Towards self-adaptation of robot organisms with a high developmental plasticity

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***Abstract*—In this work we explore several adaptation processes in systems with a high degree of developmental plasticity. It is indicated that such systems are driven by two different forces: adaptation fitness and design goals. The goals, formulated in an invariant way to environmental changes, represent an example of a self-concept, used in developmental processes. This paper gives an example of collective locomotion, introduces four different adaptive mechanisms and finally discuss the self-development of such systems.**

***Keywords*-Collective robotics, symbiotic robot organisms, self-adaptation, self-development, long-term artificial evolution.**

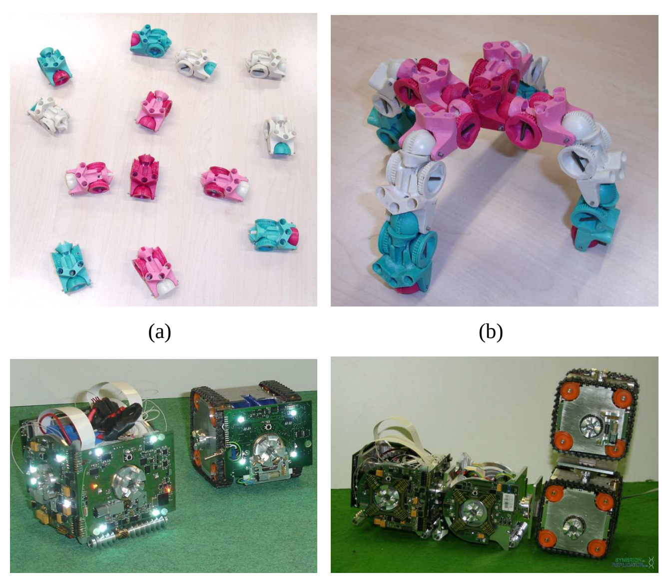
I. Introduction

Adaptability represents an important characteristic of systems working in real environments [1]. Different uncertainties, variation of parameters or even an appearance of unknown situations requires such mechanisms, which allow the system to find a compromise between achieving the main goal, set by a designer, and flexible behavior to fit environment. Finding this compromise requires three important mechanisms: plasticity of the system itself [2]; adaptive controller, which uses system's plasticity to perform adaptation [3], [4]; and finally a goal, which is formulated invariantly to environmental influences.

Plasticity of the system can be achieved by exploiting the principle of heterogeneous modularity [5]: each module is compatible with other modules and they can assemble and disassemble themselves into structures with different functionality [6], see Fig. 1. These structures are denoted as artificial organisms and represent the key idea of the SYMBRION [7] and REPLICATOR [8] projects, funded by European Union.

Structures and functionality of artificial organisms are closely related to each other, by changing macroscopic structure, the system also changes its own functionality and correspondingly behavior [9]. Relation between structures, functions and behavior can be represented as shown in Fig. 3. We denote this relationship as "generating" because the upper level generates the lower level, i.e. structures generate functions and functions generate behavior. Controllers in functions and structures – they represent *the regulative level* – allow some degree of flexibility (adaptability) for the system. In details, it depends to which extend a designer of these controllers was able to foreseen possible changes of an environment and to integrate a reaction on these changes into controllers. To react on such changes, which are not predictable on the design stage, we need to introduce the second - *generating level*, which can modify controllers. The generating level contains different deriving and evolving mechanisms, which can generate the regulative level and essentially, when not completely, change the system.

Technical systems possess goal-oriented behavior, but should be also adaptive to uncertainties and changes in environment. To some extend, these systems are driven by two different forces: by a fitness and by a goal. When the degree of adaptation is low, there are no essential conflicts between them. However, when a plasticity is high, and the system can be hindered by adaptive processes from reaching the main goal, we are facing a new conceptual problem about long-term controllability of adaptive and self-developmental processes. Obviously, that either the goal should be formulated in such an invariant way, which allows multiple approaches for its achieving, or adaptive processes should basically be limited.



(a) (b) (c) (d)

Figure 1. ***(a)** Prove-of-concept: individual robots; (b) Prove-of-concept: aggregated robots into an artificial organism; (c) Real prototypes: individual robots; (d) Real prototypes: aggregated robots (images ©SYMBRION, REPLICATOR projects).*

This paper is a combination between representing several achieved so far results and a position paper related to self-adaptation in artificial organisms. Sec. II, introduces an example of approaching adaptability for macroscopic locomotion. We represent four main mechanisms: adaptive multi-functional local drivers in Sec. II-A, adaptive self-organization of the level of interacting structures in Sec. II-B, evolving with using a global fitness and generation by using the self-concept in Sec. II-D. The unbound information-based self-concept is discussed in Sec. II-E. Finally, this paper is concluded in Sec. III.

