Spinal Rhythms - Autonomous Embodied Evolution of a Biomimetic Robot's Rhythmic Motion Behavior

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The robotic art work *Spinal Rhythms* investigates the qualities and dynamics of physical movement performed by inanimate shapes. Abstract stick-creature are actuated by elastic shape memory alloy springs and perform slow and noiseless movements. The movements are the subject of an embodied evolutionary computation process that controls the robotic performance. The system evolves the actuation signals for the robotic muscles and tries to find efficient solutions for the sensitive dynamics between software, hardware and environment. The art work presents a solution on how to bridge the gap between digital and robotic artificial life art. It introduces the shaping power of evolutionary systems – widely employed in digital artificial life – into a real-world setup full of complex dynamics and unpredictable conditions.

I. INTRODUCTION

Our culture is on the verge of a technological boom that will make it necessary to completely redefine our notions of life. Advances in science and engineering point towards the cumulative merging of biology and technology. The distinctions between natural and artificial, born and made, become obsolete which naturally gives rise to skepticism and alarm. The materialistic world view of artificial life [7] sees human beings and machines alike, only distinguished by the varying degrees of organization of matter and energy. By admitting that life is a property that is not restricted to carbon-based biology, artificial life researchers forecast the synthesis of life from non-organic matter or non-matter.

Popular writers like Kurzweil [6] anticipate radical advances in artificial intelligence based on the law of exponential growth that is evident in the development of computing equipment so far. The stage of explosive development is reached when artificial entities obtain complete autonomy and are able to evolve and adapt on their own. The forecast of an information-based posthuman form of life raises doubt about the importance of embodiment. Many belief that even if intelligence can emerge through computation, only a body and sensory elements would allow computers to develop a form of consciousness [10].

While entities of artificial intelligence and experiments in artificial life most certainly reach higher complexities in a purely digital domain, their embodied robotic counterparts still provoke a more intensified encounter with the artificial. Screen-based artificial life is easier to handle than robots with all their inaccurate and defective components, yet it still remains in its virtual space, immaterial and always easy to shut down. Robots and robotic art work [2, 5, 10, 12, 15] deliberately cross this barrier, their physical manifestation in space and time with us eliminates the need for an interface and allows true interaction. The behavioral actions of the robotic artworks are the results of complex information processing systems, dynamically linking the invisible control and the physical reality. Fed with sensory information robots are able to experience and interact with their environment in a lifelike manner that stands far from hard-coded deterministic behavior. Yet technological constraints keep robotic artificial life so far clean and stable and free of other life characteristics such as growth, reproduction or fight for survival.

FIG. 1: The robotic stick-creature.

II. CONCEPT

Spinal Rhythms investigates the qualities and dynamics of physical movement performed by inanimate shapes. By designing arobot's body as a primitive abstraction, a connected system of bare limbs linked by articulated joints, the spotlight lies on the action that brings those inorganic shapes to life - the motion. It is movement that superimposes life and characteristics onto the abstract inorganic skeleton. The movement becomes the expression of the creature's individualism, the language that communicates its identity.

The movement of typical robotic systems is actuated by electrical motors. We hear the noisy clattering of motor activation when robots perform their stiff and jerky moves. The elastic quality of shape memory alloy (SMA) springs [3] allows smoother and more resilient movements. Their noiseless activation and stepless transformation grants the robots a much more graceful and life-like appearance.

The perceived movement of the robots is the interdependent product of software, hardware and environment. The computation unit sends activation patterns to the muscles elements, they apply forces onto the mechanics of the robotic skeleton which are transformed into kinetic energy that moves the whole body against environmental forces. The close coupling between the control signals and the mechanical dynamics of the body often makes a clear definition of the origins of the resulting behavior impossible. The body puts the constraints on what the control signals are able to do. By performing evolutionary computation on the actuation patterns, the control system learns to adapt itself to the morphology it has to deal with. The robot gets the chance to experience its own body through a simple trial and error process and learns to achieve better and better results with time. The performances of different motion patterns are graded according to a fixed set of fitness functions that attempts to find activation patterns that produce more movement while consuming less energy.

Robotic control systems are usually evolved in simulation and are less efficient than expected due to a lack in complexity in the simulated testing environment. An embodied evolution solves the *reality gap* problem [9] by performing all the tests on the hardware robot itself. The fault-prone hardware-body of the robot and changing environmental conditions create an unstable fitness landscape that demands continuous adaptation of the activation patterns. The attachment of the springs to the power supply can be easily damaged by too intensive forces and lead to disconnection. The environmental temperature has an impact on the performance of the muscle elements, since SMA works on the basis of temperature changes. Overheating or too extensive strain-activation can cause considerable losses in the springs' contraction and expansion possibilities. Additionally the springs have a finite life-span and can wear out if activated too often. Of course it might be possible to try to keep all these conditions stable, but the main goal of this project is to give the robot the ability to adapt itself to whatever interferences might come along. Instead of training for a fixed set of conditions, the inclusion of possible alteration during the evolution invokes autonomous adaptation and damage repair in close interaction with the changing environment.

As the project employs the techniques of artificial evolution in an embodied setup, it tries to bridge between artificial life art in the digital domain and in robotics. The evolution of movements and motion patterns has been the subject of projects like *Strandbeests* [4] or *Evolving Virtual Creatures* [11], yet the actual evolutionary process has always been conducted in physical-world simulation programs. Embodied evolutions are yet rarely carried out in artificial life art and are more common in the evolutionary robotics discipline [9]. Even though actual reproduction and mutation techniques are only applied to the control software of the moving robots, the robotic body and all its constraints and instabilities become the main carrier of the evolutionary focus.

