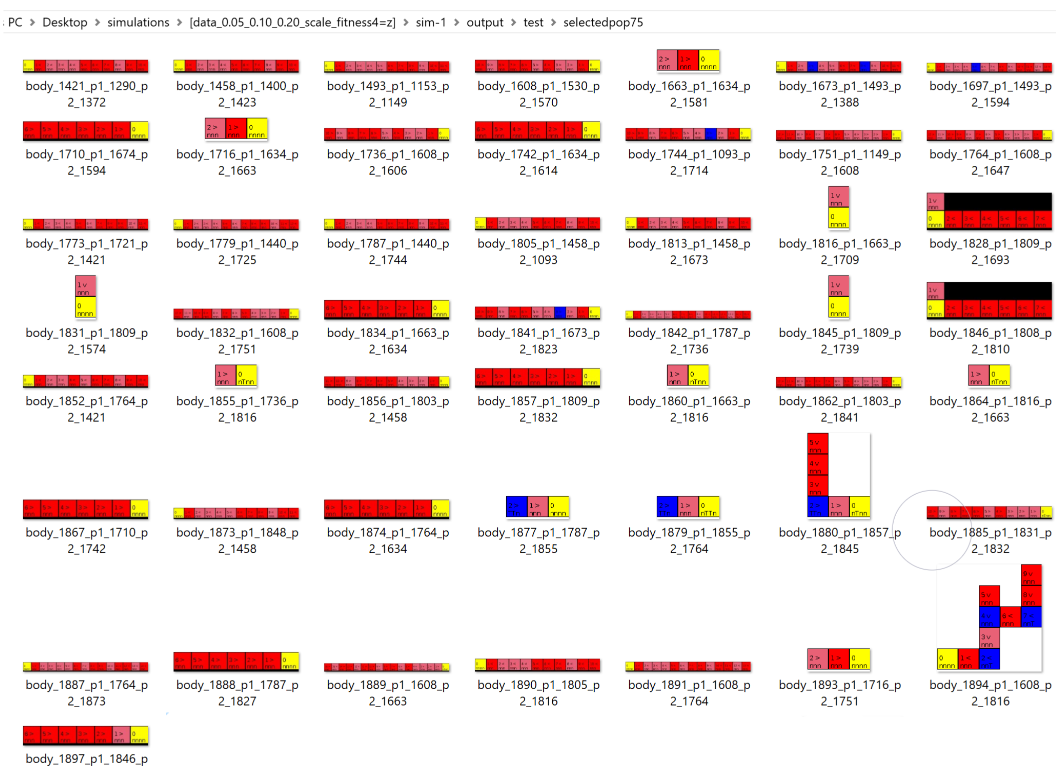
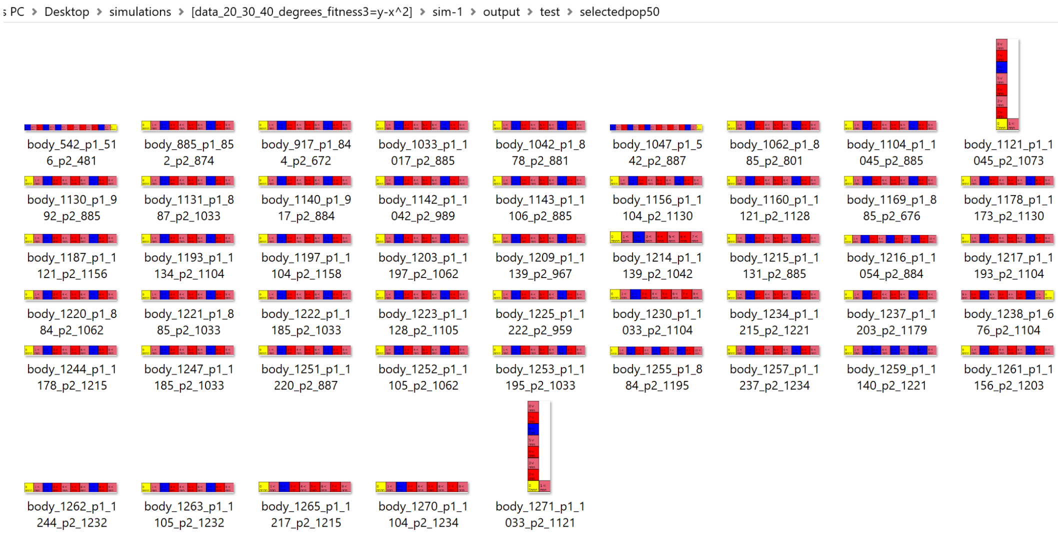


