Chapter 4

Mind-Body Co-Evolution: The Factor-10 Project

4.1 Introduction

Both the emerging fields of epigentic robotics and "smart" materials science offer a wealth of innovative research opportunities and promise a large spectrum of new products to become feasible in the mid to long term. However, a completely new discipline may develop by combining key research in these fields to work towards new types of artefacts. We envision three types of such artefacts to emerge from this combination

- **Type I:** artefacts evolving their cognition and motor control autonomously based on multimodal/multisensory feedback in a predefined and fixed body, whose structure may be optimised to perform a certain class of tasks (designed to a certain "ecology" – as is frequently the case for living organisms), e.g. the "dancing robot" of the AI lab at Zurich University or the "classical" humanoid robots;
- **Type II:** artefacts that evolve new skills in structural coupling with the environment but with bodies/effectors that flexibly adapt their shapes to structurally different tasks, e.g.
  - robots with effectors made from material with mechanical plasticity, such as shape memory alloys and/or autonomous control intelligence (peripheral nervous system) in these limbs, like truly dextrous "hands" with a highly developed sense of touch, or
  - fine grained versions of the current attempts to design "modular robots" that may change their body shape to some extent by combining basic actuator modules into different shapes,

  and
- **Type III:** artefacts that co-evolve their (possibly distributed) brains (system) and their body in permanent interaction with the enviroment over an extended period of their lifetime (embodied artificial ontogenesis).

While the implementation of the first type of artefacts largely depends on progress in control architectures of cognitive systems, the latter two will also draw heavily on methods and technology developed in materials science for self-assembling materials and structures, “constructive chemistry” and – most probably – proteomics. In particular, the third type may be be seen as a new interpretation of smart materials with tailor-made functionalities for building up macro-structures with integrated sensing and cognitive abilities.

While artefacts of first and second type can be seen as classical *allopoeitic* machines, i.e. machines that are designed and built “from the outside in”, we hold that the third type of artefact needs a fresh approach in that it can only be realised as an *autopoietic* machine built from cells, each of which implements a full recursive plan for bodily development and behaviour in a given enviroment similar or identical to the genetic code in the cells of living organisms.

Following these lines of thought, we propose to define a long-term research project called “Factor-10” or Factor-X, which aims at fully functional physical artefact (i.e. not a computer simulation), which, during an extended but limited period of time (e.g. 10 months) autonomously grows

- *the volume of its body by at least a factor of ten, thereby differentiating out “organs” and “effectors” as well as*
- *its cognitive abilities (its “IQ” and its repertoire of sensorimotor behaviours), also by at least a factor of ten.*

This vision is obviously largely inspired by the development of living organisms and the theory of “enactive” or action-centred cognition by Varela (Varela, Thompson, & Rosch, 1991) – intelligence and autonomy in can only emerge in embodied creatures (and artefacts) as the result of their permanent interaction with a real enviroment. Based on this theory, one may even argue that eventually the implementation of such artefacts would be based on (modified) biological substrates (an hence become a case for genetics) because nature has solved exactly the same problems of survivial on the earth in the optimal way – through creating living organisms for the most diverse ecological niches. This would entail, however, not only massive ethical problems, it would also delimit the range of size of the basic building blocks (i.e. biological cells) and – depending on their machanical stability – the size and properties of the artefacts. It would also require the problems of artificial metabolims to be solved.[1]

We hold that it might not be desirable but necessary to begin Factor-10 related research by studying the challenges and promises of the concept of artificial growth using “dead matter” as a starting point and – only due to technological deficits – treat mind development and bodily adaptation through (and for) interaction with the environment as two separate problems. Being aware

[1] After all, this should be considered an additional challenge – not an impediment. There can be no doubt that a highly efficient and lasting energy supply is an indispensable constituent of autonomous artefacts. It is quite likely that the solution to the totally inadequate energy cycles based on electrical batteries may be found in copying the chemical pathways found in life. One may even argue that the search for food (not to be confused with simple search for a battery loading dock), which is a special kind of interaction with the environment under time pressure that has direct consequences on the constitution of the body, is an essential driver for mind development and cannot be separated from the artefact growth process. Whilst of high importance in its own right, research into adequate energy cycles for autonomous artefacts is definitely out of the scope of this challenge.

of this conceptual deficit, we should permanently aim at overcoming this artificial separation as soon as possible and capitalise on every technology advance that offers a potential to do so. In particular, research in (molecular) biology should be constantly monitored and and regularly be evaluated for progress made there for applicability to any of the research areas contributing to Factor-10.

4.2 Motivation and objective

For at least the last five decades the general public has been promised the advent of universal robots or even human-like artefacts that would be of real help to us in our daily lives and/or possess super-human capabilities. However, as expectations rose, science consistently failed to deliver robots that can be compared to biological creatures, not even to those with very low-level intelligence.

