Robot Parkour

Tianshi Chen
Vrije Universiteit Amsterdam
Amsterdam, Netherlands
t5.chen@student.vu.nl

Zheng Zhang
Vrije Universiteit Amsterdam
Amsterdam, Netherlands
z.zhang10@student.vu.nl

ABSTRACT

This paper studies the morphology and behavior of evolving populations of modular robots that are able to move in a pre-defined trail placed with different obstacles. Also, this paper explores the possibility and impact of transferring populations of modular robots from a simple environment to a complex one. To assess these properties, we defined four different types of terrain, designed a particular fitness function, and evolved generations of modular robots on them. The result shows that transferring modular robots from an easier terrain to a complex one impacts the robots both morphologically and behaviorally. The result also shows that transferring robots from easier terrain to a complex one has the potential capability to evolve more well-optimized individuals than native complex robots.

KEYWORDS

modular robot, evolutionary computing, environment

ACM Reference Format:
Tianshi Chen and Zheng Zhang. 2018. Robot Parkour. In *Woodstock '18: ACM Symposium on Neural Gaze Detection, June 03–05, 2018, Woodstock, NY*. ACM, New York, NY, USA, 8 pages. https://doi.org/10.1145/1122445.1122456

1 INTRODUCTION

Evolutionary robotics(ER) is a new technique for the automatic creation of autonomous robots, it views robots as autonomous artificial organisms that develop their own skills in close interaction with the environment and without human intervention. [6] This study focuses on the morphological and behavioral changes in evolved robots as they evolve to adapt to different terrains. Each robot is composed of a controller (brain) and a body with a number of joints. Morphological variances are frequently ignored in ER research, which has primarily concentrated on the robot's brain, while advanced intelligence requires both the body and the brain.

There are four types of terrain used in the study: a perfectly horizontal surface with no obstacles, an acute slope, a potholed terrain with obstacles, which we will call rugged, and mixed terrain, a six-stage trail with features in previous terrain randomly aligned.

With an evolutionary algorithm and simulation, the modular robots first evolved on the three simple terrains for generations and then transferred to the mixed terrain for extra generations of evolution, respectively. The result shows that transferring impacts the robot's gaits on flat terrain significantly. The previous terrain influenced the behavior of modular robots which transferred to another environment as well. Also, the morphology of robots previously evolved in flat and rugged terrain is influenced because of the transferring.

To analyze the performance of transferring robots from one environment to another, we evolved a population of robots purely evolved on mixed terrain.

Sections 2 and 3 introduce the background of modular robot evolution and the modular robot itself. In section 4, we explain our experiment build, including the algorithm, simulation, and fitness function. In section 5, we discussed the result of the experiment from the morphology and behavior of modular robots. Section 6 concludes this paper and shows the future research path.

2 BACKGROUND AND LITERATURE

In nature, evolution produces heritable changes in the phenotypes of organisms over multiple generations for better adaptation to the environment. In robotics, evolution has been proposed as a nature-inspired approach to avoid the bias and limitations introduced by human designers and to produce better-adapted robots to environmental changes. [1] Also, evolutionary robots are considered as autonomous artificial organisms that develop their own control system and body configuration in close interaction with the environment without human intervention. [2] ER demonstrated a great potential for synthesizing efficient robot controllers that exploit the properties of a fine-grained sensorimotor coordination. Similar results were difficult to obtain with traditional engineering/AI approaches, mainly due to the lack of precise models to deal with the inherent stochasticity and uncertainty of the robot–environment interaction. [9] The first study on the evolution of robot morphology was done by Karl Sims in 1994. It was found that both the morphology of robots and the nervous system that controls muscle power are genetically determined. That morphology and behavior can adapt to each other as they evolve simultaneously. [8] Reem J. Alattas1, Sarosh Patel, and Tarek M. Sobh suggested in their research: the modular evolving robot, which is made up of numerous joints or modules and has more degrees of freedom (DOF). In other words, to allow the robot to self-reconfigure in order to accomplish various tasks in different environments. [1] In this study [3], the authors investigate how different environments affect the evolution and morphological changes of modular robots, as the evolutionary success of individuals depends on how well they are adapted to their environment and the different environments they are placed in. Previous work here has focused more on the effects of the environment on robot evolution under a particular task. The results of their study show that the morphological and behavioral characteristics of the final population are clearly differentiated by the environment.

Woodstock '18, June 03–05, 2018, Woodstock, NY

ACM ISBN 978-1-4503-XXXX-X/18/06...$15.00
https://doi.org/10.1145/1122445.1122456

3 MODULAR ROBOT

The morphology of robots in this paper is flat, composed of one head and multiple limbs. There is only one core module, which is the robot's brain, and several fixed parts next to or around the brain. To simplify the description, we consider the brain and the fixed part body to compose the head of the robot. Body parts that help move the robot are considered the limbs. As Figure1 shows, the red part is the head, and the white part is the limb.