III. THE ROBOT

The skeleton of the robots is constructed from straight wooden sticks with a cross-section of 6 x 15 mm. The length of the individual limb segments ranges from 18 to 32 cm. Small lightweight plastic hinges are used for the construction of flexible joints. To avoid too complex joint actions and overloading of the structure with too many muscle elements, most joints are equipped with either 1 or 2 degrees of freedom. Several limbs are connected together to form a skeletal body.

The spring elements employed in this project are made from 750 μm Nitinol-wire and have a coil diameter of 6 mm. The characteristic behavior of a spring element is defined by the spring constant. The spring constant describes the spring's willingness to deform when a force is applied to it and is therefore a measure of stiffness and strength. The specific feature of springs made from SMA is that their spring constant changes with the metal's temperature. A higher stiffness factor when heated up makes the spring exert more force and causes the contraction movement. While cooling down the spring constant slowly decreases and makes the element stretchable again. When passing a current of 2 A through them, the springs heat up and can contract to 29 mm, when cooled they can be extended to about 14 cm.

The activation of the muscle elements is carried out by the physical computing platform Arduino [1]. Variables defining an actuation pattern can be downloaded onto the microprocessor. The Arduino activates the robot according to the parameters of the pattern by operating switches that connect the SMA springs to an external power supply.

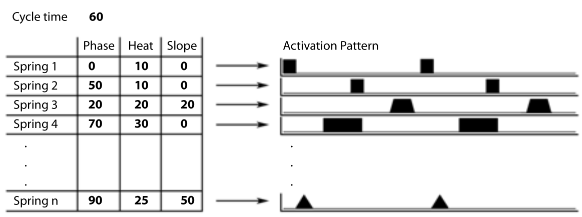

FIG. 2: The parameters defining an activation pattern.

The motion patterns that control the activation of the SMA springs are derived from rhythmic locomotion behavior in nature. Locomotion is such a common everyday activity that the nervous system created special control units to send out the necessary signals without constant supervision from the brain. The so-called central pattern generator (CPG) [13] consists of sets of interconnected neurons located in the spinal cord. CPGs produce rhythmic activation patterns for several muscles that work in unison to achieve locomotion behavior. The activation patterns

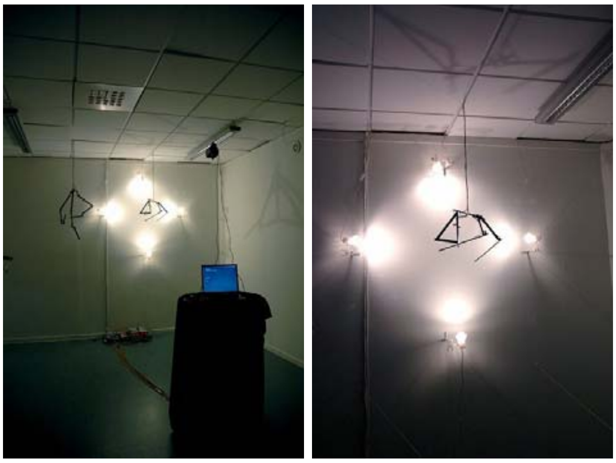

FIG. 3: Pictures of the exhibition setup.

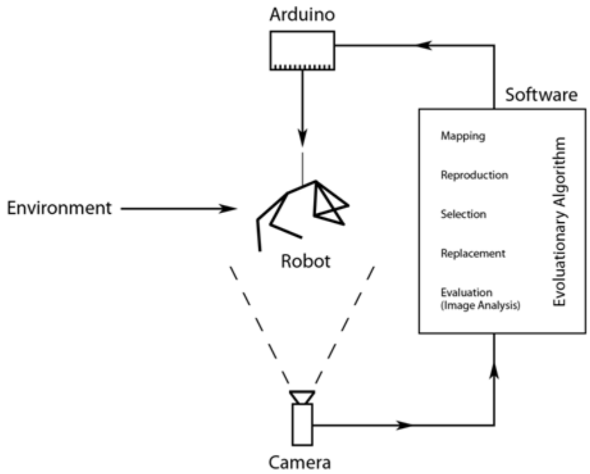

FIG. 4: Data flow

for the robot's SMA muscles are defined as a fixed set of variables. Each motion pattern is assigned a main cycle time and a set of 3 variables for each muscle element (see Figure 2). The phase, heat and slope parameters are each defined as integer values ranging from 0 to 99. The *phase* indicates at which step of the cycle the muscle's activation starts. The *heat* parameter specifies how long the activation lasts by interpreting the value as a percentage of the whole cycle time. The *slope* parameter defines the length of the PWM controlled fading in and out of the activation.

IV. EXHIBITION SETUP

When executing the evolution of the rhythmic movements the robots hang suspended in their testing environment. Experiments on the locomotion behavior of animals are performed in similar setups - the animal is suspended with a system of belts so that its movements are not disturbed by gravitational weight issues or other perturbations [8]. The animal's nerve system is stimulated artificially and its body's performs autonomous locomotion in free air. The suspended robotic creatures of *Spinal Rhythms* receive control signals from a governing computing unit that monitors their behavior with an installed video camera. The robots perform motion patterns in front of lifeless eyes that judge their presentation according to strict and rational rules.