Notwithstanding this failure, enormous progress has been made in many fields potentially contributing to the design of truly autonomous artefacts of types II and III outlined above, such as brain and cognitive science, information technology and artificial intelligence, molecular biology and chemistry that the time is ripe to combine/integrate them into new systems with autonomy and control intelligence distributed over their entire body, which in turn may adapt smoothly to a specific task.

Moreover, apart from being one the most exciting research goals to pursue, artefacts that can – at least to some modest degree – develop an autonomy of their own in the literal sense of the word[2], would also be an economical market that cannot be underestimated.[3] Despite current wave of euphoria for humanoid robots – largely fueled by industrial companies like Honda and Kawada but also by applied and basic research projects as the Japanese HRP program and the Kawato Dynamic brain projects and its continuations –, it will soon become clear that these machines (type I according to the above classification) are impressive feats of engineering and highly interesting platforms for developing basic technologies, but they hardly lend themselves to any practical use outside of robot labs. Only when the qualitative transition to type II artefacts can be achieved will we see practical solutions that will find acceptance by a broader public for many interesting applications (see (Knoll, 2002) for an incomplete overview).

However, issues central to the development of living creatures that would have to be followed to a higher or lesser degree for type III artefacts, i.e. synchronous evolution of morphology and mind, have hardly been formulated, let alone been tackled. Fortunately, due to the need for a qualititative breakthrough, already from type I to type II artefacts, and the high quality of European research in the aforementioned disciplies contributing to type II and – in the longer run – type III development, there would be a window of opportunity for Europeans to compete with

[2]Meaning "give oneself one's own laws of behaviour" through "living a plan" by evolving all aspects of one's being there, instead of just executing a designer's plan (Ziemke, 2001).

[3]While about 10 years ago the market for service robot and/or assistance systems (for both home and factory use) was projected to be larger than 1 billion EUR by the year 2000, only very few such service robots (less than one thousand) have actually been deployed so far. The world market for standard fixed production robots is about 100,000 units per year; it could also grow drastically if the perception and task-adaptation abilities of these robots increased substantially and their programming efforts were reduced just as drastically.

Japanese research at the next stage of development – the Japanse advantage in humanoids (type I) research will hardly be caught up to.[4]

Looking at the preconditions for embarking on this research journey, we note that a there is already a sizeable body of research in the diverse necessary disciplines represented in Europe (see the non-exhaustive list in the appendix), however with fragmentation across disciplines and countries.

Apart from the scientific objective of developing the basic technologies and actually designing as well as building prototypes of type III artefacts – via type II as an intermediate goal – along a far-stretched time line, it is also the purpose of the project to establish a commonly accepted paradigm for designing these artefacts. Initially, recent results will be collected and translating into a language common to all the disciplines. More importantly, however, is the development of completely new theories, methods and paradigms controlled by carefully studying how the methods from one field can guide the research directions in another (e.g. by evaluating research results on imitation from psychophysics to define paradigms of machine imitation learning that can be translated into computer-operational algorithms). In parallel, for every milestone reached, its application potential inside and outside of the artefacts will be studied so as to ensure feedback to the research community of the newly developed field as to what features would be particularly useful to have in real systems, e.g. robustness and safety after failure, behaviour stability, reaction-times, cross-modal sensory input processing etc. – all in dynamic, unpredictable, adverse and partly unknown or even completely unseen, uncharted real-world environments.

The goals of Factor-10 are indeed very demanding. Up to now, they have hardly been formulated as a common integrating challenge because of the deterring technological impediments in every single area involved. We believe, however, that in view of the progress achieved in many of the disciplines, particularly cognitive and neurosciences, Factor-10 comes at the right point in time. If Europe does not take the lead now, it might miss yet another technology train.

4.3 State of the art and projection from today's viewpoint

As of this writing, there is a small body of published work on experimental systems, design simulations, materials analysis and proposals for architectures that may serve as starting points for further research, in particular:

- **Modular robots** that are built from a certain number of identical motor modules and can be combined into different shapes and macro structures (e.g. (Kamimura et al., 2001); see (project, 2003) for an overview).

- **Evolutionary and epigenetics robotics** both in the sense that robot shapes are optimised (e.g. (Funes & Pollack, 1999)) according to certain target functions and that the principles of autonomous learning based on very basic instincts is concerned (e.g. (Nolfi & Floreano, 2000))

[4]Honda claims to have invested in excess of US$ 100 mio. into their humanoids development program, which started in 1986, and the Japanese Humanoids Research Program (HRP) received another US$ 25 mio. of direct funding. Other Japanese giants like Sony, Fujitsu, etc. have not disclosed their figures – but they may be just as high.