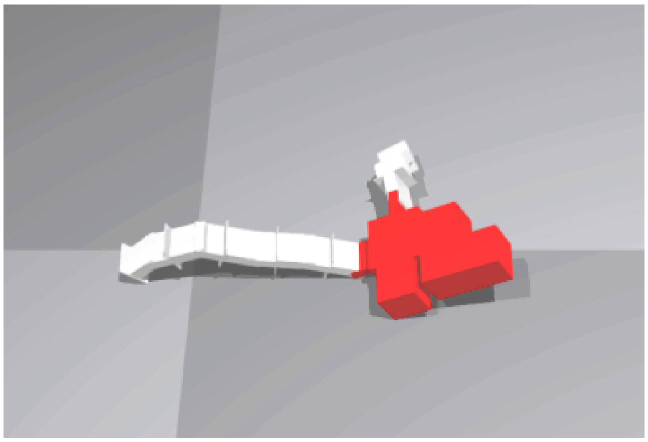

Figure 1: Modular robot in IsaacGym

Note that our modular robots were not equipped with any sensor, so the movement of robots is generated by a CPG network installed in their core. Hence, the robots are performing entirely random behaviors. Sensors could be used to suppress or encourage specific movements of robots[5], yet, our robot design did not implement this function.

4 EXPERIMENT

In our experiment, we first evolved robots with a population of 100 in three different terrains. Then we transferred them into a mixed terrain to see what would happen to them in both morphology and behavioral. As a comparison, we evolved 200 generations of a 100 populations robot natively on mixed terrain.

4.1 Evolutionary Algorithm

We set the population size of the robot at 100 during the evolution, and these robots generated 100 offspring for each generation. We implemented a 2-individual tournament selection based on fitness value to select the parents and maintain the population size. To increase the diversity of robots, mutation and crossover methodology was also set, both for the brain and the body, using MultiNEAT[7], a neuroevolution framework. Besides, to increase the diversity of the robot, the first generation is composed randomly, and the whole process is repeated ten times for different results.

4.2 Simulation

As we were trying to explore the most suitable robot design to finish the parkour task, the most important part is the simulation, since the reproduction and selection of the robot is based on the result of the simulation. In this section, we will explain our simulation from aspect of terrain design and the simulation process.

4.2.1 Terrain design. We utilized NVIDIA's IsaacGym simulation platform, which provides a high-performance learning platform to train policies for various robotics tasks directly on GPU-integrated and allows for the creation of different terrains for robot movement. [4] We chose three types of terrain, flat, tilted, and rugged. The flat terrain is a baseline of all the other terrain. As for the tilted terrain, robots were supposed to climb along a slope with a rate of 0.10. Rugged, however, is complex, composed of randomly placed three centimeters of height mountains and three centimeters of depth valleys. Each terrain is set to 6 meters long and 3 meters wide. All the three terrains show in Figure2, Figure3 and Figure4.

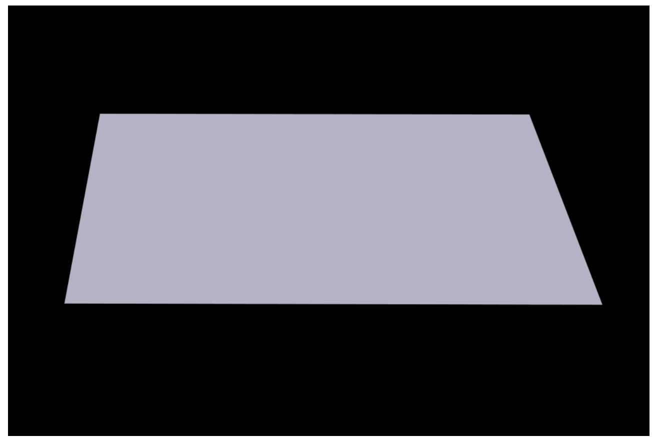

Figure 2: Flat terrain

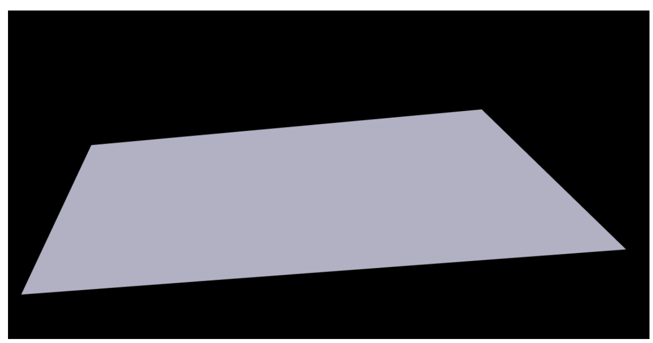

Figure 3: Tilted terrain

To make it more like a parkour task, we build a combination of the three terrains above. It is a 6-stage trail, with two of each terrain randomly aligned in a sequence. The size of this combined terrain is the same as the single-featured terrain, shown in Figure5