This dialog between two machines, one training the other to perform in a more efficient way, serves as an allegory on the future superiority of artificial intelligence that will advance without human help. It anticipates the point in time when machines intelligence will be able to perform self-adaptation in a completely autonomous way.

The robot's visible movements are exceptionally slow and they gain – performed in monotonous cyclic repetition – a certain transcendent quality. As caused by slow motion in film and video, the perception of movement is altered and amplified. Certain body movements are only perceptible when one stands and monitors the robot very closely. In order to completely immerse into the artwork the viewer has to adapt himself to the robot's slow rhythm. The movement – as subject of the meta-program performing the evolutionary computation – develops an aesthetic meaning of its own through its visual perception.

V. EVOLUTIONARY PROCEDURE

The embodied evolutionary process that slowly adapts a robot's motion pattern can be visualized as a cyclic flow of data between several components (see Figure 4). The software, that connects the individual parts, starts the iterated procedure by selecting a parent patterns out of a pool of motion patterns. The cloned and modified offspring pattern is downloaded onto the Arduino platform and its execution causes the activation of the robot's muscle elements. The dynamic motion behavior, that is the product of the activation pattern, the robot's hardware and environmental conditions, is monitored by the camera. The software captures images from the camera and analyzes them according to specific fitness criteria. The resulting fitness is then assigned to the pattern and used in the decision whether the pattern is successful enough to replace a weaker member of the pattern population. After the survival selection, the software routine restarts to handle a new motion pattern.

When a new motion pattern is downloaded onto the microcontroller and the signal for its execution is sent, the software itself goes into a waiting stage. The length of the inactivity is defined by the pattern's cycle time. Patterns need to be pre-run on the robot to assure consistent contraction and extension rates of the springs. After at least 3 cycles of pattern activation have passed the software starts to monitor the next cycle of movement by periodically capturing images from the camera. The interval between the images is set to one twelth of the cycle time. After the cycle is completed the pattern activation is terminated and the robot enters its cooling stage. During

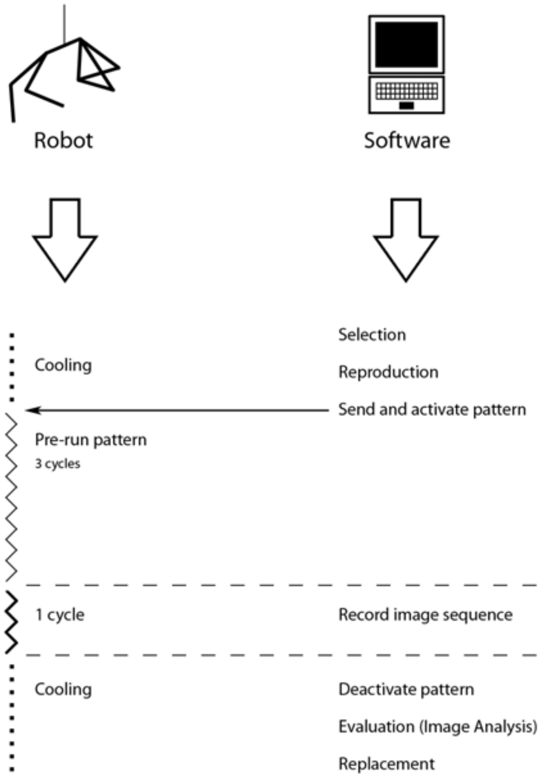

FIG. 5: Parallel activity of robot and software.

this period the software processes the stored image sequence and performs the evolutionary computation procedures.

The evolutionary run continues autonomously until it is terminated by the human supervisor based subjective reasons.

VI. EVOLUTIONARY ALGORITHMS

The time-sensitive character of the SMA metals and the need for pre-run activities before the actual evaluation process add up to even higher time demands than in typical embodied evolutionary projects. With possible cycle times of up to 2-3 minutes, the evaluation of a single motion pattern can take up to 10 minutes. To meet these demands the population size has been deliberately kept small and was set to a number of 10.

Every evolutionary run starts with the initialization of its start population. 10 individual motion patterns are generated and their parameters are set randomly. To avoid out-of-reach values the starting conditions are generated by a Gaussian distribution around chosen numbers. The bell shaped distribution of results exhibits a tight variance around the average, but also permits solution far off the center. The mean values of cycle time and heating duration for the random initialization of patterns were defined individually for every evolutionary run, yet mostly kept close to cycles of 60 seconds and a heating duration of 15 %.

Starting from the randomly initialized population the evolution tries to stepwise increase the average performance values. A *steady state* evolution [14, 16] has an offspring population size of 1. Every new successful pattern is immediately included in the parent population. To ensure that this doesn't lead to an early reduction of diversity, a non deterministic parent selection method is chosen. Reproduction solely based on asexual operators is carried out by cloning a parent pattern and mutating its parameters. The software chooses one parent among the population by using a rank-proportional selection mechanism. The mutation operators are responsible for exploiting the possible search space by producing slight variations of successful patterns.

After evaluating its performance the steady state evolution adds the new pattern to the parent population. Offspring and parents compete with each other for survival as the population size has to be reduced to its fixed value of 10. As stochastic methods were used for the parental selection, the survival selection was chosen to be deterministic. In a simple truncation action the pattern with the weakest fitness value is extracted from the ranked population.

As an unstable fitness landscape is admitted as a steering factor in the evolutionary run, changing hardware and environmental conditions falsify formerly recorded fitness results in time. This problem is solved by permitting patterns only a limited lifespan. By constantly checking the pattern's date of its last evaluation against the current generation, the pattern's age is detected and marked as *too old* if it exceeds a threshold of 35. In that case the pattern has to undergo another evaluation procedure and receives new fitness values.

