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On the Analogy in the Emergent Properties of Evolved Locomotion Gaits of Simulated Snakebot

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1. Introduction

Wheelless, limbless snake-like robots (Snakebots) feature potential robustness characteristics beyond the capabilities of most wheeled and legged vehicles – ability to traverse terrain that would pose problems for traditional wheeled or legged robots, and insignificant performance degradation when partial damage is inflicted. Moreover, due to their modular design, Snakebots may be cheaper to build, maintain and repair. Some useful features of Snakebots include smaller size of the cross-sectional areas, stability, ability to operate in difficult terrain, good traction, high redundancy, and complete sealing of the internal mechanisms (Dowling, 1997), (Worst, 1998). Robots with these properties open up several critical applications in exploration, reconnaissance, medicine and inspection. However, compared to the wheeled and legged vehicles, Snakebots feature (i) smaller payload, (ii) more difficult thermal control, (iii) more difficult control of locomotion gaits and (iv) inferior speed characteristics.

Considering the first two drawbacks as beyond the scope of our work, and focusing on the issues of control and speed, we intend to address the following challenge: how to develop control sequences of Snakebot's actuators, which allow for the fastest possible speed of locomotion achievable with Snakebot morphology.

For many tasks and robot morphologies, it might be seen as a natural approach to handcraft the locomotion control code by applying various theoretical approaches (Burdick et al, 1993), (Hirose, 1993), (Zhang et al, 22). However, handcrafting might not be feasible for developing the control code of a real Snakebot due to its morphological complexity and the anticipated need of prompt adaptation under degraded mechanical abilities and/or unanticipated environmental conditions. Moreover, while a fast locomotion gait might emerge from relatively simply defined motion patterns of morphological segments of Snakebot, the natural implication of the phenomenon of emergence in complex systems is that neither the degree of optimality of the developed code nor the way to incrementally improve the code is evident to the human designer (Morowitz, 2002). Thus, an automated, holistic approach for evaluation and incremental optimization of the intermediate solution(s) is needed (e.g. based on various models of learning or evolution in Nature) (Kamio et al, 2003), (Mahdavi &

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Bentley, 2003), (Takamura et al, 2000). The proposed approach of employing genetic programming (GP) implies that the code, which governs the locomotion of Snakebot is automatically designed by a computer system via simulated evolution through selection and survival of the fittest in a way similar to the evolution of species in the nature (Koza, 1992), (Koza, 1994). The use of an automated process to design the control code opens the possibility of creating a solution that would be better than one designed by a human (Koza et al, 2000).

In principle, the task of designing the code of Snakebot could be formalized and the formal mathematical models incorporated into direct programmable control strategies. However, the eventual models would feature enormous complexity and such models are not recognized to have a known, analytically obtained exact optimal solution. The complexity of the model stems from the considerable amount of degrees of freedom of the Snakebot, which cannot be treated independently of each other. The dynamic patterns of the position, orientation, velocity vectors, and moreover, the points and times of contact with the surface (and consequently - the vectors of resulting traction forces, which propel the Snakebot) of each of the morphological segments of Snakebot has to be considered within the context of other segments. Furthermore, often the dynamic patterns of these parameters cannot be deterministically inferred from the desired velocity characteristics of the locomotion of Snakebot. Instead, the locomotion of the Snakebot is viewed as an emergent property at a higher level of consideration of a complex hierarchical system, comprising many relatively simply defined entities (morphological segments). In such systems the higher-level properties of the system and the lower-level properties of comprising entities cannot be induced from each other. GP (and evolutionary algorithms in general) is considered as an efficient way to tackle such ill-posed problems due to the ability of GP to find a near-optimal solution in a reasonable runtime. This ability often overcompensates the drawbacks of GP, which can be summarized as follows:

(i) Relatively long runtime stemming from the significant computational effort (many potential solutions need to be evaluated before the sufficiently good solution is discovered) and poor computational performance (often the fitness evaluation is a time-consuming routine) of GP,.
(ii) Non-determinism – the exact runtime needed to obtain the solution cannot be estimated in advance. Instead, a statistically obtained probability of success for various runtime intervals is applied as a characteristic of computational efficiency of GP. The non-determinism of GP is viewed as a natural consequence of the stochastic nature of both the way of creating the initial population of potential solutions to the problem and the genetic operations applied to evolve this population (crossover, mutation, and selection), and.
(iii) Often the solution, automatically obtained via GP is quite complex and difficult to be comprehended by a human designer. Consequently, even simple man-made modification to such a solution is not a straightforward task.

As an instance of evolutionary algorithms, Genetic algorithms (GA) differ from GP mainly in the genotypic representation (i.e. chromosome) of potential solutions. Instead of representing the solution as a computer program (usually – a parsing tree) featuring arbitrary structure and complexity as in GP, GA employs a fixed-length linear chromosome. This difference implies a favorable computational advantage of GA over GP for simple problems, because the linear chromosomes are computationally efficiently manipulated by genetic operations and interpreted by fitness evaluation routines. For complex tasks however (such as evolution

of locomotion gaits of Snakebot) the runtime overhead associated with the manipulation of genotype is negligible compared to the much more significant overhead of the fitness evaluation of the evolved (simulated or real) artifact in the (simulated or real) environment. Moreover, an efficient GA (in terms of computational effort, or number of fitness evaluations) often requires incorporation of extremely computationally heavy probabilistic learning models aimed at maintaining the complex inter-relations between the variables in the chromosome. In addition, the fixed-length chromosome usually implies that the latter comprises various, carefully encoded problem-domain-dependent parameters of the solution with an a priori known structure and complexity. This might be a concern when no such knowledge is available in advance, but rather needs to be automatically and autonomously discovered by the evolving artifact. The latter is especially true when the artifact has to perform in unanticipated, uncertain environmental conditions or under its own (possibly degraded) mechanical abilities. Evolving a Snakebot's locomotion (and in general, behavior of any robot) by applying GP could be performed as a first step in the sequence of simulated off-line evolution (phylogenetic learning) on the software model, followed by on-line adaptation (ontogenetic learning) of evolved code on a physical robot situated in a real environment (Meeden & Kumar, 1998). Off-line software simulation facilitates the process of Snakebot's controller design because the verification of behavior on a physical Snakebot is extremely time consuming, costly and often dangerous for the Snakebot and surrounding environment. Moreover, in some cases it is appropriate to initially model not only the locomotion, but also to co-evolve the most appropriate morphology of the artifact (i.e. number of phenotypic segments; types and parameters of joints which link segments; actuators' power; type, amount and location of sensors; etc.) (Sims, 1994), (Ray, 2001) and only then (if appropriate) to physically implement it as hardware. The software model used to simulate Snakebot should fulfill the basic requirements of being quickly developed, adequate, and fast running (Jacobi, 1998). The typically slow development time of GP stems from the highly specific semantics of the main attributes of GP (e.g. representation, genetic operations, and fitness evaluation) and can be significantly reduced through incorporating off-the-shelf software components and open standards in software engineering. To address this issue, we developed a GP framework based on open XML standard. And to ensure adequacy and runtime efficiency of the Snakebot simulation we applied the Open Dynamic Engine (ODE) freeware software library for simulation of rigid body dynamics.