Note there is a boundary of the built terrain, which is not protected by a wall. If we create a barrier to prevent robots from falling off the playground, there might be robots exploit the wall to cheat the evaluation mechanism. Thus, the robots could fall off the built terrain if they move in incorrect directions. So we developed a

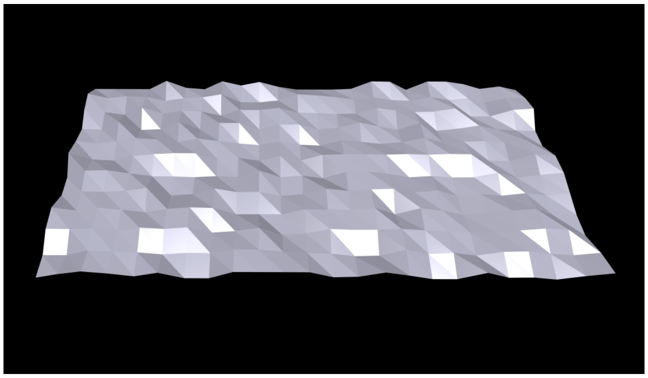

Figure 4: Rugged terrain

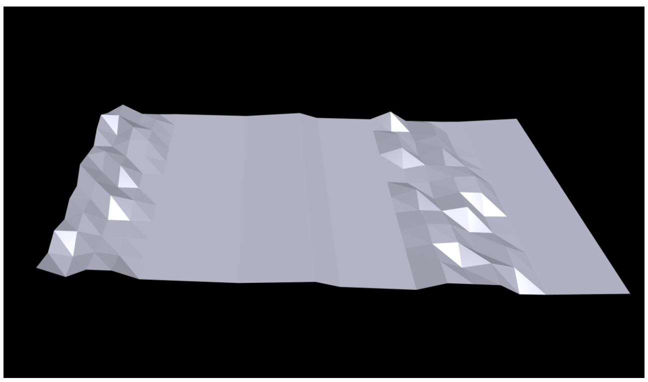

Figure 5: Mixed terrain

detection method to find out suicidal robots, which we will explain in the fitness function section.

4.2.2 Simulation process. To initiate the simulation, we located a starting and ending point, which would be transmitted into IsaacGym as parameters. Horizontally, The starting point is in the middle of the trail, approximately 0.5 meters away from the left edge of the terrain. The ending point is at the other side, 0.5 meters away from the edge.

When starting each simulation round, the robots were placed at the starting point facing four different directions. After a one-minute simulation, the last position of them would be extracted and calculate their speed in different directions and also the fitness value.

4.3 Fitness Function

The fitness function is the most crucial part of our experiment because the robots were supposed to move in a straight trail. If the robot moves too far from the correct direction, it will fall off the built terrain. We will explain our fitness function from suspicious displacement detection and linear constraint in this section. The fitness function as below, S refers to if suspicious displacement were detected, FactorX as a penalty factor, dis_x, dis_y, dis_z and dis refer to the displacement on x, y, z-axis and the total displacement respectively. A visualization of our fitness function shows in Figure6

$$Fitness = \begin{cases} speed\_y + speed\_y^2 - FactorX & (S = 0) \\ -\inf & (S = 1) \end{cases} \tag{1}$$

$$FactorX = \begin{cases} 0 & (speed\_x < 1.5) \\ speed\_x & (speed\_x >= 1.5) \end{cases} \tag{2}$$

$$speed\_x = abs(dis\_x)/t \tag{3}$$

$$speed\_y = dis\_y/t \tag{4}$$

$$S = \begin{cases} 0 & (dis < 5 \ \ \& \ \ dis\_z < 0.5) \\ 1 & (otherwise) \end{cases} \tag{5}$$

$$\begin{cases} dis\_x = last\_pos\_x - begin\_pos\_x \\ dis\_y = last\_pos\_y - begin\_pos\_y \\ dis\_z = last\_pos\_z - begin\_pos\_z \end{cases} \tag{6}$$