VII. FITNESS EVALUATION

The fitness value that determines the future of every motion pattern is the sum of several weighted fitness functions.

$$fitness = \begin{array}{l} w_1 * motion\_value \\ +w_2 * motion\_continuity \\ +w_3 * energy\_usage \\ +w_4 * cycle\_time \end{array}$$

The *motion value* indicates the degree of the pattern's visible physical movements by applying a motion detection operator. While a new pattern is executed on the robot a sequence of 12 images is captured by the camera. The motion detection analysis is based on the comparison of pixel values on two successive time step images. The function calculates the deviation for each pixel by comparing its brightness with the brightness in the following image. By comparing the deviation to the chosen threshold value of 40 *moving* pixels are distinguished from *static* ones. Noise in the resulting difference image is avoided by making the state of a pixel dependent on its neighboring movement activity. If less than 4 of its 8 neighbor pixels are categorized as *moving* a former *moving* pixels becomes *static*. The motion value of a pattern is

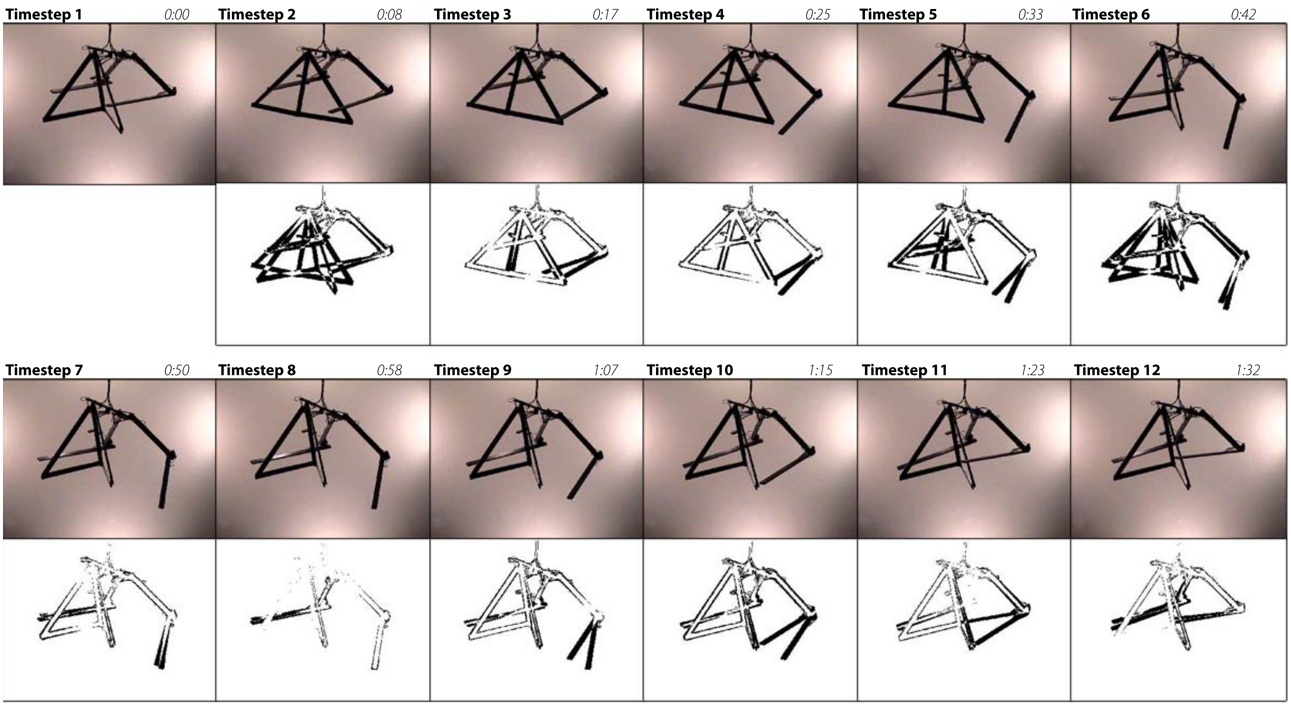

FIG. 6: The 12 captured images and the 11 processed difference images of pattern 90 of the evolutionary run *19_frog*.

retrieved by summing up the amount of *moving* pixels in all the difference images.

The *motion continuity* value judges each time steps activity in comparison to the whole cycle's average motion. This allows identifying smooth and continuous movements from abrupt and jerky ones.

The *energy usage* value is determined by adding up the the heating time in seconds for each individual spring element during one activation cycle. The summed-up value, multiplied by the demanded 2 A, represents the hypothetical quantity of electrical charge the pattern needs for activation (maximum current limits of available power supplies are not taken into account here). By weighing the energy usage negatively the evolution tries to create efficient motion patterns that achieve high fitness while employing less energy.

The *cycle time* value is included into the fitness evaluation to allow additional influence on the time character of evolved patterns. By weighing it negatively the evolution can be steered towrads faster motion loops.

The weight values for the individual fitness components were hand-chosen for the different evolutionary runs.

FIG. 7: The pair of active antagonistic wing-muscles.

