

Systemic Intelligence: Methods for Growing up Artefacts that Live

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Abstract—The ideas of systemic intelligence provide a set of methodologies and paradigms that are, beside other advantages, suitable for constructing control systems that are capable of growing up. In particular the promising methods of Systemic Architecture, Schedule of Structural Development, Memory Organization and Rules for Learning and Adaptation are presented and discussed with respect to grow up an artifact.

Of special interest is the concept of *growth* in the sense of *growing up* from a kind of infantile stage to a fully matured entity. To grow up an artifact from an infantile stage via a sequence of learned abilities to a fully matured entity is still a feature of life not yet sufficiently transposed onto technical systems.

To enable the capability to *grow up* artifacts, a set of methodologies and principles is presented in this paper. The developed methodologies are already implemented into physically existing test beds that operate, adapt (and grow up) in real time and in the real world to prove that the proposed approach is feasible under real conditions. Two realizations (robot control, audio signal processing) of a systemic architecture for an up-growing system are presented in this paper.

I. INTRODUCTION

Living entities show a tremendous variety of abilities that still decline to be ported onto technical, 'non-living' systems. The *concept of living* is close connected to the *concept of growing*. Thus the understanding of *growing* is a necessary prerequisite to model the features of *living*.

One of the most challenging features of living artifacts:

The ability to grow

One of the most interesting features of growing artifacts:

The special capability to grow up.

Biological information processing systems are heavily pre-structured, providing the living entity with a set of features necessary for surviving. One of the most interesting of these features is the ability to adapt and to learn with respect to the environment and to experience. Thus the entity gain most of it's capabilities throughout learning and restructuring during it's lifetime. The underlying structure of the information processing system is one of the keys to enable this kind of up-growing process.

The concepts of systemic intelligence [8] form one possible subset of methodologies postulated to be present within living nature. Systemic intelligence is not claiming to be a remedy for problems not solved nowadays, but to pave the way to some novel concepts for problem solving mechanisms.

II. SYSTEMIC INTELLIGENCE

Systemic intelligence is an idea to span the bridge between subsymbolic representation of knowledge (neural networks, fuzzy control, fuzzy logic, rules, differential equations, ...) and symbolic described capabilities (goals, reasoning, behavior, intention, ...). The intelligent behavior shown by living systems, and some technical artifacts is neither the consequence of the symbolic description of their tasks, nor the consequence of the subsymbolic representation of information. We postulate that intelligent behavior arise only if the design of the system has been performed adequat.

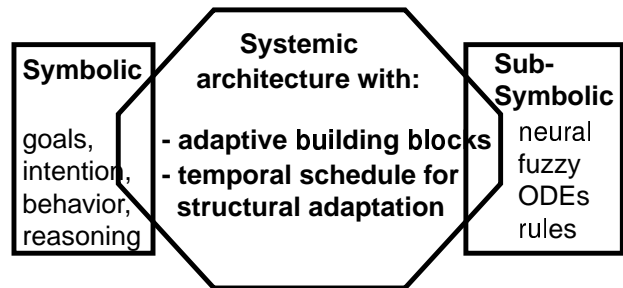


Fig. 1. Systemic intelligent is spanning the bridge from subsymbolic representation of knowledge to symbolic capabilities. The systemic architecture has adaptive building blocks with a temporal schedule for structural adaptation.

The major components of systemic intelligent systems are: the architecture of the system (*systemic architecture*) and a *schedule of development* describing the developmental stages of the system. Only the carefully designed combination of these methods permit the desired results. Therefore the system is subdivided into *building blocks* which are adaptable on multiple levels and time-scales with individual *learning rules* and individual *organization of memory* [8].

The major key features of systemic intelligent system design are listed below:

- 1) Systemic architecture,
- 2) Adaptive building blocks,
- 3) Schedule of structural development,
- 4) Rules for learning and adaptation,
- 5) Memory organization for knowledge and reasoning.