II. Approaching adaptability of artificial organisms for collective locomotion

As followed from the vast literature on the object, adaptability is related to fitting to uncertainties, introduced by changing environment, unknown parameters or unpredictable behavior of the system itself. It is often considered in biological terms of natural evolution [10] or environmental uncertainty [11] as well as in management and business processes [12]. There are undertaken several attempts to create a common theory of adaptability, like the approach suggested by Michael Conrad [11], however currently each adaptive system consider the problem in its own research domain.

More generally, adaptability is closely related to a capability of a system to react on these uncertainty/changes and as well as to a capability of a designer to forecast a reaction of environment (in general case) on the system's response. Therefore we can defined adaptability in term of the triple-relation: *environmental changes→ system's response → environmental reaction*. *Adaptability is ability of a system to achieve a desired environmental reaction in accordance with a priory defined criteria by changing its own structure, functionality or behavior initiated by changed environment*.

We consider adaptability on the example of collective locomotion, shown in Fig. 2. It displays a 2D section of an aggregated organism with several active joints. Each of the aggregate modules possesses individual independent motors (degree of freedom, displayed by a circle) and can actuate independently of each other. However, in order to move as an organism, all these motors should perform a highly synchronized individual actuations, which emerge a collective movement. Moreover, there are several requirements, such as:

- the center of gravity should not overstep the nodes A and I, other case the organism will be unstable;

- even in homogeneous case there are several non-symmetries caused by differences in docking elements, or more generally by different modules. This leads to non-symmetrical positions of several active nodes, like C and G;

- we require that some structural nodes are e.g. strongly horizontal (vertical) as e.g. D, E and F.

- all nodes have different load. This is indicated by different gray level of active nodes.

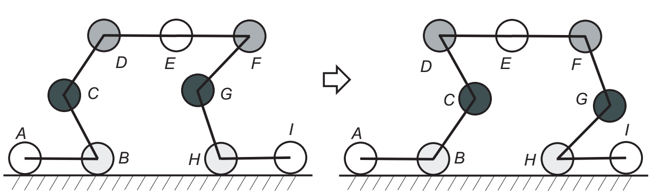


Figure 2. *2D section of an aggregated organisms, circles are active joints. Shown are two states transient by a collective locomotion.*

Each motor is controlled by a non-linear driver, which control parameters depend on internal sensors (e.g. torque of a motor). Without a loss of generality, we say this represents a simplest adaptive control on the functional level, where motors are first not connected with each other. This scheme is sketched in Fig. 3. Now, we insert a structural level, which depend on morphology of the organism. This level is represented by a coupling element $\underline{\underline{\mathbf{C}}}$, which creates "communication channels" between different nonlinear drivers. Since organisms create generally three dimensional structures, we expect at least a coupling between three elements (as e.g. a tensor of the third order). The coupling element contains values like $c_{ijk} = 1$ (direct coupling between drivers i, j, k), $c_{ijk} = 0$ (no coupling between drivers i, j, k), $c_{ijk} = -1$ (phase inversion between drivers i, j, k) or even any positive (amplification) or negative (decay) coefficients. Collective actuation depends on coefficients in this coupling elements.

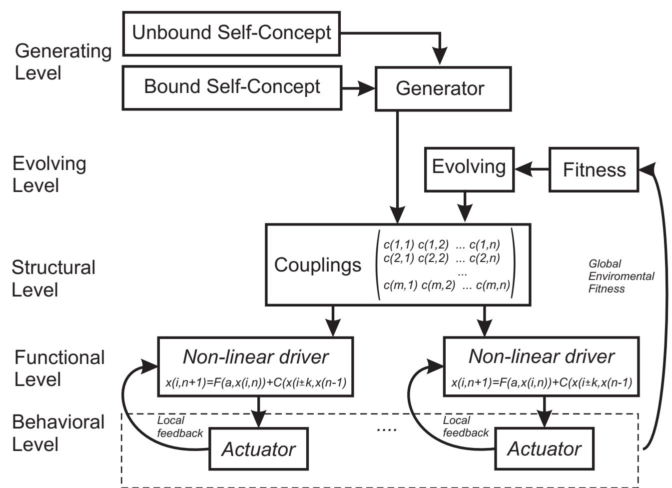


Figure 3. *Different levels of adaptive collective locomotion.*

There are four different mechanisms, which can be used in creating adaptive structure and functionality around $\underline{\underline{\mathbf{C}}}$. Firstly, individual drivers use local adaptive mechanisms, know in theory of adaptive control, as shown in Sec. II-A. Secondly drivers and $\underline{\underline{\mathbf{C}}}$ represent a coupled map lattice