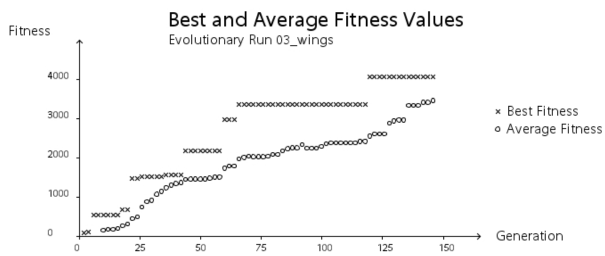

FIG. 8: Best and average fitness values over the course of the evolutionary run *03_wings*.

VIII. RESULTS

Several evolutionary runs have been conducted on two different robotic creatures. It became obvious that the evaluation process is not sophisticated enough to successfully influence the development of complex motion patterns. The two-dimensional perception of the monitoring video camera and a mere focus on simple motion detection doesn't allow identification of individual joint movements. The overall motion of the whole creature is summed together and this makes it impossible to distinguish if the resulting motion originates from active or passive relocation.

One of the first evolutionary runs, *03_wings*, was conducted to find the motor patterns for only two active springs. The chosen muscles are antagonistically

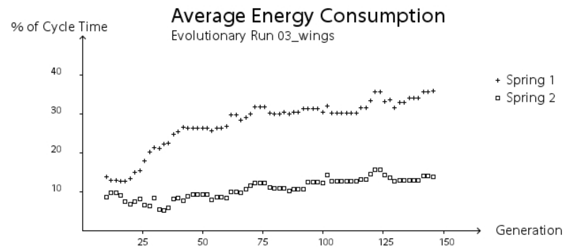

FIG. 9: The average energy consumption for every spring in the evolutionary run *03_wings*.

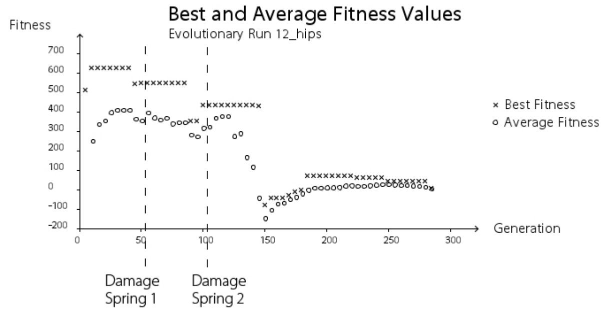

FIG. 10: Best and average fitness values over the course of the evolutionary run *12_hips*.

attached to the robotic body. By pulling against each other they operate a wing-flapping mechanism (see Figure 7). By focusing the evolutionary computation on only those two springs clearer results were achieved in a shorter time. Figure 8 shows the gradually increasing fitness during the process of the evolution. The evolution is able to successfully discover the springs' individual dynamics. The random initialization sets the heating times of the springs around a mean value of 10 percent of the cycle time. As evolution progresses the average values of the two springs show different tendencies. Figure 9 displays that the evaluation process quickly discovers that longer heating periods for spring 1 result in better performances. Whereas spring 2 only shows a slight increase to about 14 percent during the 147 generations, spring 1's heating variable increases to around 35 percent. This result confirms that the actuation of spring 1 is affected by the rather strong gravitational downward pull of the connected limb elements. The heavy load demands longer heating times to produce the necessary force, yet also enables stretching deformation sooner than with less load.

The fluctuations in hardware dynamics and environmental conditions that were meant to supply the unstable fitness landscape were mainly caused by defective electronic connections. Several springs tended to become inactive during long 24-hour-runs. This instability was not intended yet served as good steering material for the evolutionary computation. If the fitness weight values of the evaluation function were set accordingly, the evolution was able to detect which springs were inactive and to compensate for these errors.

The evolutionary run *12_hips* was conducted on only the two hip-joint muscles. The results of this run are very much determined by the fact that both of the two springs were deactivated due to malfunctioning connections. Spring 1 became inactive around generation 50, and spring 2 after generation 100. This explains the decreasing tendencies in the fitness graph (see Figure 10). Figure 11 shows that the evolution managed to steadily reduce the heating times for the individual springs shortly after their malfunctioning occurred. This behavior is caused by the negative influence of the energy usage value in the fitness evaluation. As the energy usage is determined

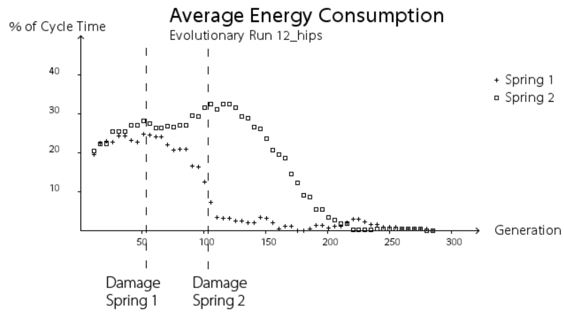

FIG. 11: The average energy consumption for every spring in the evolutionary run *12_hips*.

by heating duration and cycle time, the average cycle time slowly decreases after generation 100 until it hits a minimum around generation 200 (see Figure 12). In reducing cycle time and heating times the evolutionary computation copes with the loss of both spring modules. By slowly minimizing those values, the sudden loss in fitness performance is rectified and leads to fitness performances values around zero. This clear coping method is provoked by the high influence of energy usage in the fitness calculations. A smaller fitness weight for energy usage might have caused delays in the reduction strategy.

By taking the human designer out of the loop, the artwork shows the shift from human constraints to machine constraints. The pure information about the robot's movements is filtered and distorted by the eye of the camera. This imperfection leads to behaviors that can be perceived as *cheating*, when the evolution presents solutions that might satisfy the program's fitness evaluation yet not the human inspector. Here the system reaches a certain degree of autonomy from the human intentions that guided the design of the evolutionary framework. Departing from its foreseen path the system escapes into its own world of logic.