Although there is a high interaction between the building blocks, each one is responsible for a specialized task and will therefore be trained using an individually shaped learning- and adaptation-scheme with respect to the knowledge and the experience acquired by the artifact. The complete process

is governed by the schedule of structural development with respect to interaction with the environment the artifact resides in and with respect to the task the artifact is supposed to learn.

The initial design of this systemic architecture together with the schedule of development is the *genotype* defining the potential of the artefact. Individual experience during the process of growing will lead to individual *phenotypes* of that entity. Growing up means that the artefact has a process of ontogenesis throughout its operation time.

To enable the construction of a technical system that has the potential to exceed it's initial capabilities throughout with the capability to grow up some guidelines from the approach of systemic intelligence can pave the way to reach the desired goal [8], [10]. The following theses govern the approach of systemic intelligence:

- 1) Intelligent features are embedded in the *systems architecture* and not within the sub-symbolic realization, or the symbolic representation of knowledge.
- 2) The *system view* is the missing link between symbolic capabilities and sub-symbolic realization.
- 3) The principles of the systems architecture (which are responsible for enabling intelligent behavior), represent what is called *systemic intelligence*.
- 4) The systemic architecture of the system is variable in structure, during the lifetime of the system *tempo-structural adaptation*
- 5) A *pre-structured* system (*genotype*) enables the execution of low level functions and basic abilities from the beginning on.
- 6) The different *building blocks* of the architecture are adaptive on all levels using diverse schemes of *adaptation and learning*.
- 7) The highly pre-structured *memory organization* of the system is growing, according to experience.
- 8) The structure is adapted following the *schedule of development* defining kind and duration of adaptation.
- 9) Adaptation is done with respect to *interaction with the environment*. Thus an individual *phenotype* of the system can develop.

III. GROWING UP ARTIFACTS

The biological concept of living means among other features the capability of growing. Growing is understood in the way of growing up.

Growing up means that the artifact is starting with some basic abilities (*genotype*) and evolving to a fully matured entity, with individual capabilities (*phenotype*) as a consequence of experience and interaction with the environment.

Growing means that the artifact is starting with basic abilities and gaining additional capabilities C_j by growing its knowledge base through experience.

A distinct set of capabilities $\{C_a, C_7, C_x, \dots\}$ forming a well defined behavior may be defined as a stage S_i within the process of growing up.

The system is passing from the actual stage S_i to the next stage S_{i+1} using the learning rule r_i and the experience e_i as requested by the schedule of adaptation.

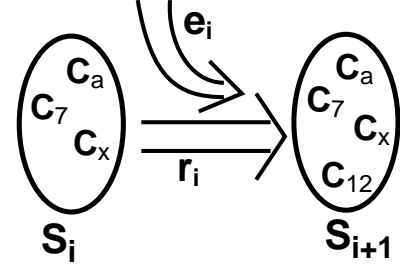


Fig. 2. The system passes from the actual stage S_i with the capabilities $\{C_a, C_7, C_x\}$, to the next stage S_{i+1} using the learning rule r_i and the experience e_i by developing the novel capability C_{12} .

It is obvious that each stage S_{i+1} reached is a function of the predecesing stages, learning rules and experiences: $S_{i+1} = S_{i+1}(S_i, r_i, e_i)$. Each stage S_i has a set of already realised capabilities C_k which might be enhanced, extended or altered for reaching a following stage S_{i+1} .

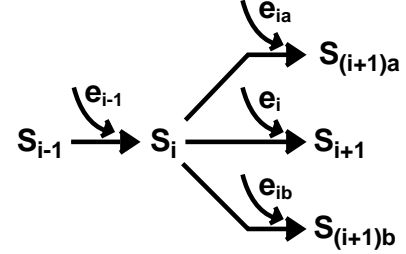


Fig. 3. Depending on the individual experience e_i the system is reaching different stages of development S_{i+1} .