$$dis = \sqrt{dis\_x^2 + dis\_y^2 + dis\_z^2} \tag{7}$$

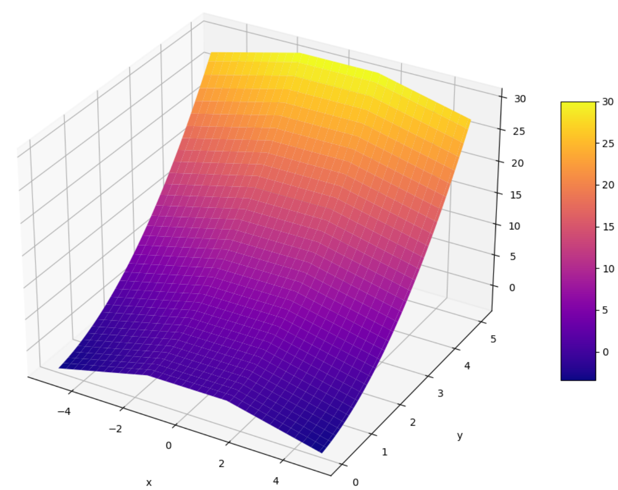

Figure 6: Visualized fitness function

4.3.1 Suspicious displacement detection. In the simulation, there are two situations that we must handle, errors in the simulation environment and the robots falling out of the terrain. In some rare cases, when robots spawn in the IsaacGym, there could be a huge displacement in random directions, this could significantly impact our experiment, so we set a threshold of five meters to detect this kind of error. A robot with a displacement larger than 5 meters would be considered an error, and the fitness value would be set to minus infinite. Similarly, to filter out the falling robot, we calculate its displacement on the z-axis, which refers to the vertical displacement. If it drops 0.5 meters, it will be recognized, and the fitness value will be set to minus infinite.

4.3.2 Linear constraint. As a parkour task, the robot has to be constrained to move along the correct direction, in our case, the y-axis. We implemented not only a penalty for moving in the wrong direction, the x-axis, but also a bonus in the correct direction. In the penalty part, we set a linear penalty on the speed on the wrong axis. Besides, a tolerance value was added, allowing a slight movement on the x-axis. If the speed_x is slower than 1.5 centimeters per second, we will ignore its influence. For the bonus, we set an exponential in speed_y to contribute to the fitness value.

5 RESULTS AND DISCUSSION

Generally, the result of the experiment is not satisfying. After 100 generations of evolution, some robots on flat and tilted terrain were able to move along to the destination point. However, no individuals who developed on rugged terrain acquired a satisfying result. On the mixed terrain, robots performed even worse. We will discuss this phenomenon in this section.

5.1 Morphology

In this section, we will evaluate the morphology of robots that evolved on different terrain. Head size, body size, and head ratio are the three basic measurements of the robot. Furthermore, we identify and evaluate the form of the robot, into three shapes, mono-limb, dual-limb, and multi-limb.

Since modular robots consist of block cubes, it is possible to measure the morphology of robots by counting the number of blocks of the heads and limbs. The overall body shape could also be measured.

5.1.1 Morphology descriptor. **Head** refers to the fixed parts of a robot. In Figure7, the yellow part is the brain where a core is installed and running the CPG network. The blue part is also fixed and cannot perform any motion. In this paper, the brain and fixed body parts are called the head. Hence, a modular robot could have multiple heads but only one brain.

Limb is the part of robot that performs motions randomly to move its body, which is the red parts in Figure7. Note that we ignore the limb with a length of fewer than two blocks because a single-block limb does not influence the overall movement. Also, if a head is connected with a limb that connects to the head on the other side, we will consider it a part of the limb in the shape context, but we count its size as a head in the body size context. Because this kind of "head" actually performs as part of the limb when robots are in actual movement, so we consider them as a limb in shape, but it is fixed and cannot actively drive the robot, so we count it as a head in size. One example is the head with block no. 3, 5, 6, 12, 14, 15 in Figure7. This head is connected to limb no. 1, which connects to the brain. We consider this head a part of limb no. 1 in shape context but count them as head in size context.

5.1.2 Discussion. We chose the best two robots from each run and recognized their shapes before and after transferring and evolving them in the mixed terrain. From Table1, Table2, and Table3, we could see that in the first 100 generations of robots from flat and rugged terrain, they evolved more limbs than tilted. After transferring the robots to the parkour trail for another 100 generations of evolution, the robot from flat terrain has an increase in limbs. In contrast, for rugged terrain, the number of limbs decreased. Besides, No impact on the robot from tilted terrain. In Table4, the morphology descriptor of robots evolved on mixed terrain is shown. In this population, the body shape did not significantly altered, and it is similar to the robots transferred from tilted terrain.