The two-dimensional view of the camera excluded for example movements that acted in parallel direction with the viewing angle of the lens. This made the evolution disregard the importance of certain joint movements. If the influence of the energy usage was high enough in the fitness evaluation, the evolution was partially able to discover this waste of energy. By

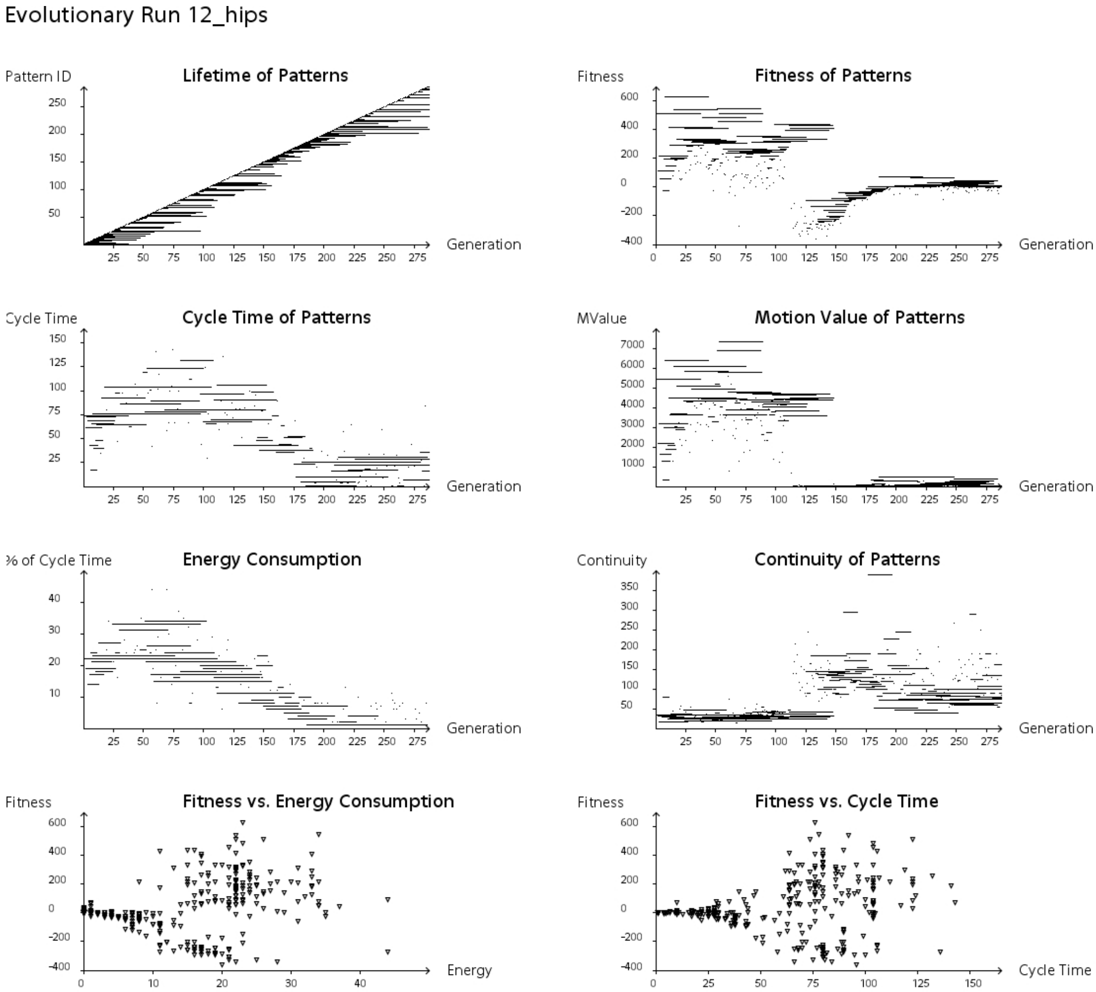

FIG. 12: Pattern lifetime, fitness, cycle time, motion value, energy consumption and motion continuity analysis for the evolutionary run *12_hips*.

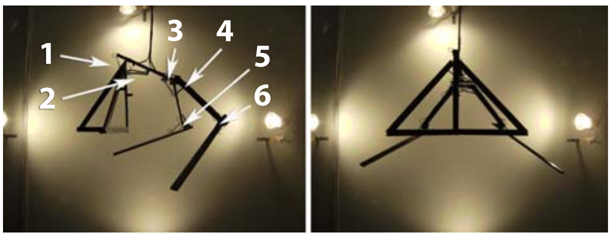

FIG. 13: The six springs on the robotic creature. Springs 1 and 2 are referred to as wing-muscles, springs 3 and 4 as hip-muscles and springs 5 and 6 as ankle-muscles.

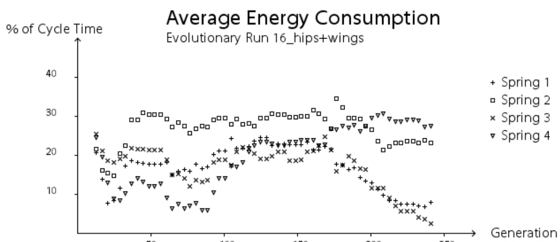

FIG. 14: The average energy consumption for every spring in the evolutionary run *16_hips+wings*.

perceiving the particular spring elements as less influental in the motion production or even inactiv, the system reacted by reducing the specific spring heating times as described before. Yet this effect was only possible if the number of active springs were kept low.