It is not unusual, that the artifact needs more than one capability C_i , or just a subset of the already acquired capabilities available at the present state C_i to be able to learn a new capability C_{new} .

Depending on the experience e_i the artifact encountered the capability $C(e)$ to be acquired using the learning rule r_j will be different.

The sequence of capabilities \mathcal{C} , and thereby the sequence of stages \mathcal{S} is not predefined, but a consequence of the interaction of the artifact and the situation experienced during learning. Therefore a carefully designed teaching sequence is of vital importance for the further development of the growing artifact. Although the genotype defines the potential of the artifact, the experience is leading to the individual phenotype governing the individual character of behavior and capabilities.

IV. SYSTEMIC ARCHITECTURE

The systemic architecture is a design concept for building and structuring the architecture of controlling systems. Based on experience and knowledge from neurosciences, neurocomputing, psychology and cognition sciences, a systemic architecture features a set of capabilities and principles to be portable onto a technical artifact ([19], [3], [17], [13]).

The design principles governing the systemic architecture are not meant to be strict, but are understood as an overall guideline for the design of the systemic architecture.

- 1) **Hierarchy**, layers of building blocks,
- 2) **Building Blocks**, consist of modules,
- 3) **Modules**, as individual processing units,
- 4) **Upstream** sensory, vs. **Downstream** actuary data.

Following these design-principles, a systemic architecture consists of a hierarchical structured network of simple and if possible independent adaptable building blocks. Each emerging building block consists of modules which process information and learn capabilities. Thereby the layers refer to the layers below by using the provided information and the range of functions and capabilities immanent in the underlying layers.

Hierarchy: The systemic architecture is organized in layers forming a hierarchy of information processing stages. Higher functions of behavior and abilities are normally implemented by using the higher levels within the hierarchy. Each layer within the hierarchy is consisting of one or more building blocks. The building blocks accept information from the adjacent layers (upstream and downstream) for processing, and project the results to these layers. Normally it is not necessary to have connections between building blocks within the same layer.

Building Blocks: All building blocks are structured the same way. They consist of modules of different types (normally two or three). The information they obtain is learned, or transduced, or modified, or used to compute, classify or associate new information to be passed to the other building blocks. The modules within one building block can have multiple connections among them.

Modules: The modules perform the core of information processing and memory within the systemic architecture. They are implementing individual functionality with respect to the individual subtask they are responsible for. Three major families of modules build the backbone of information processing within the systemic architecture:

- **Classifiers** The modules within the sensoric (upstream) path are mostly build for classification. Therefore they are performing a classification or categorization of the data within the upstream. They learn self organized and unsupervised, data driven by the statistics of the incoming data and the urge to build categories.
- **Function approximators** The function approximators perform and generate the actuary (downstream) infor-

mation for control purposes. They are mostly trained using a supervisor implemented as a reinforcement signal or adaptiv critic.

- **Associators** Associators are the major memory modules. They have to be capable of association between multiple input and output streams, and between different modules and building blocks.
- **Learn-modules** Implementing the learning rules as modules within the systemic architecture opens the possibility to regard their signals in the same attitude as the *normal* flow of information within the architecture.

Upstream vs. Downstream: Within the systemic architecture the upstream information and downstream information are regarded as two fundamental different kinds of information.

Upstream information is regarded as a kind of sensory information which is passed from the lower level building blocks to the levels above. Sensory information is categorised by passing through the layers, thus gaining quality of information.

Downstream information is regarded as information dedicated to perform an action within the system. Actuary information like commands, control signals, tasks to perform or direct motor commands are typical downstream information. The modules responsible for handling this information are normally function approximators or function generators.