- **Microscale structures** that can be assembled according to external conditions and that can serve as filters, modulators, etc. for chemical reactions..

- **Nanoscale self-asembling structures** were proposed that can build up aggregates of macroscopic size, e.g. for "muscle tissue" (?), that can be made to grow and exhibit useful properties, such as need for joints without lubricants, etc. As far as this field is concerned, were are confident to profit from nanotechnology (including nanomanipulation) to provide us with materials that can be used in different functions in the artefact. Of particular interest would be the technlogy that enables nanostructures (e.g. nanoscale motors) to build up in a controlled way – as long as these technologies have the potential to be used in an artefact. This would rule out the use of processes that rely on extremely high voltages or extremely high external pressures for the structures to from themselves.

This is just a selection of the competences needed to be integrated for a first step along the type III developments. Obviously, all of these fields are only in their beginning as far as the use of their potential for specific contributions to our goals are concerned. There are a number of research areas that may directly contribute through elucidating principles of biological development in view of what is needed for type III artefacts:

1. *Developmental biology*: Compilation of the essential principles that enable living organisms to differentiate cells to form large bodies with specific organs, but also the principles that led to the formation of both motor and sensor entities, e.g. what drives phylogenesis to get from a single photoreceptor to "open" insect facet eyes and then on to lense-based eyes, what are the driving factors behind the development of different locomotion principles, in particular muscle-joint constructs, etc.

2. *Genetics*: Contribute a set of rules that allow to encode a certain minimal set of "genes" which allow stable bodily development but also the control of the communication between the individual body cells so that they can – in interaction with the enviroment of the artefact – develop a certain desired behaviour. A controlled modification of these genes should also result in a predictable change of behaviour development of the artefact.

3. *Computational Neuroscience*: Given the freedom of growth and structural developments of information processing entities in the artefact (but also the severe technological constraints), develop *appropriate* basic processors (neurons) *along with their interaction principles and communication networks/mechanisms* that enable the parallel and interleaved emergence of motor skills and cognitive skills taking into account the hypotheses about structural coupling according to Varela. Clarify issues of "assemblies" and regions of the basic processors building up and structuring themselves according to the genetic code during the artefact's evolution and their dependence on the environment in which the arefact grows up.

It may be argued that there are good reasons to carefully discuss and review the size and functionality of the ideal basic block (and hence he variability) for the growing artefact: should this basic building block be the atom, the molecule, the constituent parts of a micromodule (analoguous to the internal parts of the biological cell), the micromodule itself (corresponding in functionality to the biological cell), assemblies of micromodules at the level of organs – or intermediate stages between these individual granules. Seen from today's perspective, the basic block of type III artefacts will probably have to have most of the properties of what is attributed to stem cells of animals (with or without the ability to cater for its own energy supply): with minor changes in its own reproduction program it can differentiate into cells for the most diverse requirements of the body, affording the different abilities for sensory, motor and processing tasks inside the complex whole of the body. It seems that there will be a natural transition in granule size between the cell-like basic unit of type III and the larger unit size for type II as we go from types II to III, but this cannot really be predicted now.

From today's point of view we see four essential threads of technology research (as opposed to the indispenable conceptual lines of work mentioned above) that should form the basis for an integrated research plan and should be pursued both individually and carefully interwoven to traverse the huge tree of possible individual actions, with (1) being the precondition for the practical implementation of (2)...(4), not, however, for the theoretical investigation of the latter three:

1. *Molecular Robotics*: exploration and design of useful materials and substrates (nanotechnology and chemistry) lending themselves to build cells that can be made to meet the different requirements in the variety of body areas/volumes, e.g. high mechanical stability (for "bones" and "joints"), ability of energy transformation (for "muscles"), for information exchange ("networks of nerves"), information processing ("neuronal assemblies"), etc. The emphasis should be on materials that have the ability to bridge the gap between the micro-level and large-scale macroscopic structures.

2. *Distributed growable sensors*: for distributed areas of sensing "cells" that are sensitive to different physical modalities (force, light, odour, temperature), it will be necessary to investigate how they can be coordinated and produce sensible results when they are located over large areas of the outer surface of the body and are physically connected together through a medium (i.e. the body) that shows a high degree of plasticity. Of equal importance is the exploration of the role of preprocessing sensor data, either directly in the sensor (such as the preprocessing taking place on our retina), over pre-structured nerve channels (such as the visual chiasm) or the early processing stages in the cortex – i.e. why/how these predetermined structures have evolved in the phylogenesis of creatures and to what extent it makes sense to mimicked this concept in the artefact.