We compared the morphology feature of robots from each environment and the result of transferring terrain, as Table5, Table6 and Table7 show, the robots evolved on flat terrain tended to acquire

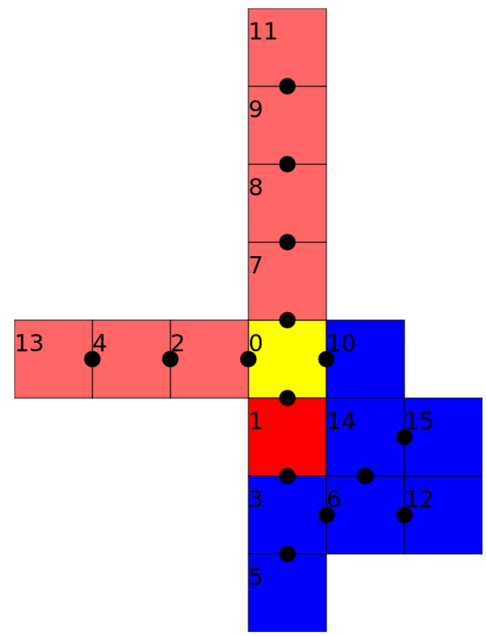

Figure 7: An example of modular robot

	Mono-limb	Dual-limb	Multi-limb
Origin	0	8	12
Transferred	0	5	15

Table 1: Robot's shape transferred from flat terrain

	Mono-limb	Dual-limb	Multi-limb
Origin	3	10	7
Transferred	2	10	8

Table 2: Robot's shape transferred from tilted terrain

	Mono-limb	Dual-limb	Multi-limb
Origin	0	7	13
Transferred	4	4	12

Table 3: Robot's shape transferred from rugged terrain

	Mono-limb	Dual-limb	Multi-limb
Gen 100	3	8	9
Gen 200	3	9	9

Table 4: Robot's shape evolved on mixed terrain

larger or more limbs. After transferring them from flat terrain to the parkour trail, the ratio between the size of head and body had a noticeable increase, while the average number of limbs remained still. On the contrary, robots evolved in rugged terrain and had a decreasing sizes after transferring them to mixed terrain. The robots trained on Rugged terrain tend to have larger heads and smaller limbs when compared with robots evolved on Flat terrain. For robots that evolved on tilted terrain, they have relatively small sizes for both head and limb, the average size of the limb slightly increased after transfer to the mixed terrain. The head size ratio for robots that evolved on rugged and tilted terrain had a relatively similar value before and after transferring, but for robots that evolved on Flat terrain had a smaller ratio than the rest two but had a greater value after transferring. The differences between the origin and transferred head size ratio demonstrate how much morphology changes that robots made to adapt to new terrain. In Table8, we could recognize that for the robots naturally evolved on mixed terrain, their head is getting smaller over generations, which is very different from any other populations. We could not recognize any correlations with robots from other terrains in this criteria. The morphology figure of all the four populations from flat, tilted, rugged, and mixed is shown in Figure8, Figure10, Figure9, and Figure11 respectively.

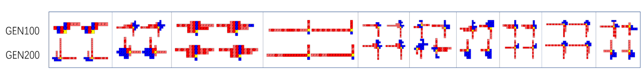

Figure 8: Robots evolved on flat terrain and transferred

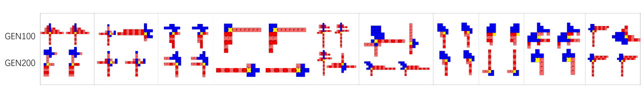

Figure 9: Robots evolved on rugged terrain and transferred

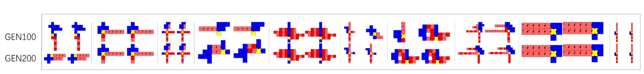

Figure 10: Robots evolved on tilted terrain and transferred

5.2 Behavioural

5.2.1 Gait descriptor. The behavior of robots is described in four types: **walking**, **rowing**, **rolling**, and **mixed**.

Walking in this paper refers to two or more limbs driving the body in turns instead of walking as a homo erectus. Rowing means different components help move the body simultaneously. rolling implies the robot's movement relies on rolling the body instead of

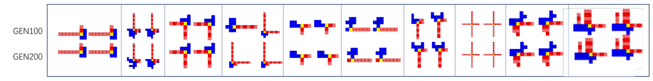

Figure 11: Robots evolved on mixed terrain

	avg.Head	avg.Limb	avg.All	Head size ratio.
Origin	7.2	16.45	23.65	0.31
Transferred	8.25	16.3	24.55	0.51

Table 5: Body size of robots evolved on Flat terrain

	avg.Head	avg.Limb	avg.All	Head size ratio.
Origin	9.4	14.7	24.1	0.41
Transferred	8.25	12.75	21	0.42

Table 6: Body size of robots evolved on Rugged terrain

	avg.Head	avg.Limb	avg.All	Head size ratio.
Origin	7.2	10.35	17.55	0.41
Transferred	7.4	11.1	18.5	0.40

Table 7: Body size of robots evolved on Tilted terrain

using limbs. However, some robots have complex behavior patterns. For example, one limb is rolling while another limb does not. We consider this motion as mixed.

In the Table9, the behavior of ten of the best-performed robots from different terrains are collected, and in Table10, the behavior statistic of the best ten robots transferred from previous terrains to mixed terrain is shown.

