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EVOLUTIONARY ROBOTICS + 3D PRINTING = RAPID & LOW-COST DEPLOYMENT OF AUTONOMOUS MOBILE ROBOTS

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ABSTRACT

The design, programming and deployment of autonomous mobile robots is a highly complex, time-consuming and expensive endeavor. In this research, we propose an approach which combines evolutionary robotics with 3D printing as an approach for rapid and cheaper method for the fabrication of autonomous mobile robots. We have purposefully chosen the domains of continuum robots and hybrid articulated-wheeled robots as the proving grounds for our approach as these two areas of autonomous robotics have been proven to be among the most complex to design and program as well as being highly cost-intensive to fabricate and deploy in the real world. Capitalizing on the automated design and optimization phases of evolutionary robotics and harnessing the rapid and relatively low cost of 3D printing, our tests show that the time required and cost involved to design, fabricate and successfully deploy evolved and 3D printed continuum robots as well as hybrid articulated-wheeled mobile robots can indeed be observably be reduced. Analysis shows that the transference from simulated to real-world robots is indeed feasible and readily achievable with functioning mobile robots with autonomous behaviors that display a good level of fidelity.

Keywords: evolutionary robotics, 3d printing, continuum robots, hybrid robots, articulated robots, wheeled robots.

INTRODUCTION

Evolutionary robotics is currently a highly favored method for the automated design of robot bodies as well as their controllers for autonomous mobile robots (Nolfi & Floreano, 2004; Doncieux, Bredeche, & Mouret, 2009). However, the vast majority of these approaches achieve transference from simulation reality through conventional fabrication processes that are both labor-intensive, costly and time-consuming (Teo & Abbass, 2003; Chin, Teo & Saudi, 2008; Walker, Garrett & Wilson, 2003). This problem is further compounded when dealing with more sophisticated autonomous robots that have many degrees of freedoms and multiple modes of locomotion, such as those found in continuum robots for the former and hybrid articulated-wheeled robots in the latter cases, respectively.

3D printing, also commonly known as rapid prototyping, has been gaining tremendous interest the over the last decade and in particular the last two years with dramatically reducing costs of the printer hardware itself that has seen entry-level units decrease in prices from hundreds of thousands of dollars to only a few thousand dollars currently (Savitz, 2012). This has entrenched 3D printing in the mainstream within the reach of many everyday users. 3D printing has also seen tremendous growth in the areas of application in recent years where not only common uses of early prototyping of end-user products are made but 3D printing of food items with whole designs that fully customizable in a true 3-dimensional modeling manner (Mosendz, 2014) as well 3D printing of food for space travel currently being explored by NASA (2013) to as far as the realms of bio-engineering where living, human tissue are being 3D printed by using 3D bio-printers (Griggs, 2014).

The use of rapid prototyping for evolutionary robotics was first explored by Lipson & Pollack (2000). However, the evolved robots were not fully autonomous as they had no sensing capabilities and relied solely on fixed motor actions derived from simulation. Although 3D printing is now commonly used in robotics, to the best of our knowledge, there have been no studies conducted that have yet attempted to use evolutionary robotics for the fabrication and deployment of complex autonomous, fully-sensing mobile robots such as continuum and hybrid robots.

Mobile robots have been showing a great success in the real world implementation. For the first time, robots were assisting in an actual urban search and rescue mission of the World Trade Center tragedy on 11 September 2001. The rescue team was assisted by search and rescue robots that had succeeded to discover and subsequently led to the rescue of more than 10 of the tragedy's victims (Angela, 2002). The successful involvement of mobile robots in real life rescue missions as such has garnered much attention from researchers.

In recent years, autonomous mobile robots including both continuum robots and hybrid robots have been designed for various functionalities and purposes. For example, hybrid robots designed for stairs climbing purposes, performing jumping behavior, in-situ robots posture reconfiguration and adaptation to uneven terrains, among many others. In general, continuum and hybrid robots can carry out their missions better in rough and uneven terrains compared to traditional wheeled or legged mobile robots. In particular, hybrid mobile robots utilize the advantages of both wheeled and legged mechanisms while compensating the downside of each other.