(CML) [13]. As we see from Fig. 2, nodes B, C, D, F, G, H have the most intensive load, which can lead to a more stronger synchronization in $\underline{\underline{\mathbf{C}}}$, where as other nodes do not need any synchronization and their connection will disappear. In this way, synchronization effects in CML represent an emerging adaptability created by self-organizing processes between behavioral, functional and structural levels. This approach is sketched shown in Sec. II-B. Then, a structure of $\underline{\underline{\mathbf{C}}}$ (and so a collective locomotion) can be evolved. Here we face the problem of deriving such local and global fitness functions, which lead to a specific collective actuation. This approach is described in Sec. II-C. Finally, a self-developmental process, based on a self-concept can be started. We distinguish two classes of bound, as shown in Sec. II-D and unbound, as shown in Sec. II-E, self-concepts, which will be further discussed.

A. Multi-functional, locally adaptive individual motor driver

As described in the previous section, individual motor drivers should demonstrate diverse dynamic behavior. In literature there are known different types of continuous drivers, e.g. [14], however due to technological reasons of controlling DC motors, we prefer time-discrete systems. Each time-step can be selected as a small as possible, for example a few μsec to guarantee a quality of control. Dynamic variables, e.g. x_n, represent voltage (current, phase), which are applied directly to DC-DC convertor or H-bridges. To obtain diverse dynamics, we use the idea of changing determinancy order of normal form (NF) and the following perturbation of nonlinear terms [15]. This can be achieved when to use hierarchical non-homogeneous coupling for any well-know low-dimensional system, for example the logistic map. This approach is very common in the community (e.g. [16], [17]). In our case, the map has the following form:

$$\begin{aligned} x_{n+1} &= cy_n + ax_n(1-x_n), \\ y_{n+1} &= cx_n + bx_ny_n(1-y_n), \end{aligned} \qquad (1)$$

where $x_n \in \mathbb{R}$, $y_n \in \mathbb{R}$, c is the coefficient of the linear coupling, b is the coefficient of the nonlinear coupling, a is the general bifurcation parameter. As turned out, the dynamics of (1) in fact has little in common with the initial logistic maps. The system (1) is denoted as the ordinary logistic-logistic (OLL) map. Several examples of qualitatively different types of behavior are shown in Fig. 4.

As shown in [18], the non-homogeneous coupling in (1) increases determinancy order of initial NF. This can be understood as a perturbation of the original logistic map by couplings. In order to obtain all possible perturbed nonlinear terms, it needs to calculate the universal unfolding that is given e.g. by

$$G(\varphi_n, \lambda_u) = \alpha_1 + \lambda_u\varphi_n + \alpha_2\varphi_n^2 + \alpha_3\varphi_n^3 + \alpha_4\varphi_n^4 + \varphi_n^5 \qquad (2)$$

with the codimension 4, where α_i are coefficients. We can see that non-homogeneous coupling method of OLL

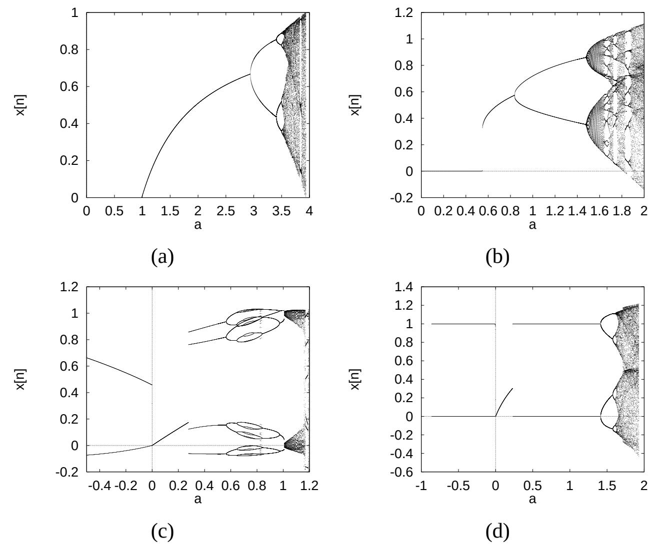


Figure 4. *Several examples of qualitatively different types of behavior of the system (1). Bifurcation diagrams of the OLL map (1) at parameters:* **(a)** $b = 1$, $c = 0.1$, $x_0 = 0.1$; **(b)** $b = 2$, $c = 0.6$, $x_0 = 0.4$; **(c)** $b = -1.5$, $c = -1$, $x_0 = 0.1$; **(d)** $b = -0.5$, $c = -1$, $x_0 = 0.1$.

map changes the codimension of local bifurcation from 1 (transcritical bifurcation contained in the logistic map) to 4.