The evolutionary run *16_hips+wings* focuses on the pattern development for four springs: the opposing wing muscles and the two hip-joint muscles. The dynamics of the heating values for the hip muscles shows rather fluctuating behavior during most of the run (see Figure 14). But beginning around generation 175 both values clearly diverge: whereas the heating values of spring 4 rise to about 30%, the values for spring 3 decrease towards a minimum of almost 0%. The orientation of the suspended robotic structure causes the hip joint, that is actuated by spring 3, to perform movements almost parallel to the view of the camera. Even though movement happens in the three dimensional space, the camera is unable to recognize it as such. Driven by the high negative weight value for energy usage the fitness evaluation tries to favor

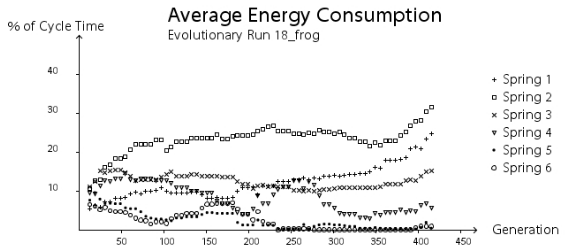

FIG. 15: The average energy consumption for every spring in the evolutionary run *18_frog*.

solutions that waste less energy. By decreasing the heating values for spring 3, the evolution finds a possibility to reduce the energy without losing too much in perceived motion value.

As changes in form cause dynamic changes in orientation, compensating rotation movements cause a high motion detection value in the image analysis process. This trend is visible in the evolution's preference for muscle elements that are located at the center instead of at the boundaries of the limb-network. Actuated joints that move their own and additional adjacent limbs, can cause more movement than joints that are located at the lower end of limb-combinations. The hip-muscles of the robotic structure are able to move the whole leg-element, whereas the ankle-muscles only affect the lowest component.

The evolutionary run *18_frog* actuated all the six muscle elements of the robotic creature: two opposing wing-muscles, two hip-muscles and two ankle-muscles (see Figure 13). Figure 15 displays that the heating duration for all the springs starts from their initialization around values of 10%. Quickly afterwards the values of the different springs diverge. The evolution increases the heating duration of spring 2 to allow the wing-flapping mechanism to achieve higher motion values. The average heating values for both ankle-muscles, spring 5 and 6, bounce between 3 and 7% until they simultaneously hit a minimum of 0% around generation 240. Due to the negative influence of the energy usage in the fitness evaluation, the evolution seems to acknowledge that the ankle-muscles are unable to produce high motion values and therefore reduces their heating duration.

When comparing the fitness result dynamics of the several tests, it can be derived that the evolution was almost always able to find a local sub-optima only after about 50 generations. This quite good start-up behavior is achieved by the diversity in the randomly initiated start population. Quickly selecting more successful patterns the evolution focuses on their fine-tuning and gains better fitness results in small steps. After this first steady increase in the average performances the development rather seems to freeze. First hardware damages lead to the loss of possible movability and the necessary re-evaluation of patterns leads to a drop in the best fitness values. The dynamic behavior of most evolutionary runs after generation 50 can be seen as a fractured up-and-down development. Even though the Gaussian mutation function allows large diversity in the reproduced patterns, this element of randomness doesn't input enough variability in the evolutionary run.

Mostly driven by the randomness in the mutation function the parameters of the patterns fluctuated during the run. If patterns for more than 4 springs were evolved, the evolution usually wasn't able to successfully distinguish the impacts of the individual springs. The more springs were employed the more complex the cause-and-action relationship of activation and movement became and the less obvious trends could be recognized in pattern design. This missing talent of coping with higher complexity can maybe be explained with the too small population size, the too high mutation rates and the too short evolutionary runs.

Even though most evolutions didn't necessarily produce highly representable results in terms of evolutionary strategies, they still succeeded in creating different rhythmic motion behaviors. In the real-time exhibition setup the movements of the robotic creatures emphasize more the slowness and noiselessness of the SMA springs, whereas speeding up the recorded movements digitally underlines the individual characteristics of the repetitive rhythmic actions. Displaying cycle times of 60 seconds as a 3 seconds loop, transforms the former abstract limb actuations into associative flapping, hopping or walking behaviors. The time lapse videos allow to recognize the fine distinctions between the individual patterns much better and create much higher mimesis effects in the mind of the viewer. The creatures suddenly become animals performing locomotion techniques in free air and draw associative character traits like jerkiness or jumpiness.

IX. CONCLUSIONS

The autonomous adaptation of a robot's motor patterns to an unstable fitness landscape is carried out in an embodied evolution. This research proposes the use of evolutionary algorithms to deal with the instabilities in the behavior of SMA springs. Embodied evolution is favored over a digital simulation due to the sensitive and not always predictable dynamics of SMA behavior. The fitness evaluation tries to steer the evolution towards more efficient movement behavior. A series of evolutionary runs have been conducted and partially show successful development towards higher fitness performances. A loss of control is visible when the evolution has to deal with a large search space. Runs conducted on patterns consisting only of a few muscle elements show noticeable rising trends whereas patterns with many muscle elements diverge into unclear and random behavior.

A. Future research

Further development of the projects' core ideas would demand a more intensive study of possible evolutionary strategies. The long time-requirements for conducting the tests largely inhibited experimental investigations on different strategies. More carefully designed selection and reproduction mechanisms and better tuned setup parameters might improve the obtained results.