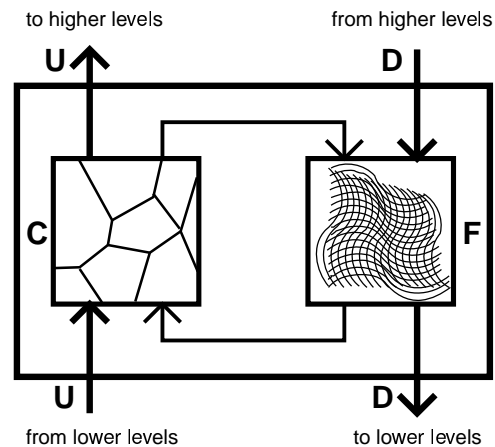


Fig. 4. A typical building block with the two modules: classifier C within the upstream U path; and the function generator F within the downstream D information path. The internal connections between the two modules implement a local feedback loop.

The systemic architecture is one part within a bundle of several methodologies springing from systemic intelligence: modular building blocks, adaptive on multiple ways, system design, learning rules, data connections between the several building blocks, control connections between the several building blocks, a schedule of when to train the capabilities, and when to exploit the capabilities, a schedule of converting the subsequent stages of envisaged capabilities into a sequence of correlated teaching, training and adaptation phases.

V. SCHEDULE OF STRUCTURAL DEVELOPMENT

Of significant importance for the up growing capability is a carefully designed schedule of structural development. The evolution of the complete system is performed by a sequence of subtasks, where the later tasks rely on already acquired capabilities $\mathbf{S}_{i+1} = \mathbf{S}_{i+1}(\mathbf{S}_i)$. Training of a subtask depends on the successful completion of one or more already trained subtasks, using these capabilities as prerequisites.

Not only the sequence of capabilities \mathcal{C} is controlled by the schedule of development, but each building block, and thereby each capability \mathbf{C}_i is trained incrementally. Each fraction of the capability to be acquired is trained one after the other, by only teaching new data when the other data is mastered sufficiently.

The system is only capable to grow up, if the teacher is presenting the training data and the training feedback (reinforcement, critic, ...) in a well shaped order with respect to the capabilities the system acquired so far. In contrast to conventional systems that are being programmed, there exist some systems with the capability to learn some sub-functionality through a learning algorithm. In both ways, the capabilities are acquired by the system within one single bunch.

No living system is learning the high sophisticated tasks from scratch. The living system is passing from one stage of ability to a next one, in a well defined manner ([4], [3], [9], [19]). Growing up is a carefully controlled trail through the jungle of possible subtasks, leading from one stage of capability to the next stage with new acquired capabilities.

The schedule for structural development is triggering the transition from one stage \mathbf{S}_i to the next stage \mathbf{S}_{i+1} governed by the four following aspects:

- 1) **Time:** Some transitions are to be triggered after a distinct time, to guarantee the possibility for novel experience, although some of the capabilities might not have been learned completely.
- 2) **Capability:** When the system has reached a distinct set of capabilities, the transition to the next stage is triggered.
- 3) **Internal events:** Internal processes might be the cause for explicitly triggering the transition to a next stage, even if the processes within the actual stage are not yet accomplished.
- 4) **External events:** External events (shock, novel situation or environment, teacher, ...) may cause the system to react by switching to a subsequent, or even to a pre-deciding stage.

We are convinced, that in direct comparison to the learning rules and the structure of the controlling unit, far more knowledge is transported into the living artifact via the schedule of structural development than most designers expect. A teacher training the artifact carefully, with respect to the already achieved capabilities is one of the essentials in growing up artifacts.

VI. RULES FOR LEARNING AND ADAPTATION

In direct coordination to the building blocks of the systemic architecture the rules for learning and adaptation has to be chosen. The variety of learning rules from the established fields of machine learning, optimization, neural networks, genetic and evolutionary algorithms may be used: supervised, reinforcement, self-organised, feed-back error learning, self generated trial and error, learning finite state machines, or adaptive hidden Markov models may sever as examples ([9], [12], [20] [21], [6],[7]). Completely novel forms of learning might show up to be necessary to fulfil the more sophisticated tasks of growing up an artifact.

Following the ideas of systemic intelligent architectures, the modules within the upstream path are trained in an unsupervised, self-organizational way.