Diverse dynamics of the system (1) can be used in the mechanisms of local adaptation. Coefficients a, b and c can be connected to locomotive sensors (for example a torque sensor). When a load on motor is increased, a local control mechanism (e.g. PID regulator [19]) adapt e.g. coefficient a to provide more current on motor so that to achieve the required torque on the given load. In the next section we will see several adaptive effects, which arise when many of individual motor drives, like (1), are connected into one system.

B. Adaptive mechanisms based on self-organization

Considering multi-robot organisms, to synchronize the behavior and especially the collective locomotion for non predefined morphology is a huge challenge. The first problem, which occurs in such high distributed system, is how to reach synchronized behavior and at the same time to minimize the data load between the robots. Based upon well investigated CML approach for self-organization, we use this approach in order to develop adaptive behavior primarily for collective locomotion problem. The synronization effect of spatiotemporal chaotic pattern can be applied to multi-robot organisms and decrease the amount of communication data between robots.

In our first investigation we consider each site of a lattice as a communication load between neighboring robots. As a “basic” system for CML we use an logistic map coupled homogeneously as e.g. the system (1).

Each basic system is additively coupled with one neighbor systems. Synchronization appears due to interaction between nonidentical systems which leads to a locking of their phases, whereas their amplitudes remain uncorrelated. Our investigation is done with one-way ring map lattices of length m:

$$x^i_{n+1} = (1-e)ax^i_n(1-x^i_n) + eax^{i-1}_n(1-x^{i-1}_n) \quad (3)$$
$$x^{i+m}_n = x^i_n$$

where $x_n \in \mathbb{R}$, $y_n \in \mathbb{R}$, $i = 1,..,m$, e is a small coupling parameter and a is a bifurcation parameter. The synchronization occurs within $0.16 \leq e \leq 0.19$, observable as bright area in Fig. 5. During the iteration process we simulated a disturbance in bifurcation parameter a, which can be associated with the disturbance in a communication load. The simulation shows that if the range of these fluctuations are small, the system become again synchronized (area in a red box). Each highlighted area represents ten coupled sites with slightly changed bifurcation parameter from time step up $n = 150$.

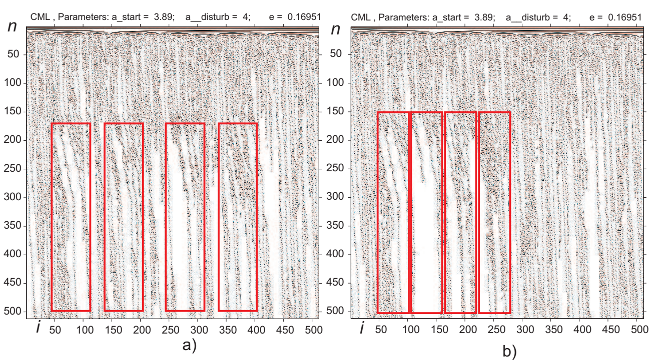


Figure 5. *One-way coupled map. Disturbance at different points (i-axis) are simulated occurred from the time step $n > 150$ (n-axis). In (a) disturbed sites (i.e motor voltage drops) are in a large distance and do not affect each other. In (b) sites are in local range and affect each other*

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In Fig. 5 a) and b) we investigated the behavior of four disturbed ranges (i.e. series of motors) and analyzed fluctuation impact of sites slighted far away or in direct adjacencies. As can be observed, the synchronization after disturbance in the bifurcation parameter is better performed if disturbed areas are close to each other (local impact). On a real robot organism that means that robots in a local range perform better synchronization than robots far away from each other.

This method can be extended by coupling the sites in the CML in all four directions and allow not only synchronization in chain like multi-robot orgaisms (Fig. 1 (d)) but also investigate synchronization behaviour in 3D structured organisms (Fig.1 (a)).

C. Fitness driven adaptability

Because it is very hard, to break down a desired behavior into the individual behavior of each robot in a swarm or a multi-robot organism [20], we use bio-inspired approaches in addition to the adaptive mechanism based on self-organization from the previous section. The key focus (see Fig. 6) is the genome which contains the codified coupling matrix C_{ijk} and control parameters. This genome maps to the coupling of motors within the organism and thus to the behavior of the organism. A different strength of the coupling can lead to a different behavior. So in order to adapt to a certain structure, which requires a non-trivial coupling, the strength of the coupling can be evolved.