The *objectives* of our work are (i) to explore the feasibility of applying GP for automatic design of the fastest possible, robust, general and adaptive locomotion gaits of realistically simulated Snakebots and (ii) to investigate the emergent properties of these locomotion gaits. Inspired by the fast sidewinding locomotion of the rattlesnake *Crotalus cerastes*, this work is motivated by our desires (i) to model the sidewinding locomotion of natural snakes, (ii) to explore the phenomenon of emergence of locomotion of complex bodies from simply defined morphological segments comprising these bodies. The remainder of this document is organized as follows. Section 2 emphasizes the main features of the GP proposed for evolution of locomotion gaits of the simulated Snakebot. Section 3 presents empirical results of emergent properties of evolving locomotion gaits of Snakebot and discusses robustness, generality and adaptation of sidewinding in various fitness landscapes caused by various, unanticipated environmental conditions and partial damage of Snakebot. The same section explores the relevant practical implications of the observed analogy between the emergent properties of the robust and adaptive sidewinding locomotion gaits of Snakebot. Finally, Section 4 draws conclusions.

2. The Approach

2.1 Representation of Snakebot

Snakebot is simulated as a set of identical spherical morphological segments ("vertebrae"), linked together via universal joints. All joints feature identical finite angle limits and each joint has two attached actuators ("muscles"). In the initial standstill position, the rotation axes of the actuators are oriented vertically (vertical actuator) and horizontally (horizontal actuator) and perform rotation of the joint in the horizontal and vertical planes respectively (Figure 1). The task of designing the Snakebot locomotion can be rephrased as developing temporal patterns of desired turning angles of horizontal and vertical actuators of each segment, that result in the fastest overall locomotion.

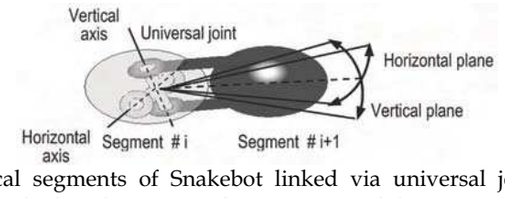


Fig. 1. Morphological segments of Snakebot linked via universal joint. Horizontal and vertical actuators attached to the joint perform rotation of the segment #i+1 in vertical and horizontal planes respectively.

The proposed representation of Snakebot as a homogeneous system comprising identical morphological segments is intended to significantly reduce the size of the search space of the GP. Moreover, because the size of the search space does not necessarily increase with the increase of the number of morphological segments of Snakebot, the proposed approach allows achievement of favorable scalability characteristics of the GP.

An alternative approach of employing phase automata has been recently proposed for representing and programming the functionality of segments in modular chain-type artifacts (Zhang et al., 2003). The approach is based on an event-driven input/output state automaton with an initial phase delay, and promises great versatility, robustness and scalability. However, the eventual automatic programming of these locomotion gaits (rather than handcrafting them) is still an open issue in this approach.

In the proposed representation of Snakebot, no anisotropic (directional) friction between the morphological segments and the surface is considered. Despite the anticipated ease of simulation and design of eventual morphological segments featuring anisotropic friction with the surface (using simple attached wheels (Hirose, 1993) or "belly" scales), such an approach would have the following drawbacks:

(i) Wheels, attached to the morphological segments of Snakebot are mainly effective in two-dimensional locomotion gaits. However, neither the fastest gaits in unconstrained environments nor the adaptive gaits in challenging environments (narrow tunnels, obstacles etc.) are necessarily two-dimensional. In three-dimensional locomotion gaits the orientation (the pitch, roll and yaw angles) of morphological segments at the instant of contact with the surface are arbitrary, which renders the design of effective wheels for such locomotion gaits a non-trivial engineering task.

(ii) Wheels may compromise the potential robustness characteristics of Snakebot because they can be trapped easily in the challenging environments (rugged terrain,

obstacles, etc.).

(iii) Wheels potentially reduce the application areas of the Snakebot because their engineering design implies lack of complete sealing of all mechanisms of Snakebot.

(iv) Belly scales (if implemented) would not promote any anisotropic friction when Snakebot operates on smooth, flat, clean and/or too loose surfaces which compromises the generality of derived locomotion gaits and their robustness to various environmental conditions.

Belly scales are efficiently utilized as a source of anisotropic friction in some locomotion gaits of natural snakes. However, these gaits usually require an involvement of a large amount of complex muscles located immediately under the skin of the snake. These muscles lift the scales off the ground, angle them forward, and then push them back against the surface. In the Snakebot, implementing actuators, which mimic such muscles in the natural snakes, would be expensive and thus infeasible from an engineering point of view.

2.2 Algorithmic Paradigm

2.2.1 GP

GP (Koza, 1992), (Koza, 1994) is a domain-independent problem-solving approach in which a population of computer programs (individuals' genotypes) is evolved to solve problems. The simulated evolution in GP is based on the Darwinian principle of reproduction and survival of the fittest. The fitness of each individual is based on the quality with which the phenotype of the simulated individual is performing in a given environment. The major attributes of GP - function set, terminal set, fitness evaluation, genetic representation, and genetic operations are elaborated in the remainder of this Section.

2.2.2. Function Set and Terminal Set

In applying GP to the evolution of Snakebot, the genotype is associated with two algebraic expressions, which represent the temporal patterns of desired turning angles of both the horizontal and vertical actuators of each morphological segment. Since locomotion gaits are periodical, we include the trigonometric functions sin and cos in the GP function set in addition to the basic algebraic functions. The choice of these trigonometric functions reflects our intention to verify the hypothesis, first expressed by Petr Miturich in 1920's (Andrusenko, 2001), that undulative motion mechanisms could yield efficient gaits of snake-like artifacts operating in air, land, or water.