From these tables, we recognized that most of the best-fitted robots were walking, and only a few were rolling. The reason that almost no robot was rolling is that, in most cases, the robots have one limb rolling and others walking and rowing. Thus its behavior is identified as mixed. Overall, changing environments did not significantly impact the behavior of robots that evolved on tilted and rugged terrain, but for robots that evolved on flat terrain, the transfer of terrain increased the behavior of rowing.

5.2.2 Trajectory. The trajectory of the robots that evolved in flat, rugged, and tilted terrain are shown in Figure12, Figure13 and Figure14 respectively, in these figures, the destination is at the right side. We can see that robots from flat terrain have the best performance since it is the easiest terrain to move on. In rugged terrain, only a few robots move toward the destination for one meter, while in tilted terrain, no robot can move a single meter to the destination. In rugged terrain, it might be because the terrain is too complex for the robot that they can hardly evolve an individual that performs better. However, in tilted terrain, most robots move in the wrong direction. Since moving to the destination point is climbing, it is easier for robots to move aside because they will not be penalized for less than 0.9-meter displacement.

However, after another 100 generations of evolution transferred the modular robots to the mixed terrain, the robots seem to be able to move faster. The trajectories of robots' performance on the mixed

	Avg.Head	Avg.Limb	Avg.All	Head size ratio
Gen 100	7.95	11.05	19	0.42
Gen 200	7.6	11.9	19.5	0.39

Table 8: Body size of robots evolved on mixed terrain

	Walking	Rowing	Rolling	Mixed
Flat	5	0	1	4
Tilted	4	5	0	1
Rugged	5	2	0	3

Table 9: Behavior of robots in different terrain

	Walking	Rowing	Rolling	Mixed
Flat	3	4	0	3
Tilted	5	4	0	1
Rugged	5	2	2	1

Table 10: Behavior of robots transferred to mixed terrain

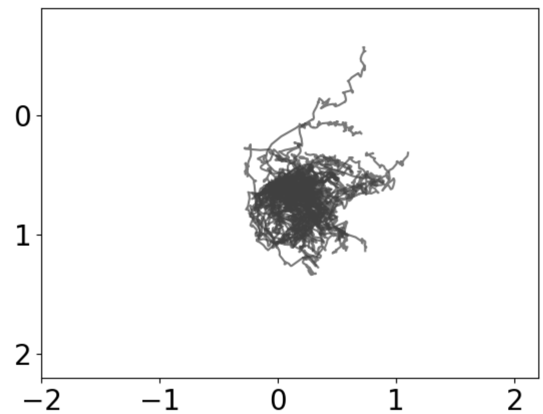

Figure 13: Trajectory of robots on rugged terrain - 100 generations

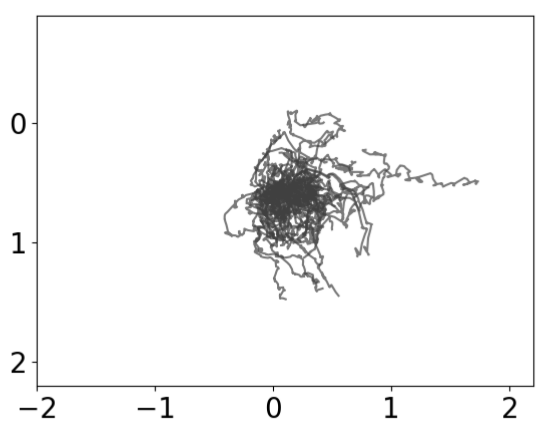

Figure 12: Trajectory of robots on flat terrain - 100 generations

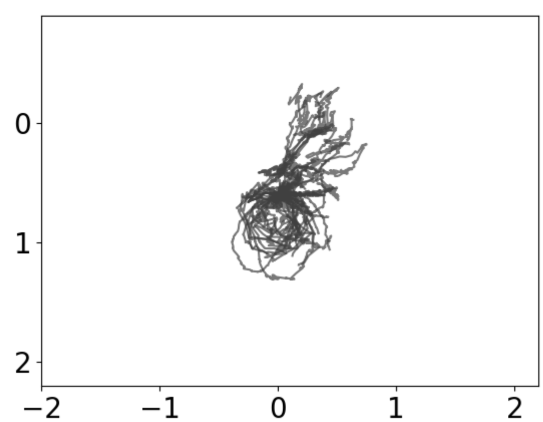

Figure 14: Trajectory of robots on tilted terrain - 100 generations

terrain are shown in Figure15, Figure16 and Figure17. From these trajectories, we could see that robots from every terrain performed better in the mixed terrain. For robots transferred from flat terrain, the trajectory is the most dispersed, but it could also move farther than others. On the other hand, robots transferred from a tilted environment. Their trajectories are the most concentrated, but little robots could move as farther as robots from other terrains.