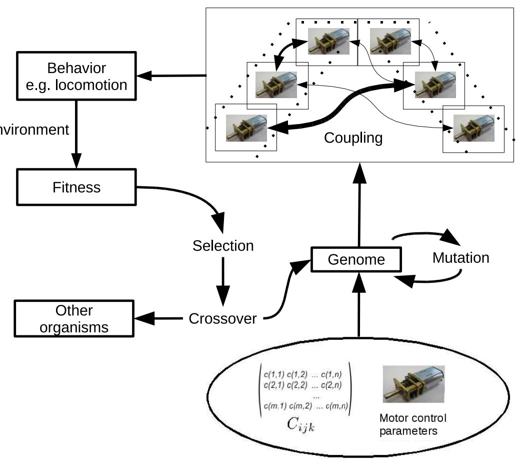

Figure 6. *Evolutionary Concept.*

A crucial point for evolution is the feedback from the environment. By evaluation of the current coupling structure in respect to a desired task (e.g. locomotion), a fitness value measures the performance of the organism in the current environment. In the case of locomotion the fitness function could be influenced by multiple factors like power consumption, number of couplings (high number of coupling may lead to higher communication traffic) or velocity of an organism. Unfortunately, some of the evaluated objectives like velocity and power consumption can build a contradiction. For example, it may be possible to move very fast, but with a high need of power. Other locomotion types may be slower, but consume less power. Consequently, there are several good candidates converging on a Pareto Frontier [21], [22]. For locomotion, we look for the non-dominated alternatives, which consumes power in a commensurate ratio to the required speed and task.

To cover each point potentially in the search space, mutation operators are used. This mutational steps can range from a single random change of a cell to swapping of cells or complete rows. In an environment with multiple organisms, we can use the evolutionary principle of cross-over. Two or more organisms can exchange their coupling matrices to

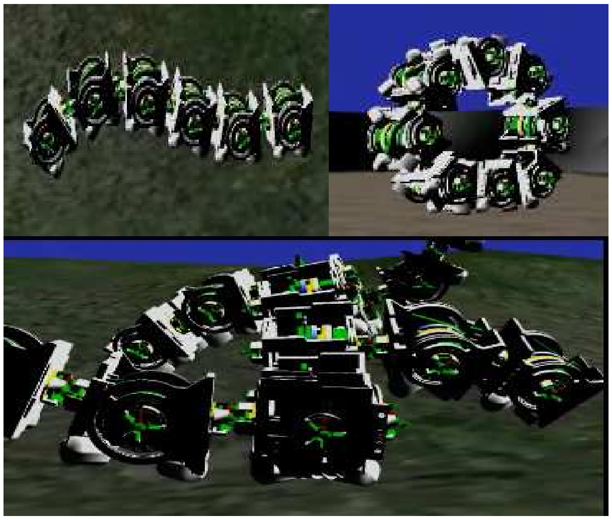

Figure 7. *Exemplary organism structures in simulation (caterpillar-like, ring-like and four-legged organism) [23].*

each other. Depending on the fitness value of both parents, a total or a partial exchange of the genome can be done. The new structure can be either placed in one individual or both.

With the help of the Symbricator simulator [23] different shapes of organisms can be co-evolved with feasable genomes. In Fig. 7 different shapes of organisms can be seen. The comparison of multiple (symmetrical and asymmetrical) shapes and linked coupling matrices with the reached fitness values (in simulation) can lead to very efficient organisms and locomotion patterns.

D. Bound self-concept and structural generation

To explain the idea of a self-concept and a structural generator, we consider the case when locomotion should have a specific form, such as a symmetric movement of legs, segmented (like by insects) construction of body, or there are imposed constraints or a priory desired properties. The self-concept contains in a compressed form a description of these constraints/properties. The notion of self-concept is originated from human psychological research (e.g. [24]) and is basically related to self-developmental processes. In this way, the self-concept contains a goal of the system being invariant to adaptive processes. There are several mechanisms expressing such an invariant character of the generating level: symmetries, templates and conservation laws, production, decomposition rules as well as self-reference. In this work we can briefly demonstrate using of symmetries and symmetry breaking [25] as well as ideas of developmental modularity [26] expressed in the form of "templates".