From another perspective, the introduction of sin and cos in the function set of GP reflects our intention to mimic (at functional, rather than neurological level) to some extent the central pattern generator (CPG) in the central nervous system (usually located in the ganglia or spinal cord) of animals, believed to be necessary and sufficient for the generation of rhythmic patterns of activities. CPG for robot control typically comprises coupled neural controllers, which generate (without the need of external feedback) the motion pattern of actuators in the respective morphological segments of the artifact. The approach of employing CPG for developing the locomotion gaits of the Snakebot would be based on an iterative process (e.g. employing the machine learning and/or evolutionary computations paradigms) of tuning the main parameters of CPG including, for example, the common single frequency across the coupled oscillators, the fixed phase-relationship between the oscillators, and the amplitude of each of the oscillations. The proposed approach of applying GP for evolution of locomotion gaits of Snakebot shares some of the features of CPG-based

approaches such as the open-loop control scheme and the incorporation of coupled oscillators. Conversely to the CPG-based approaches however, the proposed method incorporates too little domain-specific knowledge about the task. The comparative flexibility of GP, resulting from not considering all the domain-specific constrains, can potentially yield an optimal solution with the following properties, typically uncommon for CPG:

(i) The optimal oscillations of segments might be an arbitrary superposition of several oscillations featuring different frequencies. Moreover, the proposed method of using GP does not necessarily imply that the frequency across the oscillators is common,

(ii) The relationship between the oscillators in the morphological segments of Snakebot is not necessarily a simple phase relationship. Arbitrary relationships involving amplitude, phase, and frequency are allowed to be developed by the simulated evolution via GP, and

(iii) The evolved optimal phase relationship between the oscillators in the morphological segments might vary along the body of Snakebot, rather than being fixed.

The above-mentioned features are achieved via the incorporation of the terminal symbol segment_ID (an unique index of morphological segments of Snakebot), which allows GP to discover how to *specialize* (by phase, amplitude, frequency etc.) the temporal motion patterns (i.e. the turning angles) of actuators of each of the identical morphological segments of the Snakebot. In addition, the terminal symbols of GP include the variables time and two constants: Pi, and random constant within the range [0, 2]. The introduction of variable time reflects our objective to develop *temporal* patterns of turning angles of actuators. The main parameters of the GP are summarized in Table 1.

Category	Value
Function set	{sin, cos, +, -, *, /, ADF}
Terminal set	{time, segment_ID, Pi, random constant }
Population size	200 individuals
Selection	Binary tournament, ratio 0.1
Elitism	Best 4 individuals
Mutation	Random subtree mutation, ratio 0.01
Fitness	Velocity of simulated Snakebot during the trial.
Trial interval	180 time steps, each time step account for 50ms of "real" time
Termination criterion	(Fitness > 100) or (Generations > 40) or (no improvement of fitness for 16 generations)

Table 1. Main Parameters of GP.

The rationale of employing automatically defined functions (ADF) is based on the empirical observation that the evolvability of straightforward, independent encoding of desired turning angles of both horizontal and vertical actuators is poor, although it allows GP to adequately explore the potentially large search space and ultimately, to discover the areas which correspond to fast locomotion gaits in solution space. We discovered that (i) the motion patterns of horizontal and vertical actuators of each segment in fast locomotion gaits are highly correlated (e.g. by frequency, direction, etc.) and that (ii) discovering and preserving such correlation by GP is associated with enormous computational effort. ADF, as

a way of limiting the search space by introducing modularity and reuse of code in GP (Koza, 1994) is employed in our approach to allow GP to explicitly evolve the correlation between motion patterns of horizontal and vertical actuators as shared fragments in algebraic expressions of desired turning angles of actuators. Moreover, we observed that the best result is obtained by (i) allowing the use of ADF in the algebraic expression of desired turning angle of vertical actuator only, and (ii) by evaluating the value of ADF by equalizing it to the value of the currently evaluated algebraic expression of the desired turning angle of the horizontal actuator.

2.2.3 Fitness evaluation

The fitness function is based on the velocity of Snakebot, estimated from the distance which the center of the mass of Snakebot travels during the trial. The energy consumed by the Snakebot during the trial is not considered in our work. The real values of the raw fitness, which are usually within the range (0, 2) are multiplied by a normalizing coefficient in order to deal with integer fitness values within the range (0, 200). A normalized fitness of 100 (one of the termination criteria shown in Table 1) is equivalent to a velocity, which displaced Snakebot a distance equal to twice its length. The fitness evaluation routine is shown in Figure 2.

2.2.4 Representation of genotype

The slight performance degradation in computing the desired turning angles of actuators by traversing the DOM/XML-based representation of genetic programs during fitness evaluation is not relevant for the overall performance of GP. The performance profiling results indicate that the fitness evaluation routine consumes more than 99% of the GP runtime. However, even for relatively complex genetic programs featuring a few hundred tree nodes, most of the fitness evaluation runtime at each time step is associated with the relatively large computational cost of the physics simulation (actuators, joint limits, friction, gravity, collisions, etc.) of phenotypic segments of the simulated Snakebot (routine dWorldStep in Figure 2, line 20), rather than computing the desired turning angles of actuators. Inspired by its flexibility, and the recent widespread adoption of the document object model (DOM) and extensible markup language (XML), we represent evolved genotypes of simulated Snakebot as DOM-parse trees featuring equivalent flat XML-text, as first discussed by (Tanev, 2004). Our approach implies that both (i) the calculation of the desired turning angles during fitness evaluation (function EvalDesiredAngle, shown in Figure 2, line 15) and (ii) the genetic operations are performed on DOM-parse trees using off-the shelf, platform and language neutral DOM-parsers. The corresponding XML-text representation (rather than S-expression) is used as a flat file format, feasible for migration of genetic programs among the computational nodes in an eventual distributed implementation of the GP. The benefits of using DOM/XML-based representations of genetic programs are (i) fast prototyping of GP by using standard built-in API of DOM-parsers for traversing and manipulating genetic programs, (ii) generic support for the representation of grammar of strongly-typed GP using W3C-standardized XML-schema; and (iii) inherent Web-compliance of eventual parallel distributed implementation of GP.

2.2.5 Genetic operations

We employ binary tournament selection – a robust, commonly used selection mechanism, which has proved to be efficient and simple to code. The crossover operation is defined in a strongly typed way in that only the DOM-nodes (and corresponding DOM-subtrees) of the

same data type (i.e. labeled with the same tag) from parents can be swapped. The sub-tree mutation is allowed in a strongly typed way in that a random node in the genetic program is replaced by a syntactically correct sub-tree. The mutation routine refers to the data type of the currently altered node and applies a randomly chosen rule from the set of applicable rewriting rules as defined in the grammar of the GP.

```
1. function Evaluate(GenH, GenV: TGenotype): real;
2. // GenH and GenV is the evolved genotype: a pair of algebraic
3. // expressions, which define the turning angle of horizontal
4. // and vertical actuators at the joints of Snakebot.
5. Const
6. TimeSteps    =180; // duration of the trial
7. SegmentsInSnakebot=15; // # of phenotypic segments
8. var
9. t, s      : integer;
10. AngleH, AngleV : real;//desired turning angles of actuators
11. CAngleH, CAngleV: real;//current turning angles of actuators
12. InitialPos, FinalPos: 3DVector; // (X,Y,Z)
13. begin
14. InitialPos:=GetPosOfCenterOfMassOfSnakebot;
15. for t:=0 to TimeSteps-1 do begin
16. for s:=0 to SegmentsInSnakebot-1 do begin
17.  // traversing XML/DOM-based GenH using DOM-parser:
18.  AngleH := EvalHorisontalAngle(GenH,s,t);
19.  // traversing XML/DOM-based GenV using DOM-parser:
20.  AngleV := EvalVerticalAngle(GenV,s,t);
21.  CAngleH := GetCurrentAngleH(s);
22.  CAngleV := GetCurrentAngleV(s);
23.  SetDesiredVelocityH(CAngleH-AngleH,s);
24.  SetDesiredVelocityV(CAngleV-AngleV,s);
25.  end;
26. // detecting collisions between the objects (phenotypic
27. // segments, ground plane, etc.):
28. dSpaceCollide;
29. // Obtaining new properties (position, orientation,
30. // velocity vectors, etc.) of morphological segments of
31. // Snakebot as a result of applying all forces:
32. dWorldStep;
33. end;
34. FinalPos := GetPosOfCenterOfMassOfSnakebot;
35. return GetDistance(InitialPos, FinalPos)/(TimeSteps);
36. end;
```

Fig. 2. Fitness evaluation routine.