The modules within the downstream path can be trained using the output from the self organized classification for comparison between the module to be trained, and the output of an already learned sub-unit.

Other building blocks are designed to perform bi-directional association learning during the complete time of operation of the artifact. They will need a learning rule capable of incremental learning without losing track of the already acquired information.

VII. MEMORY ORGANIZATION

The building blocks of the systemic architecture are designed to learn their individual solution to the task they are responsible for. Learning means, that they have to memorise the trained capabilities somehow. Most building blocks are special forms of memory, keeping the functionality they are realizing within their structure.

The major types of building blocks from the systemic architecture are self organised classifiers, controllers and associators. Especially the associators connecting different branches of the systemic architecture need to have bi-directional associative features.

A growing artefact is acquiring more and more data during its time of operation. Therefore the data to be memorised is increasing with time. To avoid an infinite request for memory resources a process for forgetting, generalizing has to be implemented into the organizational principles for memory. Although the technical development of memory systems provide faster and larger memory solutions, the memory is still a limited resource. An important design feature for memory is competition between the different tasks for the resources. Competition is not only necessary to cope with the un-avoidable limitation, but engenders a variety of novel opportunities, e.g. forgetting, generalization, decay, displacement, inference, extracting of principles instead of learning by heart, ...([17], [13], [4], [21]).

A second important feature of memory is the competency to deal with temporal events, and with storage in time. Sensory stores, short term stores and several forms of long term stores are necessary to be present for an artifact operating within

a complex environment, learning to enhance its capabilities, and memorising and preserving the successful behavior for the future.

Memory shall be organised with respect to the different forms of learning and adaptation rules like: supervised, reinforcement, self-organised, feed-back error learning, self generated trial and error.

Depending on the task the building block has to perform, the organization of memory will be different. Each individual task has individual requirements to be met. Therefore each individual form of memory will be shaped individually to be prepared for the special task. It is unlikely that one single form of memory will cover all necessary requirements, but the different peculiarities of memory can be the result of an individual shaping of a master template, with respect to the task to be performed.

VIII. PRE-STRUCTURING THE ARCHITECTURE

Knowing that the process of growing up an artifact can be compared to climbing a ladder, the steps must be carefully designed. Before reaching the top of the ladder a lot of steps has to be performed, each one relying on past acquired capabilities ([14], [15], [19]). It is crucial to know at what stage of capabilities the system should start its process of growing through learning and adaptation. Starting with too few capabilities the system may end up with only primitive behavior, or might develop into a direction lying not within the targeted class of behaviors. Starting with too sophisticated capabilities the new tasks to be learned might be too complex for the chosen structure.

The two fundamental questions arise:

What kind of capabilities shall be pre-structured ? and Which capabilities shall be trained using experience ?

Using engineered capabilities it is rather reliable that the capabilities will operate the calculated way, supposed the circumstances are within the pre-calculated limits. A pre-engineered system will have difficulties to be adapted onto a novel environment. Thus a pre-engineered system is losing flexibility.

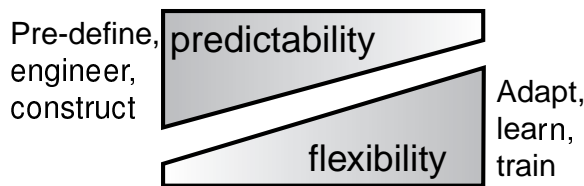


Fig. 5. Flexibility-predictability dilemma

Using learned capabilities acquired during a training process, the system can cope with the circumstances experienced during teaching. Thus the system is gaining flexibility. On the other hand there is no guarantee that a trained system is capable of performing the desired tasks.

Even worse, the system might evolve into a direction that was never planned to reach. Training and learning goes on, and seems to be successful, but somehow the system might have found a way of bypassing the desired results (loss of predictability).