The most obvious way to generate well-scalable structural symmetries is to create a circulant [27] coupling $\underline{\underline{\mathbf{C}}} = \begin{pmatrix} T & 0 & c_1 \\ 0 & T & 0 \\ c_{n-1} & 0 & T \end{pmatrix}$ where $\underline{\underline{\mathbf{T}}}$ is a Toeplitz band matrix [28] $\underline{\underline{\mathbf{T}}} = \begin{pmatrix} c_0 & c_{n-1} & c_{n-2} \\ c_1 & c_0 & c_{n-1} \\ c_2 & c_1 & c_0 \end{pmatrix}$ (taking into account dimensions n for $\underline{\underline{\mathbf{C}}}$ and for $\underline{\underline{\mathbf{T}}}$). The idea of introducing $\underline{\underline{\mathbf{T}}}$ consists in a segmented construction of robot's body and scalable kinematics of locomotion independently of the total size of this body. In this way, the basic building block is defined by circulant coupling $\underline{\underline{\mathbf{C}}} = circ(c_0, c_1, c_2, ..., c_{n-1})$. Well-known property of circulant coupling is a possibility of its diagonalization by the Fourier matrix $\underline{\underline{\mathbf{F}}} = \frac{1}{\sqrt{n}} \begin{pmatrix} 1 & 1 & 1 \\ 1 & w & w^2 \\ 1 & w^2 & w^4 \end{pmatrix}$, where $w = \cos\left(\frac{2\pi}{n}\right) + i \sin\left(\frac{2\pi}{n}\right)$. The eigenvalues can be calculated as $\lambda_j = \sum_{i=1}^{n} c_i (w^{j-1})^{i-1}$. Maximal eigenvalue $\lambda_{max} = \lambda_1 = \sum_{i=1}^{n} c_i$, i.e. when circulant coupling has only a fixed number of c_i for any n, the stability and several other properties of $\underline{\underline{\mathbf{C}}}$ are invariant to the dimension of the whole system. Both, circulant and Toeplitz band matrices demonstrate ideas of invariances in the self-concept. From the view point of the group theory, $n \times n$ circulant can be viewed as a cyclic group Z/nZ of order n and can be generated by a generator g^n in Z/nZ.

To integrate symmetry breaking constrains, we can use approach [29]. Kiziltan and Milan in [29] defined four generators: R_f, C_f which the flip first two rows/columns of a matrix and R_s, C_s which shift the first row/column to the last position. For any generators, the notation $g \circ g = g^2$, (e.g. $R_f \circ R_f = R_f^2$) is used. Any two matrices are equivalent when they are obtained from each other by applying any of $R^n C^n$ generators, e.g. 3×3 coupling $\underline{\underline{\mathbf{C}}}$ has 36 symmetrical matrices. The idea of breaking a symmetry is to apply constrains, which order all symmetric objects, like the proposed lexicographical order.

Another concept behind self-generation are so-called templates. They are well-known in cognitive science [30] (also as "schemas" or "prototypes"), in topological research (in knot and braid theory) [31], as well as known as "frames" in AI community [32]. The idea of a template is to describe most general "stereotypical" properties or features of some common class of situations/processes/objects. Concrete instance of a template can be reconstructed or generated by parametrization. There are several attempts to find an universal template, however it seems that different classes of solutions need different templates.

Since we are focusing on dynamic properties of collective actuation, we can assume each motor is driven by a periodic control. In this way a collective actuation represents a system of coupled oscillators with adaptive feedback, as e.g. described in [14]. As known, such systems possess self-adapting properties. Specific (desired, required) dynamic motion pattern can be generated when to parameterize the CML-driving-system with a specific set of control parameters as well as to provide a way to change these parameters, see Fig.8. Thus we can map the problem of finding a dynamic template to the problem of finding such a bifurca-

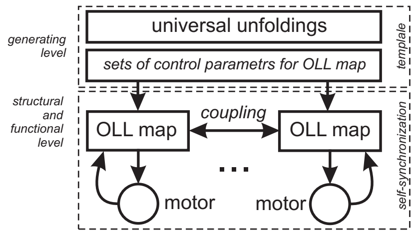

Figure 8. *Template for collective locomotion.*

tion dynamics, which property reflects the needed changes. Speaking more technically, we are looking for universal unfolding [15]. Obviously, that universal unfolding together parameter sets can be viewed as templates for collective actuation. Unfolding can be explained in the following way: let the normal forms of a local bifurcations be given by

$$\begin{aligned} \underline{\mathbf{q}}_{n+1} &= \underline{\underline{\Lambda}}_u(\{\alpha\},\{\beta\})\underline{\mathbf{q}}_n + \underline{\mathbf{g}}^{(2)}(\underline{\mathbf{q}}_n,\{\alpha\},\{\beta\}) + \\ &+ \quad ... + O(\underline{\mathbf{g}}^{(r+1)}), \end{aligned} \tag{4}$$