2.2.6 ODE

We have chosen Open Dynamics Engine (ODE) (Smith, 2001) to provide a realistic simulation of physics in applying forces to phenotypic segments of Snakebot, for

simulation of Snakebot locomotion. ODE is a free, industrial quality software library for simulating articulated rigid body dynamics. It is fast, flexible and robust, and it has built-in collision detection. The ODE-related parameters of the simulated Snakebot are summarized in Table 2.

Parameter	Value
Number of phenotypic segments in snake	15
Model of the segment	Sphere
Radius of the segment, cm	3
Overlap between segments, %	25
Length of the Snakebot, cm	66
Volume of the segment, cm3	113
Density of the segment, g/cm3	0.9
Mass of the segment, g	100
Type of joint between segments	Universal
Initial alignment of segments in Snakebot	Along Y-axis of the world
Number of actuators per joint	2
Orientation of axes of actuators	Horizontal – along X-axis and Vertical – along Z-axis of the world
Operational mode of actuators	dAMotorEuler
Max torque of actuators, gcm	12000

Table 2. ODE-related parameters of simulated Snakebot.

3. Empirical Results

This section presents the experimental results verifying the feasibility of applying GP for evolution of the fast locomotion gaits of Snakebot for various fitness and environmental conditions. In addition, it investigates the emergent properties of (i) the fastest locomotion gaits, evolved in unconstrained environmental conditions and (ii) the robust locomotion gaits evolved in challenging environments. The section also discusses the gradual adaptation of the locomotion gaits to degraded mechanical abilities of Snakebot. These challenges are considered as relevant for successful accomplishment of various practical tasks during anticipated exploration, reconnaissance, medicine and inspection missions. In all of the cases considered, the fitness of Snakebot reflects the low-level objective (i.e. *what* is required to be achieved) of Snakebot in these missions, namely, to be able to move fast regardless of environmental challenges or degraded abilities. The experiments discussed illustrate the ability of the evolving Snakebot to learn *how* (e.g. by discovering beneficial locomotion traits) to accomplish the required objective without being explicitly taught about the means to do so. Such *know-how* acquired by Snakebot automatically and autonomously can be viewed as a demonstration of emergent intelligence in that the task-specific knowledge of *how* to accomplish the task emerges in the Snakebot from the interaction of the problem solver and a fitness function (Angeline, 1994).

3.1 Emergent Properties of Evolved Fastest Locomotion Gaits

Figure 3 shows the fitness convergence characteristics of 10 independent runs of GP (Figure 3a) and sample snapshots of evolved best-of-run locomotion gaits (Figure 3b and Figure 3c) when fitness is measured regardless of direction in an unconstrained environment. Despite the fact that fitness is unconstrained and measured as velocity in any direction, sidewinding locomotion (defined as locomotion predominantly perpendicular to the long axis of Snakebot) emerged in all 10 independent runs of GP, suggesting that it provides superior speed characteristics for Snakebot morphology. The evolved locomotion gait is quite similar to the locomotion of the natural snake *Crotalus cerastes*, or "sidewinder". In the proposed representation of Snakebot, similarly to the natural snake, no anisotropic (directional) friction between the morphological segments and the surface is considered. Consequently, no forward locomotion (which requires an extensive utilization of anisotropic friction) emerges as a locomotion that is fast enough to challenge the achieved velocity of sidewinding.

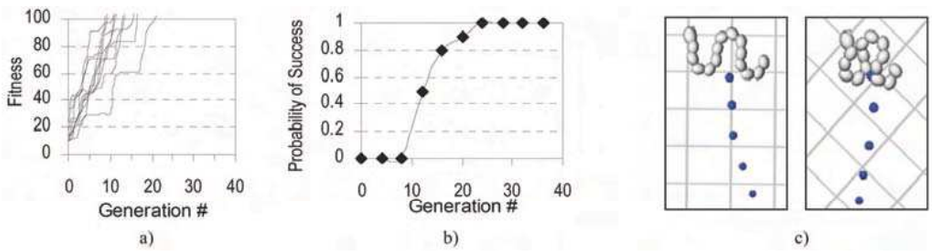


Fig. 3. Evolution of locomotion gaits for cases where fitness is measured as velocity in any direction. Fitness convergence characteristics of 10 independent runs (a), probability of success (i.e., probability of attaining a fitness value of 100) (b), and snapshots of sample evolved best-of-run sidewinding locomotion gaits of simulated Snakebot (c). The dark trailing circles in (c) depict the trajectory of the center of the mass of Snakebot. Timestamp interval between each of these circles is fixed and it is the same (10 time steps) for both snapshots.

The genotype of a sample best-of-run genetic program is shown in Figure 4. The dynamics of evolved turning angles of actuators in sidewinding locomotion result in characteristic circular motion pattern of segments around the center of mass as shown in Figure 5a. The circular motion pattern of segments and the characteristic track on the ground as a series of diagonal lines (as illustrated in Figure 5b) suggest that during sidewinding the shape of Snakebot takes the form of a rolling helix (Figure 5c). Figure 5 demonstrates that the simulated evolution of locomotion via GP is able to invent the improvised "cylinder" of the sidewinding Snakebot to achieve fast locomotion.

By modulating the oscillations of the actuators along the snake's body, the diameter of the cross-section of the "cylinder" can be tapered towards either the tail or head of the snake, providing an efficient way of "steering" the Snakebot (Figure 6a, 6b). We consider the benefits of modulating the oscillations of actuators along the body of Snakebot as a straightforward implication of our understanding of the emergent form of a rolling helical Snakebot. Such modulation is implemented as a handcrafted (rather than evolved) feature of

evolved best-of-run sidewinding Snakebots. Snapshots, shown in Figure 6c and 6d illustrate the ability of Snakebot to perform sharp turns with a radius similar to its length in both clockwise and counterclockwise directions.

$$GenH = (sin(((sin(-8)) * (segment\ id - time)) + (3 * time)))/(sin(-8));$$
$$GenV = sin(ADF)$$

Fig. 4. Normalized algebraic expressions of the genotype of a sample best-of-run genetic program: dynamics of turning angle of horizontal (GenH) and vertical (GenV) actuators. The value of the automatically defined function ADF, in GenV, is evaluated by equalizing it to the value of the currently evaluated GenH.