Figure 15: **Morphologies in Selected Populations for Tilt world (Horiz. Speed)**

(a) Gen 50: 20 degrees



(b) Gen 75: 30 degrees

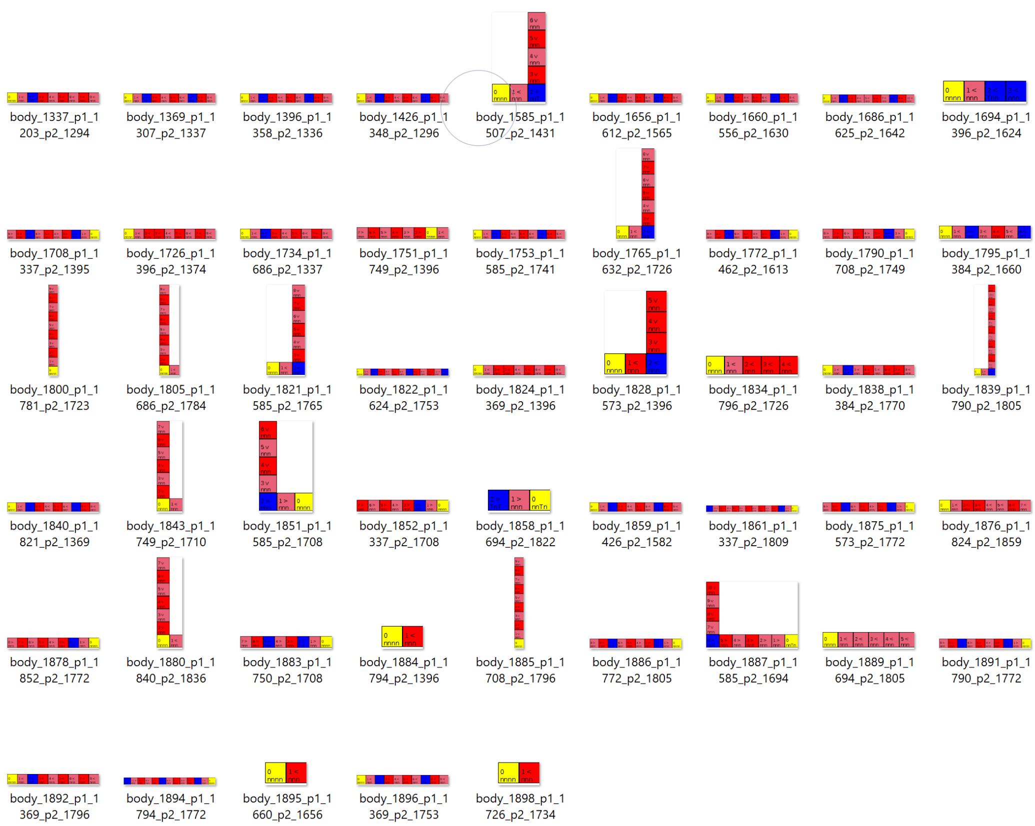


Figure 16: **Morphologies in Selected Populations for Tilt world (Up. Speed)**

(a) Gen 50: 20 degrees

(b) Gen 75: 30 degrees