where the term $\underline{\underline{\Lambda}}_u$ presents the diagonal matrix of eigenvalues, $\underline{\mathbf{g}}$ are the resonance terms, dependent on both $\{\alpha\}$ and $\{\beta\}$ and r is the determinancy order. Universal unfolding includes all possible perturbations of this normal form, which are equivalent to original bifurcation problem [15]. In this way, unfolding represents in some sense an invariance to perturbations. Finding universal unfolding allows defining the most general form of the desired dynamics, i.e. template.

E. Unbound information-based self-concept

This subsection summarizes the different topics of the previous subchapters on a more general and over viewing, high level description. Self-organization in an organism takes always part in parallel and distributed in different levels. At the lower level of genes or cells the sustainable building pattern and controlling is an adequate definition of information. Especially on the lower level of genes the combination of to genes is only driven by an increase of information. We define the concept of information by four characteristic attributes:

1) There is a mechanism installable that synchronizes the communication between two or more agent (partners) meaning the semantic compatibility of the agents (active units) that start a communication session.
2) The receiver of a message has in the sense of Pulitzer not only to acknowledge the received message; but even more important is the demand, that he "understands" the matter of the sender and behaves (reacts) like it is assumed by the sender.
3) Two agents (components) only start the "negotiation" respectively the combination if the total information of the two participants is greater as the sum of the individual information (closed system) or it is less (open, living system).
4) The process of information gathering in (in the sense of generalized entropy)in a closed system endeavors information increase in an iterative way. This process ends if the supremum (maximum) of information combination has been achieved. If the system is not closed (e.g. continuous energy or heat exchange with the environment) then the individual information can be reduced and the combined information of two agents might be less than their sum of individual information. In this case we are looking for infimum (minimum) of the combined information.

Now we proceed to define the concept of information and we do it on the base of chemical potential, statistical potential and quantum field theory. Our first expression will be presented in general. The "chemical potential" of an agent is:

$$\begin{aligned} \mu_j &= \sum_{k=0}^{K}\sum_{m_j=0}^{M}(g_{jk}\ln(\hat{\mathbf{a}}_{jk}^{\dagger}(m_j)\hat{\mathbf{m}}\hat{\mathbf{s}}_{jk} + \\ &+ \quad g_{jk}^{*}(\ln(\hat{\mathbf{a}}_{jk}(m_j)\hat{\mathbf{m}}\hat{\mathbf{s}}_{jk}^{\dagger}) \end{aligned} \tag{5}$$

The activity of an agent is defined by a creation fermionic operator $\hat{\mathbf{a}}^{\dagger}$ and annihilation operator $\hat{\mathbf{a}}_{jk}$. All interactions are only generated by message exchange, here represented by the bosonic creation operator $\hat{\mathbf{m}}\hat{\mathbf{s}}_{jk}^{\dagger}$(message creation) and annihilation operator $\hat{\mathbf{m}}\hat{\mathbf{s}}$(message receive). The activity operators and the message operators are as usually dynamically governed by ordinary coupled differential equations that are dictated by an interaction Hamilton operator.

The characteristic of this definition of μ_j is the fact, that the two operators $\hat{\mathbf{a}}^{\dagger}$ and $\hat{\mathbf{m}}\hat{\mathbf{s}}$ and their Hermitean conjugated are complex operator. This means e.g. that beside the claim of the need of synchronization (compatibility) of two agents the interacting operations between the two participating agent can in addition stabilized by phase locking.

The index *k* represent all agents, even a self-interaction is allowed (*j* = *k*), m_j describe the internal states of agent *j*. The coupling coefficients g_{jk} define the coupling strength between the agents *j* and *k*. These coefficients have not to be symmetric but if two interacting agents are synchronized, symmetric then these coefficients are symmetric and can be considered as a metric tensor that describe, similar to a weight matrix, the connection strengths (signs) of all agents to agent *j*. The internal states of agent *j* are noted by m_j. The transition between a ground state $m_j = 0$ to an excited state $m_j \neq 0$ is only possible if an arriving message has been come, and if $\mu_j(m_j = 0) > \mu_j(m_j \neq 0)$ is fulfilled.