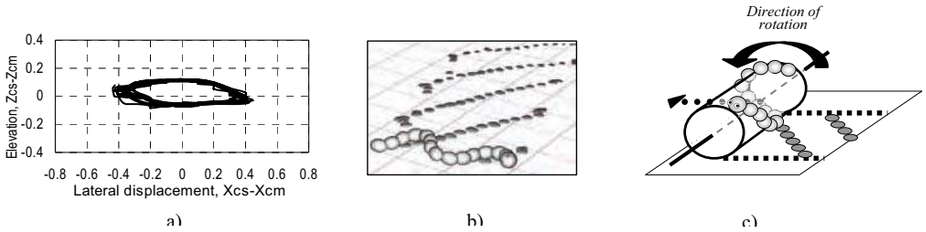


Fig. 5. Trajectory of the central segment (cs) around the center of mass (cm) of Snakebot for a sample evolved best-of-run sidewinding locomotion (a), traces of ground contacts (b), and Snakebot, wrapped around an imagined cylinder taking the form of a rolling helix.

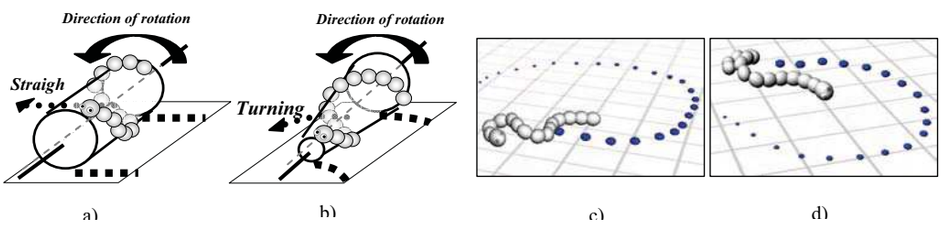


Fig. 6. Steering the Snakebot. The Snakebot moving straight is wrapped around an imagined cylinder taking the form of a rolling helix (a). By modulating the oscillations of the actuators along the snake's body, the diameter of the cross-section of the "cylinder" can be tapered towards either the tail or head of the snake, providing an efficient way of "steering" the Snakebot: (b) illustrates the Snakebot turning counterclockwise. The images in (a) and (b) are idealized: in the simulated Snakebot (and in snakes in Nature too) the cross-sectional areas of the imagined "cylinder" (a) and "cone" (b) are much more similar to ellipses (as shown in Figure 5a) rather than to perfect circles as depicted here. The snapshots shown in (c) and (d) illustrate the Snakebot performing sharp turns in both clockwise and counterclockwise directions, respectively.

In order to verify the superiority of velocity characteristics of sidewinding locomotion for Snakebot morphology we compared the fitness convergence characteristics of evolution in an unconstrained environment for the following two cases: (i) unconstrained fitness measured

as velocity in any direction (as discussed above), and (ii) fitness, measured as velocity in the forward direction only. The results of evolution of forward locomotion, shown in Figure 7, indicate that non-sidewinding motion features much inferior velocity characteristics, compared to sidewinding.

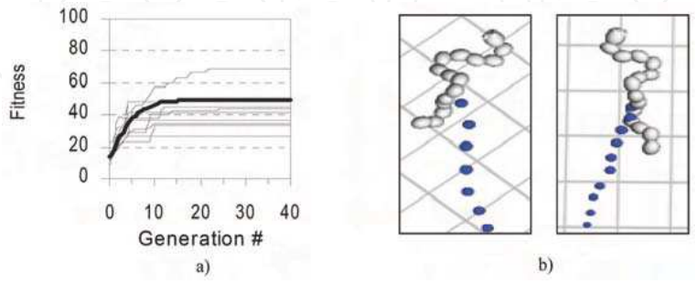


Fig. 7. Evolution of locomotion gaits for cases where fitness is measured as velocity in the forward direction only: fitness convergence characteristics of 10 independent runs of GP (a) and snapshots of sample best-of-run forward locomotion (b). Timestamp interval between the traces of the center of the mass is the same as for sidewinding locomotion gaits, shown in Figure 3c.

The results of evolution of rectilinear locomotion of the simulated Snakebot confined in a narrow "tunnel" are shown in Figure 8. The width of the tunnel is three times the diameter of the cross-section of the segment of Snakebot. Compared to forward locomotion in an unconstrained environment (Figure 7), the velocity in this experiment is superior, and comparable to the velocity of sidewinding (Figure 3). This, seemingly anomalous emergent phenomenon demonstrates the ability of simulated evolution to discover a way to utilize the walls of the "tunnel" as a source of (i) extra grip and (ii) locomotion gaits (e.g., vertical undulations) which are fast yet unbalanced in an unconstrained environment. Indeed, as soon as the Snakebot clears the tunnel, the gait flattens (Figure 8c) and velocity (visually estimated as a distance between the traces of the center of gravity of Snakebot) drops dramatically.

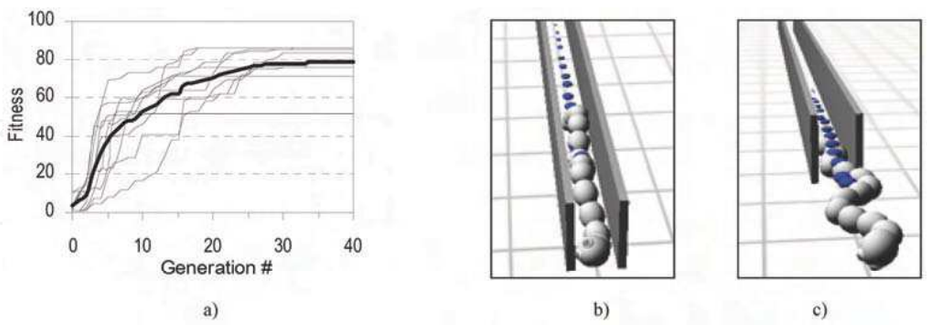


Fig. 8. Evolution of locomotion gaits of Snakebot when confined in a narrow "tunnel": fitness convergence characteristics of 10 independent runs of GP (a) and snapshots of sample evolved best-of-run gaits at the intermediate (b) and final stages of the trial (c).