There are many successful examples of hybrid mobile robots which are built and designed for wide range of operations. A group of researchers from a few universities in Japan had developed a hybrid wheeled-legged platform through a retracting mechanism inspired by the armadillo (Tadakuma *et al.* 2009). The idea of a retractable wheeled-legged module is that the specially-designed wheels can be transformed into a legs-like mechanism. The PAW robot, proposed by McGill University, is a four-legged robot with wheels equipped at the end of each leg (James, Inna & Michael, 2006). PAW is the first to combine wheeled mode locomotion with dynamically stable legged locomotion. University Lübeck in Germany developed WheeHy which is capable of doing in-situ reconfiguration of its posture (Bojan *et al.* 2010). One of the key features of WheeHy is that the robot can perform adaptation of its posture during its traversal over uneven terrain. National Taiwan University proposed a Quattroped platform with hybrid legged-wheeled locomotion. The proposed system utilizes a transformation method where the morphology of its wheels can be directly transformed into legs (Shen *et al.* 2009).

Gregor used of contexts and context blocks in GP to co-evolve the control and morphology of robots (Gregor, Spalek & Capak, 2012). While co-evolution of robot morphology and behavior has provided an alternative in evolutionary robotics design, there are also researches carried out on hybridizing different evolutionary approaches for optimization to co-evolve controllers and robot bodies. Howard had shown that the idea of hybridizing genetic algorithm with genetic programming is capable of discovering the relationship between the sets of data and perform more efficiently compared to classical evolutionary methods (Howard & Angelo, 1995). Lee had integrated the idea in evolutionary robotics where a hybrid genetic programming and genetic algorithm approach is used for co-evolving controllers and robot bodies to accomplish tasks (Lee, Hallam & Lund, 1996).

The main goal of this study is to investigate the applicability of 3D printing for evolutionary robotics. Specifically, we intend to show that the highly complex and cost-intensive design, fabrication and deployment of (i) continuum robots and (ii) hybrid articulated-wheeled robots are feasible by combining evolutionary design optimization algorithms with 3D printing. Simulation will be carried out for the automated design optimization phases, after which the final, evolved designs will be transferred to the real world through 3D printing. In this paper, the scope of our study covers only the evolutionary optimization phases of the proposed approach which were conducted using and includes real-world transference to the physical, 3D printed robots.

MATERIALS AND METHODS

We will present this study in two parts. The first part encompasses our results achieved thus far in the evolution of 3D-printed hybrid articulated-wheeled robots; and in the second part, evolution of 3D-printed continuum robots.

Methodology for evolving hybrid articulated-wheeled robots

The evolution process takes place during the simulation in Webots. Webots is a development environment used to model, program and simulate mobile robots. With the high fidelity physical-based robot simulation, Webots have been widely used by researchers internationally. Webots is integrated with powerful application programming interfaces (APIs) where user can program robots controller using 200 API functions available in 6 different languages such as C, C++, Java, Python, Matlab, and URBI. Most importantly, Webots file format (.wbt) can be opened and modified with regular text editors where the content is human readable. Thus, users can modify or generate Webots file with their own tools.

In the current stage of our on-going study, this paper aims for solving a single objective problem which is to minimize the size of the robot body and reducing the number of collisions between the robot and the obstacle during the climbing motion. The evolutionary algorithm is presented next.

The evolution starts with initiating Webots robot devices such as servos, sensors and other components, then the robot is simulated to perform climbing motion. The controller of the climbing motion is manually designed. In each generation, the robot is only given 25 seconds to perform the climbing motion. When the time runs out, a message will be sent to supervisor controller to obtain the position coordinate of the robot in order to calculate the fitness score as shown below:

$$Fitness = (b + l) \times (1 + d \times 10) + c / 50 \qquad (1)$$

Where

b = robot body size;
l = robot leg length;
d = robot final distance from target destination;
c = number of collision occurs during simulation.

Our fitness function is designed as in the way that the lesser is the fitness score, the fitter the robot is. Thus, the first part of the fitness function is a direct addition of the robot body size with the robot leg length where our objective is to obtain a smaller robot. Besides that, the ability of the robot to climb over obstacle is also an important criterion in determining the fitness of a robot. Thus, the distance of the robot final position from the target destination is multiplied with the first part of the equation to give merit to the fitness score if the robot succeeded to climb over obstacle and reach its destination. The last part of the equation is to penalize the fitness score of the robot with the number of collision occurs during the climbing obstacle motion. The total number of collisions occurs during the simulation is divided by fifty as to scale down the penalty score where the number of fifty is the maximum number of collision it may occur in one run.

After the fitness score is obtained, it will be compared to the fittest robot fitness score. If the current fitness score is better than the fittest robot fitness score, the current robot

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will be kept as the fittest robot. Then the fittest robot will undergo mutation and produce a new robot for next generation. After replacing the Webots file with the new robot, a message will be sent to supervisor controller to revert the simulation. The simulation will be repeated until the maximum number of generation is reached.