There could be two reasons the robots on mixed terrain move farther than before. One is the extra 100 generations of evolution, which evolved features that make the robots move faster. Another is that the mixed terrain has six randomly aligned phases. Some mild stages, e.g., flat terrain, could be placed at the beginning of the parkour, which could also lead to an increase in distance. Similarly, since robots evolved on tilted terrain are more focused on the climbing skill instead of running faster, which caused slower movement on the parkour trail.

However, when the previous populations were compared with the trajectory of native mixed terrain robots, we could see that although the native population could move farther than the other three terrains in the first 100 generations, which is shown in Figure18, it still lose to the robots transferred from flat terrain in 200 generations. The number of individuals who could move farther is approximately the same as robots transferred from rugged terrain. The trajectories of native mixed terrain robots in 200 generations are shown in Figure19. This might indicate that modifying the environment could cause more diversities in the population and thus create more possibilities to generate some well-optimized individuals.

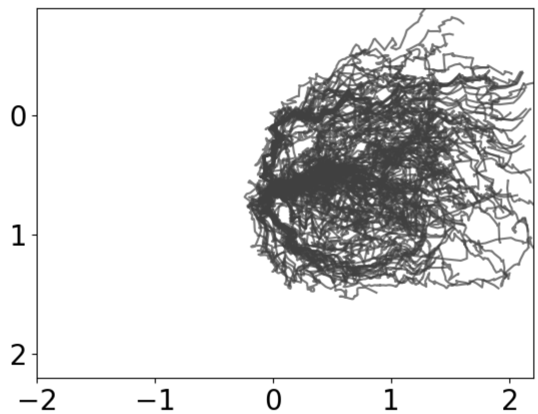

Figure 15: Trajectory of robots on flat terrain - 200 generations

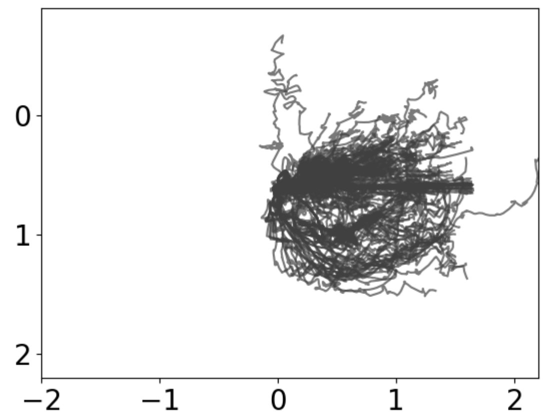

Figure 17: Trajectory of robots on tilted terrain - 200 generations

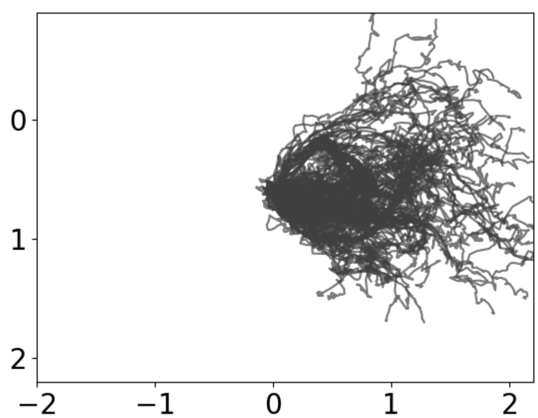

Figure 16: Trajectory of robots on rugged terrain - 200 generations

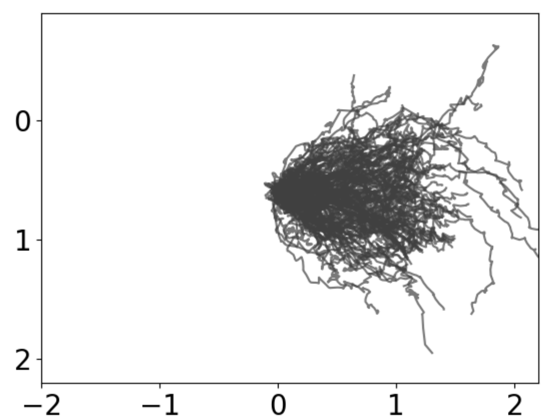

Figure 18: Trajectory of robots on mixed terrain - 100 generations

5.2.3 Cheating Robot. As shown in the trajectory figures, the trajectories of robots evolved on all terrains have some "arcs". This is a symbol of robots cheating on the experiment build. In our experiment, as a simulation time of one minute was implemented, the robots found a way to move easier through the valleys between the hills and achieve a high fitness score within the simulation time. However, these robots could never arrive at their destination because they would eventually return from the farthest point or fall off the terrain. Extending the simulation time could somewhat mitigate this because the robot would get a penalty if they were not on the right track, which could be detected after the simulation. However, this method requires much more time to finish the evolution process, so we did not implement it.