3.2 Robustness via Adaptation to Challenging Environment. Generality of the Evolved Robust Gaits

Adaptation in Nature is viewed as an ability of species to discover the best phenotypic (i.e. pertaining to biochemistry, morphology, physiology, and behavior) traits for their survival in a continuously changing fitness landscape. Adaptive phenotypic traits are the result of beneficial genetic changes which occurred in due course of the evolution (phylogenesis) and/or phenotypic plasticity (ontogenesis – learning, polymorphism, polyphenism, immune response, adaptive metabolism, etc.) occurring during the lifetime of the individuals. In our approach we employ GP for adaptation of Snakebot to changes in the fitness landscape caused by (i) a challenging environment and (ii) partial damage to 1, 2, 4 and 8 (out of 15) morphological segments. The former case is discussed in this subsection, while the latter case is elaborated in the following subsection 3.3. In both cases of adaptation, GP is initialized with a population comprising 20 best-of-run genetic programs, obtained from 10 independent evolutionary runs in unconstrained environments, plus an additional 180 randomly created individuals.

The challenging environment is modeled by the introduction of immobile obstacles comprising 40 small, randomly scattered boxes, a wall with height equal to 0.5 diameters of the cross-section of Snakebot, and a flight of 3 stairs, each with height equal to 0.33 diameters of the cross-section of Snakebot. Both the wall and the stairs have a finite length. However, because no feedback from the environment to steer the snakebot is employed in our experiment, any attempt of the Snakebot to bypass the wall would lead to a sort of sustained cycling trajectories of the snakebot. However, these trajectories would be discouraged by the simulated evolution because they feature inferior distance between the position of the snakebot at the start and the finish of the trial, and consequently, inferior fitness values. The fitness of adapting Snakebot is measured in any direction.

The empirical results of adaptation of the sidewinding Snakebot, obtained over 10 independent runs reveal the poor performance of the best-of-run Snakebots initially evolved in unconstrained environments. The fitness of the best-of-run Snakebots immediately drops from initial value of 100 in the unconstrained environment to only 65 when Snakebot is first tested (at Generation #0) on the challenging terrain, which indicates the poor initial robustness of these locomotion gaits. However, adapting to the new environment, the evolving Snakebots are able to discover locomotion gaits which are robust enough to allow the Snakebots to overcome the various kinds of obstacles introduced in the environment. About 20 generations of computational effort is required to reach fitness values of 100 in the challenging environment with probability of success 0.9. Snapshots illustrating the performance of a sample best-of-run Snakebot initially evolved in unconstrained environment, before and after the adaptation to the challenging environment are shown in Figure 9.

The emergent properties of the robust sidewinding gaits are shown in Figure 10. As depicted in the Figure, the additional elevation of the body, required to negotiate the obstacles faster represents the emergent know-how in the adapting Snakebot. As shown in Figure 10e, the trajectory of the central segment around the center of the mass of sample adapted Snakebot is almost twice as high as before the adaptation (Figure 5a). Moreover, as the snapshots of the adapted gaits of Snakebot viewed from the above (Figure 10b and 10d) reveal, the robust locomotion gaits are associated with much higher winding angle of locomotion (about 120°) yielding longitudinally more compact sidewinding Snakebots. Again, as with the emergence of sidewinding, the result of the artificial evolution is analogous to the solution discovered by Nature – it is recognized that natural snakes also change the winding angle of the locomotion in order to adapt themselves to the various environmental conditions.

The generality of the evolved robust sidewinding gaits is demonstrated by the ease with which Snakebot, evolved in known challenging terrain overcomes various types of unanticipated obstacles such as a pile of or burial under boxes, and small walls, as illustrated in Figures 11, 12, and 13.

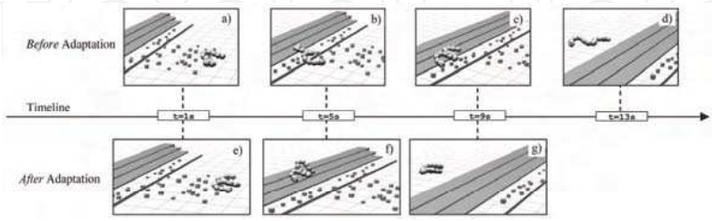


Fig. 9. Snapshots illustrating the sidewinding Snakebot, initially evolved in unconstrained environment, before the adaptation – initial (a), intermediate (b and c) and final stages of the trial (d), and after the adaptation to challenging environment via GP - initial (e), intermediate (f) and final stages of the trial (g). The challenging environment is modeled by the introduction of immobile obstacles comprising 40 small, randomly scattered boxes, a wall with height equal to 0.5 diameters of the cross-section of Snakebot, and a flight of 3 stairs, each with height equal to 0.33 diameters of the cross-section of Snakebot.

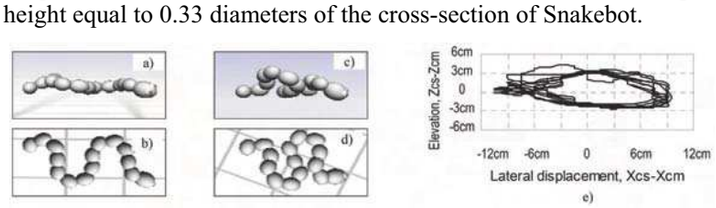


Fig. 10. Snapshots of frontal view (a, c) and view from the above (b, d) of sample sidewinding Snakebots before and after the adaptation, respectively. The frontal views (a and c) comparatively illustrates the additional elevation of the body of the adapted Snakebot. The trajectory of the central segment (cs) around the center of mass (cm) of Snakebot for sample best-of-run sidewinding locomotion after the adaptation (e) to challenging environment indicates that the elevation of the central segment after the adaptation (a) is twice as high as before the adaptation (as illustrated in Figure 5a).

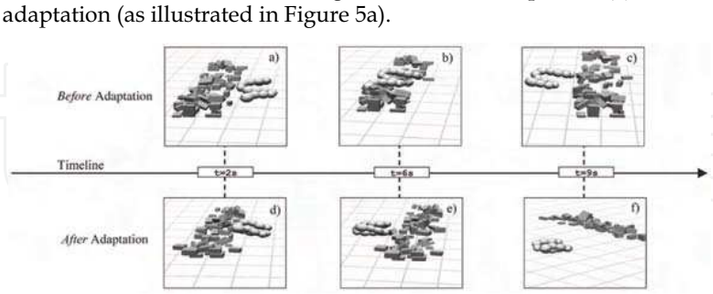


Fig. 11. Snapshots illustrating the generality of sidewinding Snakebot adapted to the challenging environment depicted in Figure 9. Before the adaptation to the challenging environment the Snakebot overcomes an unanticipated pile of boxes slower (a, b and c) than after the adaptation (d, e, and f).