Methodology for evolving continuum robots

Again using the Webots simulator, the continuum robot, also known as a modular robot, is constructed through a combination of blocks with difference sizes. The size of each block is created according to the segment length specified in tree-based structure unit. A touch sensor is installed in the middle of each block. If either side of the block is being touched, a HIGH output is produced by the touch sensor, or else the sensor output remains LOW. Distinct from multiple-branching modular robots, the snake-like modular robot is equipped with an infra-red sensor in front of the first segment. Such an infra-red sensor will give a LOW output if an object is sensed, else it remain HIGH. In order to avoid segments overlapping in simulation, bounding box features are implemented. A bounding box is attached to every block with the same dimension which makes the virtual block segment become a solid object.

For the simulation environment, an open area environment is used for multi-branching modular robots evolutionary process whereas a narrow straight path is designed for snake-like modular robot evolutionary process.

In the artificial evolutionary process, each population consists of ten individuals. Genetic Programming and Differential Evolution were performed on the population, each individual is run in the same environment one following another. After a particular period of running time, each individual modular robot will be evaluated using the fitness function modeled. The fitness function for the snake-like modular robot is the total distance travelled by the modular robot in meters. On the other hand, the fitness function of the multi-branching modular robot is shown below:

$$Fitness\ score = \cos\theta \times score \quad (2)$$

$$where,$$

$$\theta = angle\ deviate\ from\ origin \quad (3)$$

$$score = \sum_{t=0}^{runtime} coordinate\ in\ x - axis$$

RESULTS AND ANALYSIS

Results for evolved hybrid articulated-wheeled robots

Six legged articulated-wheeled hybrid mobile robots with various parameters of morphology are obtained from the mutation operation during the evolution process. Numerous robots with different combinations of wheels, leg and body sizes have been tested in the simulation on its ability for climbing obstacles. In the evolution stage, smaller robots with the ability to climb over obstacles without collision will have the best fitness score. Thus, robots with large body sizes or robots which are too small to perform the climbing motion are discarded from the evolutionary-optimization process.

Before the simulated of artificial evolution is conducted, a six legged articulated-wheeled hybrid mobile robot had been manually designed for climbing obstacle purposes. The robot was used as the initial generation of the evolution. Table-1 shows the comparison of the initial robot and the fittest robot produced from the evolution. The hand designed robot is shown in Figure-1.

Table-1. Comparison of the first generation robot and the last generation robot.

Object	Initial robot	Fittest robot
Wheels radius (mm)	15	22
Robot leg length (mm)	50	45
Robot body (mm)	200	150
Fitness score	0.403	0.195
Number of collisions	8	0

From the experiment, a fitter six legged articulated-wheeled hybrid mobile robot is obtained which having fitness score of 0.195 comparing to initial human design robot 0.403. The fitter robot evolved from the evolution simulation is smaller in size compared to the initial human-designed robot while having zero collision with obstacles during the climbing motion. The fittest robot evolved from the evolution simulation process is shown in Figure-2.

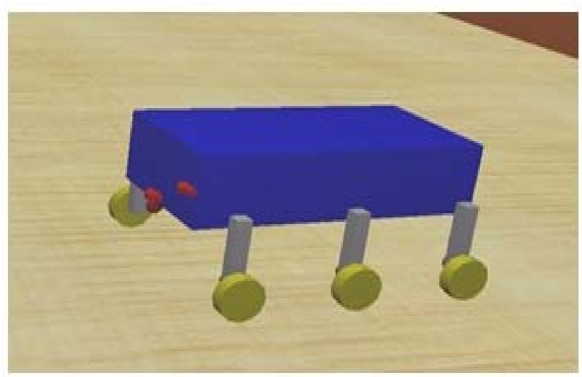

Figure-1. Hand-designed six legged-wheeled hybrid mobile robot presented in Webots.

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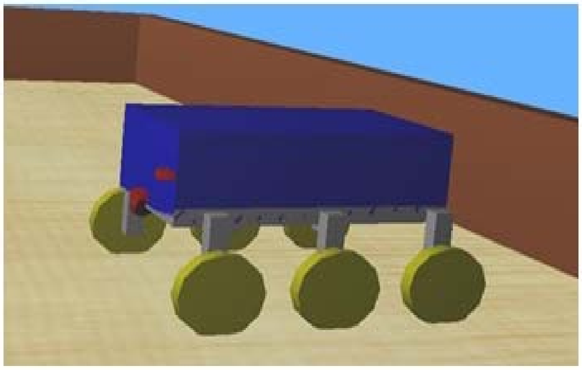

Figure-2. The fittest six legged-wheeled hybrid mobile robot evolved from the evolution simulation process.