Before we implemented the suicidal detection, we found there were robots with the highest fitness score but they move to the edge of terrains and fell off intentionally. Although a suspicious displacement detecting function is integrated with the revolve2, the robots still exploit the feature of the terrain builds to acquire a high score. Falling detection mitigated this kind of behavior, but we are still unclear about the reason behind them.

5.3 Limitation

First of all, the terrains we built were not enough, they were designed based on the three types of playground, which is too few for a real parkour task. To reduce the impact of this, we made the last parkour trail a random combination.

IsaacGym itself is also a limitation, a single simulation instance takes up more than four-gigabyte graphic memory, significantly drawback the number of threads that work at the same time. We choose to use it because it integrated with different terrain that we

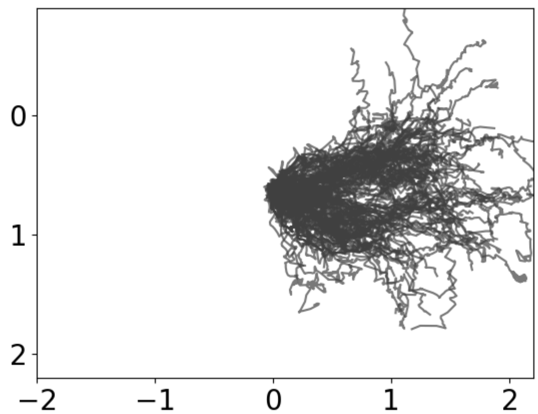

Figure 19: Trajectory of robots on mixed terrain - 200 generations

could modify to adapt our parkour tasks. Thus, other light-weighted robot simulation software such as mujoco could be a better choice.

In the experiment, the population size could be set larger to increase diversity so that more possibilities could be found, and a more powerful fitness function could be implemented to encourage the robots to move toward the destination point. Also, the simulation time should be extended because, in the current setting, non of the robots were able to reach the destination point of the parkour task.

6 CONCLUSION AND FUTURE WORK

In general, we researched the influence of transferring the evolution of modular robots from one environment to another. We built four types of parkour trails, set up our fitness function, and discussed the result from both morphological and behavioral. In morphology, we discussed the size of the heads and bodies of robots that evolved in four different terrains, as well as the different impacts in their shapes. While in behavior, we discussed the gaits and trajectories change of robots from different environments. Besides, cheating behavior and its mitigation methodologies are discussed. These lead to the conclusion that transferring modular robots from one environment to another would significantly impact their morphology and behavior. Moreover, more individuals in populations transferred from flat terrain move farther in mixed terrain than native mixed terrain robots.

Much work remains to be researched, such as implementing more different terrains into this topic, mixing the individuals from different populations of modular robots evolved in multiple terrains and evolving them together in a new environment to see what would happen, or even extending the topic from modular robots to other entities.

REFERENCES

[1] Reem J Alattas, Sarosh Patel, and Tarek M Sobh. 2019. Evolutionary modular robotics: Survey and analysis. *Journal of Intelligent & Robotic Systems* 95, 3 (2019), 815–828.
[2] Josh C Bongard. 2013. Evolutionary robotics. *Commun. ACM* 56, 8 (2013), 74–83.
[3] Matteo De Carlo, Daan Zeeuwe, Eliseo Ferrante, Gerben Meynen, Jacintha Ellers, and A.E. Eiben. 2020. Robotic task affects the resulting morphology and behaviour in evolutionary robotics. In *2020 IEEE Symposium Series on Computational Intelligence (SSCI)*. 2125–2131. https://doi.org/10.1109/SSCI47803.2020.9308272
[4] Viktor Makoviychuk, Lukasz Wawrzyniak, Yunrong Guo, Michelle Lu, Kier Storey, Miles Macklin, David Hoeller, Nikita Rudin, Arthur Allshire, Ankur Handa, et al. 2021. Isaac gym: High performance gpu-based physics simulation for robot learning. *arXiv preprint arXiv:2108.10470* (2021).
[5] Karine Miras and Agoston E Eiben. 2019. Effects of environmental conditions on evolved robot morphologies and behavior. In *Proceedings of the Genetic and Evolutionary Computation Conference*. 125–132.
[6] Stefano Nolfi and Dario Floreano. 2000. *Evolutionary robotics: The biology, intelligence, and technology of self-organizing machines*. MIT press.
[7] S. Ryan P. Chervenski. [n. d.]. MultiNEAT, project website. http://www.multineat.com/,.
[8] Karl Sims. 1994. Evolving 3D morphology and behavior by competition. *Artificial life* 1, 4 (1994), 353–372.
[9] Vito Trianni. 2014. Evolutionary Robotics: Model or Design? *Frontiers in Robotics and AI* 1 (2014). https://doi.org/10.3389/frobt.2014.00013