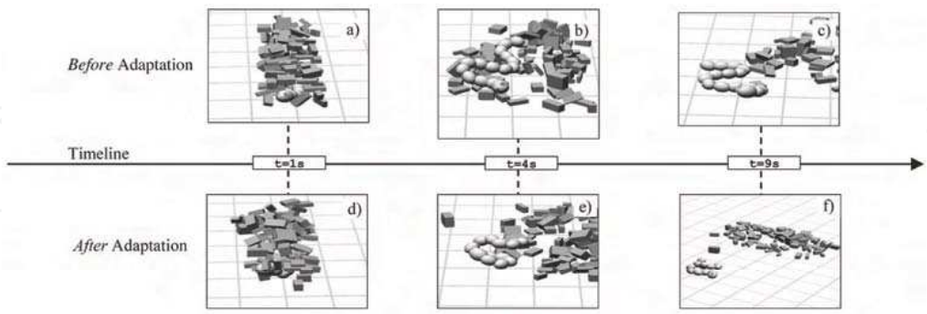


Fig. 12. Snapshots illustrating the generality of sidewinding Snakebot adapted to the challenging environment depicted in Figure 9. Before the adaptation to the challenging environment the Snakebot emerges from an unanticipated burial under a pile of boxes slower (a, b and c) than after the adaptation (d, e, and f).

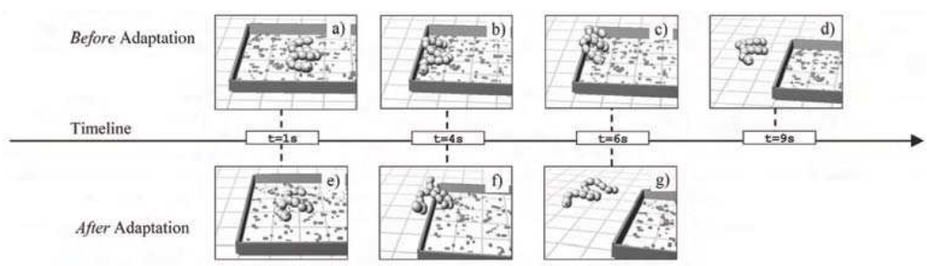


Fig. 13. Snapshots illustrating the generality of sidewinding Snakebot adapted to the challenging environment depicted in Figure 9. Before the adaptation to the challenging environment the Snakebot clears unanticipated walls forming a pen slower (a, b, c and d) than after the adaptation (e, f and g). The walls are twice as high as in the challenging terrain of Figure 9, and their height is equal to the diameter of the cross-section of Snakebot.

3.3 Adaptation to Partial Damage

The adaptation of sidewinding Snakebot to partial damage to 1, 2, 4 and 8 (out of 15) segments by gradually improving its velocity is shown in Figure 14. Demonstrated results are averaged over 10 independent runs for each case of partial damage to 1, 2, 4 and 8 segments. The damaged segments are evenly distributed along the body of Snakebot. Damage inflicted to a particular segment implies a complete loss of functionality of both horizontal and vertical actuators of the corresponding joint. As Figure 14 depicts, Snakebot quickly and completely recovers from damage to a single segment, attaining its previous velocity only in 7 generations. Also in the case of 2 damaged segments, Snakebot recovers to an average of 100% of its previous velocity. With 4 and 8 damaged segments the degree of recovery is 92% and 72% respectively. The emergent properties of adapted sidewinding locomotion gaits are shown in Figure 15.

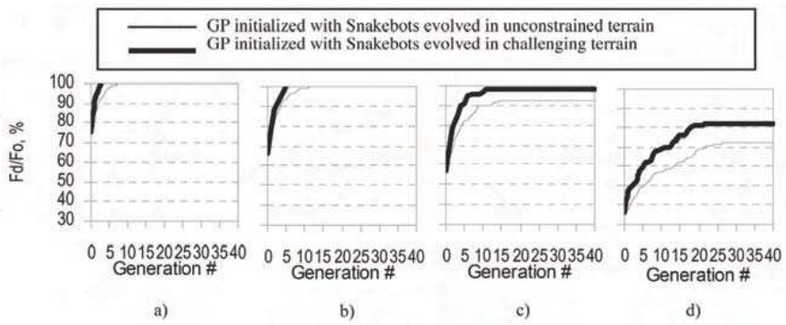


Fig. 14. Adaptation of Snakebot to damage of 1 (a), 2 (b), 4 (c) and 8 (d) segments, respectively. The results are averaged over 10 independent runs of GP for the cases when GP is initialized with the best-of-run Snakebots evolved in unconstrained and challenging terrain respectively.

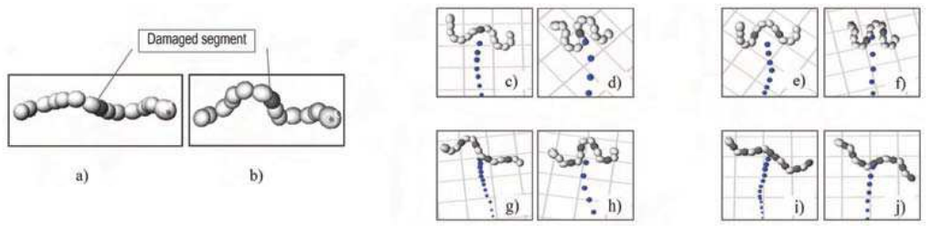


Fig. 15. The emergent properties of adapted sidewinding locomotion gaits: frontal view of the Snakebot before (a) and after the adaptation (b) to the damage of a single segment demonstrates the additional elevation of the adapted Snakebot. View of the shape of the sidewinding Snakebot from above reveals the emergent tendency of increasing the winding angle of locomotion in a way similar to adaptation to the challenging environment (as shown in Figure 10): Snakebot with 1 (c, d), 2 (e, f), 4 (g, h) and 8 (i, j) damaged segments before and after the adaptation, respectively.

3.4 Genetic Similarity of Adapted Snakebots

In order to investigate whether the analogy in the emergent properties of locomotion gaits result from similar genotypes, we analyzed the correlation between the frequencies of occurrence of tree nodes in a particular context (i.e. the parent- and the descendant tree nodes) in the genetic representations of the three categories of Snakebots – (i) evolved in smooth unconstrained environment, (ii) adapted to challenging environment, and (ii) adapted to the degraded mechanical abilities – as elaborated earlier in Sections 3.1, 3.2 and 3.3 respectively. For each of these three categories of Snakebots we aggregated the frequencies of occurrence of tree nodes obtained from the genotypes of the 20 best-of-run Snakebots (from 10 independent runs of GP). The results are as follows:

(i) The correlation between genotypes of the Snakebots evolved in smooth environment and the Snakebots adapted to challenging environment is $C_{S\text{-}C}=0.34$,

(ii) The correlation between genotypes of the Snakebots evolved in smooth environment and the Snakebots adapted to degraded mechanical abilities due to partial damage is $C_{S\text{-}D}=0.32$, and.

(iii) The correlation between genotypes of the Snakebots adapted to challenging environment and the Snakebots adapted to degraded mechanical abilities due to partial damage is $C_{C\text{-}D}=0.91$.