Table-2 shows the parameters of each of the fittest robots evolved in five different runs of evolutionary simulation. Results show that every evolved fittest robot has better fitness score than the initial human-designed robot. Besides that, the results also show that the fitness scores of the fittest robot from different runs are quite similar to each other. This shows that all the fittest robots that were obtained from the evolution are near to the optimum parameter values which are small enough but yet have a good ability in performing the climbing motion.

Table-2. Parameter of the fittest robot in five runs.

Object	Run One	Run Two	Run Three	Run Four	Run Five
Wheels radius (mm)	21	20	20	19	19
Robot leg length (mm)	45	47	47	50	48
Robot body (mm)	150	150	150	150	150
Fitness score	0.195	0.197	0.197	0.2	0.198
Number of collisions	0	0	0	0	0

As seen in Table-2, the evolved robot with 0.195 fitness score have legs with lengths of 45mm is the optimal length of the leg for a robot to perform climbing motion in the current simulation setup. Robots with legs which are shorter than 45mm are too short that it cannot reach the top of obstacle while robots with legs which are longer than 45mm are credited with poorer fitness score which can be seen in Table-2. Figure-3 shows the fitness score of the fittest robot over the evolutionary optimization process for five runs. Results show that the fittest solution can be obtained even in the early stages of the evolutionary optimization process.

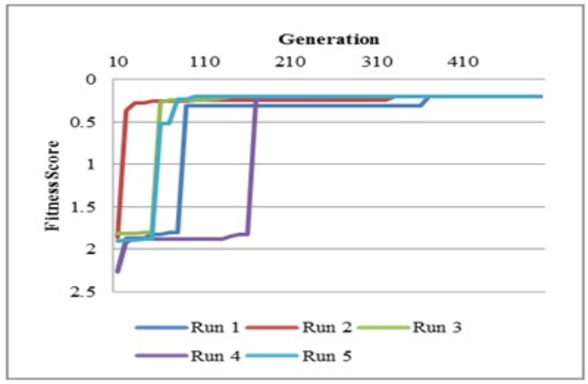

Figure-3. Fitness score of the fittest robot over 500 generations for five runs.

Results for evolved continuum robots

After each generation of the evolutionary process, the system will automatically compare the performance score of each individual according to the number of segments possessed by the modular robot individual. The system will store the robot individual's information under two conditions: (a) if the fitness scores of the current individual is higher than the previous stored individual with the same number of segments (b) if the individual with the particular total number of segments does not yet exist throughout the evolutionary process. The fitness scores of multi-branching modular robots at different generations are shown in Table-3. Meanwhile the distance travelled (in meters) by the snake-like modular robots are shown in Table-4.

Table-3. Multi-branching modular robot fitness score.

Segment Numbers	5th Generation	10th Generation	20th Generation	40th Generation
3		3.3983	3.3983	3.3983
4	38.0616	38.0616	38.0616	38.0616
5		-18.8675	-18.8675	-18.8675
6	145.2788	231.4221	249.8193	396.7809
7		-441.3252	109.8865	109.8865
9		-239.3834	114.0557	114.0557
10	318.0996	318.0996	318.0996	318.0996
11		-12.1256	103.4066	103.4066
12	-109.4888	-66.1687	-66.1686	-66.1686
13		-4.0802	449.2480	449.2480
15			-57.6467	195.1755
16			190.3900	190.3900
17			175.3790	175.3790

Table-3 and Table-4 show that the modular robots are able to improve their performances from generation to generation through the evolutionary optimization process. Besides that, it can also be observed that new individuals with different structures and total number of segments are able to be created eventually through the evolutionary optimization process. From both Table-3 and 4, it can be seen that there are some