A further additional benefit of the approach with the chemical potential is the possibility to describe the adaptation of an agent by different phase transitions (e.g. solid state $\rightarrow$ fluid state $\rightarrow$ gas state). This can be initiated by special messages and appropriate coupling constants that generate an appropriate state transition. By this way it is obvious that e.g. environmental restrictions are considered as dedicated messages from outside. Further on, it also possible to describe diffusion processes by this potential.

The total individual state S_j of an agent j with several internal states (state sum) is defined by:

$$S_j = \sum_k e^{(\mu_j(<{N_{jk}}^2>-<N_{jk}>^2)-W_{jk})/<{N_{jk}}^2>}, \quad (6)$$

Here $<N_{jk}>=<\hat{\mathbf{ms}}^{\dagger}_{jk}\hat{\mathbf{ms}}_{jk}>$ is the expectation value for the number of messages that agent *j* receives in total and $<{N_{jk}}^2>=<\hat{\mathbf{ms}}^{\dagger}_{jk}\hat{\mathbf{ms}}_{jk}\hat{\mathbf{ms}}^{\dagger}_{jk}\hat{\mathbf{ms}}_{jk}>$. The expression $(<{N_{jk}}^2>-<N_{jk}>^2)$ defines the expectation value of the quadratic fluctuations (dispersion). W_{jk} represents the individual knowledge state of agent *j* after it receives a message from agent *k*.

According to rule 1 all agents are cooperative that means that the different messages are not coming into a bunch but they obey e.g. the Poisson distribution defining fixed time differences between two messages.

Finally, the statistical potential of an individual agent is defined by (only rules 1 and 2 are fulfilled)

$$\Omega_j = -<{N_{jk}}^2> \ln \sum_k e^{\frac{(\mu_j(<{N_{jk}}^2>-<N_{jk}>^2)-W_{jk})}{<{N_{jk}}^2>}},$$

where the coupling constants are integrated in the definition of the chemical potential.

This definition is very close to that one of a statistical potential. Because we consider μ_j as a dynamic changing variable, the individual states S_j can beside physical or chemical descriptions also characterized by states of non-linear dynamics like equilibrium states, periodic states or even chaotic states. The individual information of agent j, after receiving a message from agent k, is:

$$Inf_{jk} = -\frac{\partial \Omega_j}{\partial <N^2_{jk}>} \quad (7)$$

The total information of agent j is $Inf_k = \sum_k Inf_{jk}$, and for agent k $Inf_j = \sum_j Inf_{kj}$

If two agents j and k (components) try to combine themselves to a bigger object (e.g. fusion of to genes or cells) than they have to fulfill the four above mentioned rules, and the information of the combined component increases $(Inf_j \circ Inf_k > Inf_j + Inf_k)$ if the system is closed; or decrease $(Inf_j \circ Inf_k < Inf_j + Inf_k)$ if the system is open (in physics in this case the free energy is minimized).

This means that the ultimate goal for the fusion e.g. of two or even more cells is the continuous generation of information increasing or information decreasing under the assumption that rule 4 is true. The process of information increase/decrease usually happens in evolutionary steps and might never stop (open ended evolution). In mathematical terms this is an iterative process. Such an iteration might never stop (open ended evolution). Then we are looking for the supremum $sup(Inf^i_{jk})$, whereas i defines the iteration step.

The activities of different genes/cells are usually clearly different and they might have strong coupling constants. This fact implies that such units can operate as "seeds" for morphological networks that are constructed by strong message exchange and can be considered as the predefinition of a final structure. The result is a topological framework to describe the structure of an organism. The representation of the structure of a creature can be considered like a semantic net that is used in image processing to describe structured objects and their possible movements.

A concept of a fitness function has to be considered separately from the meaning of information. The fitness function tells us how well the adaptation of an agent or set of agents e.g. to environmental restrictions or to other internal restrictions has been performed. The ramification of this view is to consider the fitness in a strong connection to a given task. The fitness of genes to circumvent a high mutation rate in order to conquer cancer might be very low but the information between two genes is in this case very high because the activities of the affected genes are very high.

But the opposite case can also occur. The diversity of genes (cells, species) can be explained by a maximum of information that fabricate a high adaptation that causes in consequence a result that creates several high valued fitness functions in different environments (e.g. different landscapes, in water or finally in air).

III. Conclusion

In this paper we demonstrated a common picture of adaptive processes, which include bound and unbound self-concepts and presented an example of these concepts for collective locomotion. The self-concept describes a goal of the system in some invariant form such as symmetries, optimization principles, templates or information-based metrics. It can even generate an unlimited complexity and diversity, as proposed by von Neumann, in L-Systems as well as in self-referred dynamics [33]. Performing experiments with the scheme from Sec. II represents our further goal.

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