These results suggest that there is little similarity between the genotypes of Snakebots adapted to both changes in the fitness landscape (i.e., due to challenging environment and partial damage) and the Snakebot evolved in smooth environment. We assume that this limited similarity ($C_{S\text{-}C}=0.34$, and $C_{S\text{-}D}=0.32$) is due to the shared genotypic fragments, which are relevant for the very ability of Snakebot to move, regardless of the environmental conditions and/or the mechanical failures. These results also show that in both cases the genotype of Snakebots adapts to changes in the fitness landscape by drifting away from the genotype of the common ancestor – the Snakebot evolved in smooth environment, used to initially feed the adapting populations of Snakebots. Moreover, the strong correlation between the genotypes of adapted Snakebots ($C_{C\text{-}D}=0.91$) suggests that the adaptation in both cases is achieved through a drift towards adjacent niches in the genotypic space of the Snakebot. This, in turn, yields the discovered phenotypic analogy between the adapted Snakebots, as discussed above in Sections 3.2 and 3.3.

3.5 Cross-verification of Generality of Adapted Locomotion Gaits

The anticipated practical implications of the analogy between the emergent properties of the sidewinding gaits, adapted to different fitness landscapes, are related to the possibility to develop a general locomotion gait which could be autonomously activated in case of any degradation of velocity of Snakebot. This activation could be done without the necessity for the Snakebot to diagnose the underlying reason for such degradation (e.g., either a challenging environment or degraded mechanical abilities). To verify the feasibility of such an approach, we examined the performance of the same three categories of best-performing Snakebots – (i) evolved in a smooth environment, (ii) adapted to challenging environment, and (ii) adapted to degraded mechanical abilities due to damage of 8 segments (as elaborated earlier in Sections 3.1, 3.2 and 3.3 respectively). The performance, aggregated over 20 best-performing Snakebots, obtained from 10 independent runs of an evolution with the condition Fitness>100 removed from the termination criterion of GP (refer to Table 1), is shown in Figure 16.

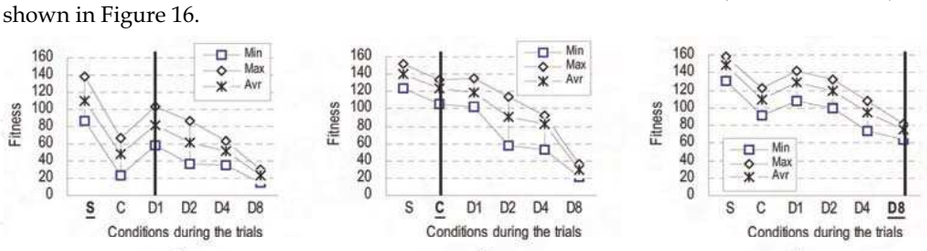


Fig. 16. Performance of the best-performing Snakebots evolved in a smooth environment (a), evolved in challenging environment (b), and adapted to the degraded mechanical abilities due to damage of eight morphological segments (c) in various "unexpected" fitness landscapes corresponding to a smooth environment (S), challenging terrain (C), and degraded mechanical abilities due to a damage to one- (D1), two- (D2), four- (D4) and eight (D8) – out of 15 – morphological segments.

As Figure 16a illustrates, the average fitness of the Snakebots, evolved in smooth environment drops more than twice in challenging terrain and to 70%, 55%, 45% and 10% of the initial value for Snakebots with one, two, four and eight damaged segments, respectively, indicating relatively poor generality of these locomotion gaits. Conversely, the average fitness of the Snakebots, evolved in challenging terrain (Figure 16b) increases to 116% of its initial value in smooth terrain, and drops only to 97%, 75%, and 60% of the initial value for Snakebots with one-, two- and four- damaged segments, respectively. However, the average fitness of the Snakebots with eight damaged segments is only 25% of the initial value, suggesting that the degradation of the performance, inflicted by such damage is so heavy that it requires a specially adapted locomotion gait. The performance of Snakebots adapted to degraded mechanical abilities due to damage of eight segments, shown in Figure 16c, support this conclusion. Indeed, the average fitness of the heavily damaged (with eight broken segments) specially adapted Snakebots, is more than twice as high as the equally damaged Snakebots obtained from evolution in a challenging environment (Figure 16c). For Snakebots with one-, two- and four damaged segments these locomotion gaits are slightly superior to the gaits obtained from evolution in challenging terrain, and, naturally, somewhat inferior to them in a challenging environment.

As Figure 16 indicates, not only that the adaptations to a challenging environment and degradation are general and robust, but these adapted gaits have a higher fitness in the smooth environment. However, because the energy efficiency of the adapted gaits (due to the additional elevation of the segments of Snakebot) is lower than the gaits evolved in a smooth terrain, we assume that the Snakebot generally utilizes the partially inferior (in terms of velocity) gaits evolved in a smooth environment and switches to the more general and robust gates only when difficulties are encountered.

4. Conclusion

We considered the adaptation of evolved locomotion gaits of a simulated snake-like robot (Snakebot) to two distinct changes in the fitness landscape which, in the real-world, are most likely to cause a degradation of the performance of Snakebot – (i) a challenging terrain and (ii) a Snakebot's partial mechanical damage. We focused on the generality of the locomotion gaits, adapted to these changes in the fitness landscape, and observed the emergence of an additional elevation of the body and increased winding angle as common traits in these gaits. Discovering the strong correlation between the genotypes of the adapted gaits, we concluded that the adaptation is achieved through a drift towards adjacent niches in the genotypic space of the evolving Snakebots. Finally, we verified experimentally the generality of the adapted gaits in various fitness landscapes corresponding to a smooth environment, challenging terrain, and mechanical failures of one-, two-, four- and eight (out of 15) morphological segments. We argue that due to the generality of the adapted gaits, in response to an eventual degradation of its velocity, the Snakebot might only activate a general locomotion gait, without the need to diagnose and treat the concrete underlying reason for such degradation. We consider this work as a step towards building real Snakebots, which are able to perform robustly in difficult environment.

Viewing the situational awareness, or situatedness (Pfeifer& Scheier, 1999) as a necessary condition for any intelligent autonomous artifact, in our future work we are planning to investigate the feasibility of incorporating sensors that allow the Snakebot to explicitly perceive the surrounding environment. We are especially interested in sensors that do not

compromise the robustness of the Snakebot – such as, for example Golgi's tendon receptors, incorporated inside the potentially completely sealed Snakebot.

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The range of potential applications for mobile robots is enormous. It includes agricultural robotics applications, routine material transport in factories, warehouses, office buildings and hospitals, indoor and outdoor security patrols, inventory verification, hazardous material handling, hazardous site cleanup, underwater applications, and numerous military applications. This book is the result of inspirations and contributions from many researchers worldwide. It presents a collection of wide range research results of robotics scientific community. Various aspects of current research in new robotics research areas and disciplines are explored and discussed. It is divided in three main parts covering different research areas: Humanoid Robots, Human-Robot Interaction, and Special Applications. We hope that you will find a lot of useful information in this book, which will help you in performing your research or fire your interests to start performing research in some of the cutting edge research fields mentioned in the book.

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