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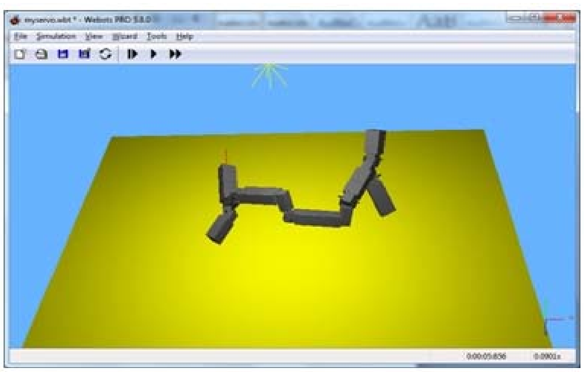
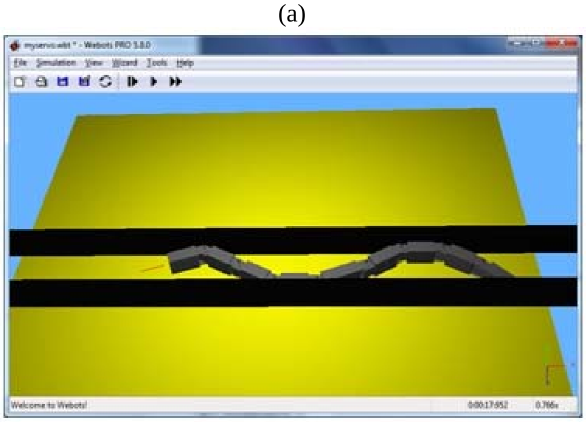
individuals created but the fitness score did not change following that. This is because such individuals were created only once during the evolutionary process. However the created individuals did not perform better compared to its parent. As a result, it was discarded from the population and no further evolutionary process was performed on it to improve upon its behavior. Yet, the information of such an individual will still be stored by the system as there is no individual with that particular number of segments throughout the artificial evolutionary process. Figure-4 below shows the evolved continuum robots with multi-branching and snake-like morphologies.

Table-4. Snake-like modular robot travelled distance (meters).

Segment Numbers	5th Generation	10th Generation	15th Generation	20th Generation
4	0.4809	0.4809	0.4809	0.4809
5		1.7197	2.2288	2.2323
8	2.4157	2.9985	2.9985	3.1485
10	2.0859	3.0344	3.0344	3.1338
12	1.6554	2.0822	2.0822	2.0822
15			2.2947	2.2947
16	1.6566	1.6566	1.6566	1.6566
17		2.0799	2.0799	2.0799
18			2.0025	2.0025
20			2.0908	2.4214



(a)



(b)

Figure-4. (a) Simulation for multi-branching modular robot in open area. (b) Simulation for snake-like modular robot within a specified path.

By comparing Table-3 and 4, it is noted that very often, a significant step jump in the fitness score of the multi-branching modular robot happens as compared to the case of the snake-like modular robot. This is because the body structure orientation of the multi-branching modular robot is able to be altered during the evolutionary process as compared to the snake-like robot, where the attachment of every segment is being constrained to connect in a straight line.

As a result, the multi-branching individual will have a totally different behavior if there is change on the orientation of its body structure. Since a totally different behavior is being evolved, the performance score can be achieved by the individual will also vary significantly. Although the snake-like modular robot structure's orientation is fixed, the segment length of the robot is still evolvable, which also contributes to the robot's moving behavior. The evolved segment lengths for the snake-like modular robot with eight segments are shown in Table-5.

Table-5. Snake-like modular robot segment length (8 segments).

Segment Sequence	5th Generation	10th Generation	15th Generation	20th Generation
1	0.1100	0.1100	0.1100	0.1100
2	0.1200	0.1200	0.1200	0.1200
3	0.1300	0.1120	0.1120	0.1183
4	0.1400	0.1047	0.1047	0.1013
5	0.1700	0.1251	0.1251	0.1170
6	0.1800	0.1800	0.1800	0.1800
7	0.1840	0.1316	0.1316	0.1000
8	0.1940	0.1772	0.1772	0.1874

Resulting 3D printed robots

The results of transferring evolved robots from simulation to the real-world robots are achieved through 3D printing based on the fused deposition modeling methodology. Figure-5 below shows the fabricated and deployed evolved hybrid articulated-wheeled mobile robot and Figure-6 which follows shows the fabricated and deployed evolved continuum robot.