Within the up growing process we have to face the *flexibility-predictability dilemma*:

**The more we pre-define the capabilities
the more predictability we gain,
at the expense of flexibility.**

**The more we train the capabilities
the more flexibility we gain,
at the expense of predictability.**

IX. APPLICATION TO AUDIOSIGNAL PROCESSING

As an application using the systemic architecture a learning audiosignal processing system has been built. The approach consists of three layers of systemic architecture's building blocks, making benefit of the classification capabilities [16], [10].

Let's suppose a stream of audio information which is not just random, but is following an underlying set of rules (e.g. pre-stage of a language). This incoming audio data is classified by the first level of the systemic architecture into a stream of basic elements the data is consisting of. This stream of classified data (symbols) is then fed into the second layer classifying and/or correlating this information into larger components (comparable to signs or words). The stream of signs resulting from the second stage of classification is the input for the third level, where another classification takes place to find the correlations between subsequent signs, to extract the statistics the underlying rules (grammar).

As an alternative the result from the second layer can be fed into an associating building block, where the detected signs are associated with an external event (e.g. detected by a second tree of systemic architectural modules). Thus the system learns to combine signs with external events, and thereby learns to combine signs with meanings, and vice versa.

When using both branches of the systemic architecture: upstream sensory information and downstream actuary information the output from the upstream classification of audio data into elements, can be used to control the downstream actuary branch to produce sounds similar to what the sensory system heard (speak what you hear). After articulating a sound, the sensors detect what has been produced, thus the sensory-actuary loop is closed. The classifiers within the sensory branch can now serve as critic, to control the adaptation process of the actuary branch: the system learns to speak correctly. Closing these sensory-actuary loops via external feedback is performed on every layer of the architecture.

X. APPLICATION TO LEARNING ROBOT CONTROL

The second applications uses the systemic architecture for the task of controlling an animat by means of adaptable sensory-actuator control loops [10], [11].

The applications demonstrates, that already a single-layer systemic architecture, with just one building block consisting of the two typical branches (the upstream sensory branch, and the downstream actuator branch) is sufficient to control the animat and generate complex behavior.

Adding further layers of building blocks to the architecture more complex behavior can be achieved. The information processing within the different building blocks can be engineered to reach a specific behavior of the animat. The more interesting and challenging way is to let the animat learn its behavior. Using the proposed architecture, the teaching process of the animat is changed into an up growing process.

Several exemplary tasks with increasing complexity, with thereby increasing complexity, and as an approach with additional systemic architectural layers are presented: move with obstacle avoidance, neighbourhood processing and motion detection, environmental processing and associative processing. Since each task could be performed using one layer of the architecture, the system results in a four layered structure. Within the systemic approach to control animats (autonomous robots) every additional layer gives rise to additional functionality, without losing the acquired capabilities. Thus the systemic architecture is the way to enable an artifact to grow up.

XI. DISCUSSION AND CONCLUSION

Within this paper the approach of using paradigms from systemic intelligence (e.g. systemic architecture, schedule of learning, memory organization, rules for learning and adaptation) has been described and focused to a set of design rules for creating systems with the potential to grow up.

Starting with basic abilities the system passes through a sequence of stages, gaining additional functionality based on experience and already acquired capabilities. Thus the artifact evolves from an infantile stage to a fully matured entity: the artifact grows up.

Capabilities of artifacts are often measured using tasks from the fields of robot control and language learning and language understanding. The approach presented here has been shown to be feasible to fulfil some subtasks from robot control and language learning. Actually we are extending the applications into the direction of more complex tasks.

In the future, living artifacts will need to be far more adaptable than current technology permits. They will learn the tasks on their own, instead of being engineered to do so. The forthcoming artifacts are to be capable of dealing with a wide variety of un-foreseeable conditions, to carry out tasks

that can only be specified in a very general way, it will be necessary to devise the novel approach of using the benefits of systemic intelligence to develop adaptable and robust systemic architectures to trigger the up-growing process of artifacts.

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