Results much truer to the body-control-dynamics would be accomplished if the needed evaluation feedback would originate from the robotic body itself. This could be achieved by employing stretch sensors in parallel with the spring modules or by incorporating rotation sensors into the mechanical joint design.

A revision of the robots' mechanical design would allow the introduction of modularity into the system. The main morphology of the robot could become subject of the evolutionary development as well.

Instead of constructing the robotic bodies out of wood and metal and just granting the muscle elements elasticity, the whole structure could be manufactured out of compliant materials. The possible use of shape decomposition methods would add additional variability in the construction process. In becoming more soft and flexible the robots would underline the merge of biology and technology.

Success in the development of efficient and easy-to-handle EAP products might provide a future alternative for the SMA springs. The polymers promise a greater force-potential and could free the robotic sculptures from their untouchable position in suspension.

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Evolutionary Run 19_frog

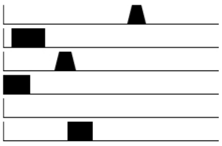
Pattern 21

	P	H	S
SPR 1	63	11	0
SPR 2	88	11	0
SPR 3	7	7	27
SPR 4	1	14	0
SPR 5	6	10	0
SPR 6	77	12	44

Cycle Time	60	
Energy Usage	34	
Motion Value	3257	2862
Motion Continuity	21	40
Fitness	**384**	**288**

Pattern 41

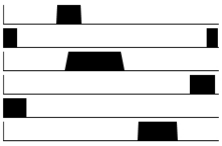
	P	H	S
SPR 1	42	9	26
SPR 2	96	16	0
SPR 3	76	10	24
SPR 4	0	13	0
SPR 5	56	0	3
SPR 6	70	12	0



Cycle Time	69	
Energy Usage	38	
Motion Value	3498	3096
Motion Continuity	32	27
Fitness	**391**	**341**

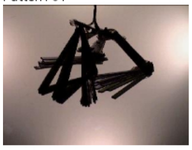
Pattern 48

	P	H	S
SPR 1	75	12	5
SPR 2	5	12	3
SPR 3	71	28	7
SPR 4	13	12	3
SPR 5	0	11	3
SPR 6	37	19	4

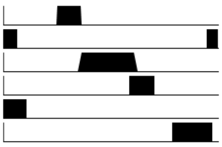


Cycle Time	63	
Energy Usage	56	
Motion Value	3298	2639
Motion Continuity	17	35
Fitness	**396**	**261**

Pattern 61



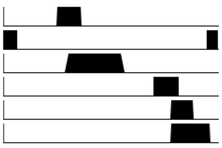
	P	H	S
SPR 1	75	12	5
SPR 2	5	12	8
SPR 3	65	28	7
SPR 4	41	12	0
SPR 5	0	11	2
SPR 6	21	19	0



Cycle Time	81	
Energy Usage	73	
Motion Value	3748	3341
Motion Continuity	24	29
Fitness	**432**	**361**

Pattern 65

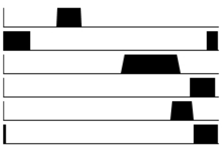
	P	H	S
SPR 1	75	12	5
SPR 2	5	12	3
SPR 3	71	28	7
SPR 4	30	12	3
SPR 5	22	11	6
SPR 6	22	19	4



Cycle Time	100	
Energy Usage	89	
Motion Value	4093	3374
Motion Continuity	36	49
Fitness	**441**	**306**

Pattern 90

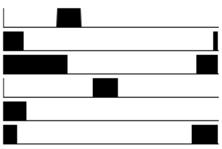
	P	H	S
SPR 1	75	12	5
SPR 2	5	18	14
SPR 3	45	28	7
SPR 4	13	12	0
SPR 5	22	11	9
SPR 6	11	13	4



Cycle Time	100	
Energy Usage	87	
Motion Value	4049	2220
Motion Continuity	29	44
Fitness	**449**	**144**

Pattern 108

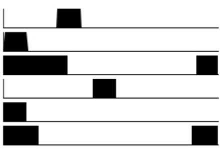
	P	H	S
SPR 1	75	12	5
SPR 2	2	12	8
SPR 3	10	40	7
SPR 4	58	12	0
SPR 5	0	11	0
SPR 6	12	19	0



Cycle Time	123		
Energy Usage	125		
Motion Value	4186	4139	4037
Motion Continuity	39	42	44
Fitness	**425**	**413**	**393**

Pattern 128

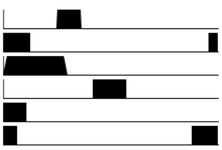
	P	H	S
SPR 1	75	12	5
SPR 2	0	12	8
SPR 3	10	40	7
SPR 4	58	11	0
SPR 5	0	11	0
SPR 6	12	29	11



Cycle Time	141	
Energy Usage	151	
Motion Value	4338	4013
Motion Continuity	36	46
Fitness	**435**	**368**

Pattern 131

	P	H	S
SPR 1	75	12	7
SPR 2	4	17	8
SPR 3	0	30	7
SPR 4	58	16	0
SPR 5	0	11	0
SPR 6	12	19	0



Cycle Time	129	
Energy Usage	129	
Motion Value	4400	4111
Motion Continuity	41	50
Fitness	**447**	**386**

FIG. 16: Selection of patterns with the highest performance values over the course of the evolutionary run *19_frog*. Each pattern's fitness results are listed in consecutive order.