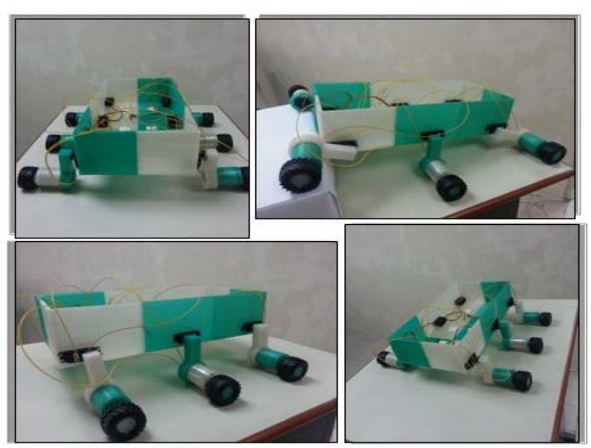


Figure-5. Evolved and 3D printed hybrid articulated-wheeled mobile robot.

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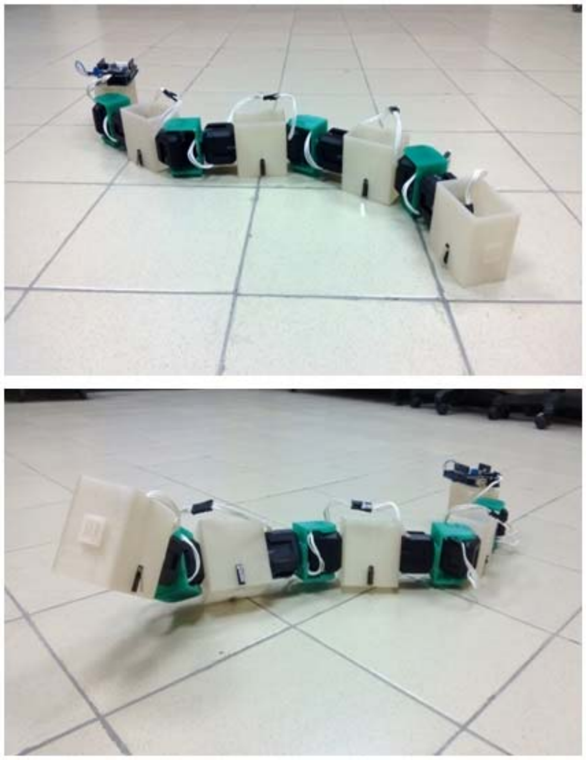

Figure-6. Evolved and 3D printed continuum robot.

The robots were verified to be fully-functioning in the real world, mimicking the expected autonomous locomotion behavior exhibited and achieved during the evolutionary optimization phases of the experiment. Hence, the real-world transference from simulation has shown that the proposed approach of hybridizing 3D printing with evolutionary robotics is indeed feasible and achievable. Compared to conventional fabrication processes, the time and cost involved were much lower. Elementary comparisons for both the hybrid articulated-wheeled robot as and the continuum robot are given below in Table-6 and Table-7 respectively.

Table-6. Time and cost comparison for deployment of hybrid articulated-wheeled mobile robots.

Traditional hybrid mobile robot design and production	3D printed and automatically evolved hybrid mobile robot
Complex design task and controller programming (time consuming: 70 hours)	Robot evolved in simulation by evolutionary algorithm (time consuming: 18 hours) 3.8X Faster
High production cost with purchasing of chassis kit, aluminum/metal parts, etc. (cost: RM300)	Production with 3D printed parts. (cost: RM150) 100% Cheaper

Table-7. Time and cost comparison for deployment of continuum robots.

	Traditional Robot Fabrication	Evolutionary 3-D Printing Robot Fabrication
Time	- Real time testing - Repeated manual calibration - Complex modeling and design - Material purchasing and part fabrication ~ 500 hours	- Simulated robot - Requires only fitness function - Automatically evolved and evaluated - Instant part printing 83 hours
	6x FASTER!	
Cost	- Damages easily during experimentation - High engineering cost - High manufacturing cost - Requires extensive part modification ~ RM700	- Troubleshoot problem while still in simulation - Automatically designed and fabricated - Easily self-printing in-situ - Accurate and exact part printing RM75
	9x CHEAPER!	

CONCLUSIONS

We have proposed a novel approach to the hybridization of evolutionary robotics to 3D printing for the rapid and cost-effective design, fabrication and deployment of both continuum and hybrid articulated-wheeled mobile robots that are fully autonomous with sensing capabilities. The evolved robot morphologies from the high-fidelity simulations show that efficient designs can be automatically evolved using our approach. Furthermore, these evolved designs in simulation were successfully transferred to real-world robots via 3D printing that was less labor-intensive, faster and cheaper.

In future work, we will be incorporating multi-objective evolutionary optimization into our approach to enable multiple objectives to be achieved during the evolutionary optimization phase, such as minimization of the robot's weight in addition to the current maximization of its primary locomotion behavior.

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