3. *Growable distributed information processing*: this is a most demanding research area because the information processing system must control the growing artefact from the first moment of its "inception" on. This implies that it not only has to permanently control the artefact's evolving sensors and effectors, it also has to exert control of the interaction with the environment for exploration and task purposes so as to control its own development – while it is growing itself in physical size as well as complexity and is to develop cognitive and motor skills in parallel with the sensors' processing capacities. The challenge is hence

not only to achieve a stable learning and growth behaviour of the information system for body control but also to make the system develop its own new structural skills, e.g. the emergence of the concept of "memory".

4. *Growable motor entitites and spatially distributed actuators*: the actuators must also be controllable as they develop both their actuation part (the muscle portion) as well as the support structure (the skeleton/joint portion). Their evolution must be in sync with the size and mass of the artefact and they must be supported in the artefact body so that mechanical stiffness and stability is achieved along with a maximum of locomotion effectiveness, energy efficiency and durability.

Ideally, it will be possible to formulate – at an appropriately high level of abstraction – principles of growth (like the competition metaphors for selection of species – but also for the development of synaptic connections), which govern the growth processes in the artefact, i.e. a straightforward and easy-to-formulate principle in terms of a target function like entropy maximisation, energy minimisation, sparseness etc., such as the principles recently discovered for the development of the different types of neuronal cells.

From a technology development view point, we suggest to lay out a plan which initially centers about the basic building block (BBB) in view of the four aspects above:

- *Functional properties*: what are the components that the BBB consists of? What is the minimum amount of functions integrated into one BBB? How can BBBs arranged in such a way as to form a large area distributed sensor, a distributed actor or passive support structures, respectively? Would it be possible to retain a certain amount of bodily plasticity/flexibility throughout the entire lifetime of the artefact?

- *Technological issues*: how can the individual components be realised – and using what substrate material – including the ubiquitous question of a suitable source of power? Is it economical to use just one type of BBB that can differentiate into various uses or should there be more than one class of BBBs?

- *Interaction patterns*: how can the individual parts interact over different communication channels, not necessarily only through electrical connections? Studying the interaction patterns is particularly important because, unlike with nanostructures whose interaction is completely static (i.e. binding forces), there can be a diverse range of patterns between the BBBs with different reach, with different time-scales, signal amplitudes, etc. These have to be clearly defined with respect to achievable plasticity, networking parallelism, scaling from a few to millions of nodes and further parameters.

In parallel, the development of convincing application scenarios scenaria should be advocated. This not only pertains to useful deployment on the factory floor, in private homes, outdoor support etc., but it also involves the transfer of parts of the technology to applications that could profit from, say, microscale machinery with integrated sensing and information processing abilities for medical use.

4.4 Expected Results: What will it be good for?

In Table 4.1 we have listed some of the possible applications of spinoff knowledge of potential research carried out within the framework of Factor-10 for adaptive and growing body structures. This table presupposes a development line from type II to type III artefacts with parallel basic research that in the first step is targeted at machines with relatively large BBBs using technology as available today, and then moves on to define the requirements for microscale BBBs, capitalising on nanotechnology modules. It may turn out to be more useful to start with the development of the latter type of BBBs right away, but this will have to be cleared up in a separate step. We have also listed some of the spin-off applications that may be the result of partial aspects of the developments. In particular for type III artefacts, the range of applications that one can imagine is so huge that it would be beyond the scops of this roadmap-contribution to describe them all. Suffice it to say that given the basic blocks are cheap enough all kinds of "intelligent structures" of small to large sizes may build themselves and can also change their shape according to various user needs. However, only the future cann tell if such a vision may come true and if such potential applications, which are far beyond the current conception and understanding of robotics, are a desirable addition to our daily life in terms of cost/benefit ratios. On the other hand, it is clear that the small-size artefacts we shall be enabled to build can most certainly finally deliver what robotics science has promised for a long time.

Expected Result	**Application of the Result and Users**
From Research targeted at **type II** *artefacts*	
Artefacts with early-cognitive properties such as context and attention-dependent visual scene analysis or with human-like pattern of intention-driven behaviour.	Applications that require only low-level adaptation to user needs, e.g. advanced human-machine interfaces.
Adaptive, cooperative prosthetics or physical support for senses, limbs and a combination thereof.	Handicapped and elderly people.
Artefacts with perception systems that share similar principles for human use and industrial automation and possess a high degree of robustness as typical of biological systems	Medium and small scale production of goods not to be automated up to now. Revolution of the production of variants and a "batch size of one".
Easily instructible "disappearing" robot systems for use in service (home and factory floor) that can adapt their body structure to become highly task-adaptive and that have some basic understanding of their own being there (self-awareness), react to and show emotions etc.	Small production shops and "home-workers", new generations of handy "intelligent tools", more demanding cleaning and housekeeping than just automatic vacuum cleaning, simple plumbing tasks, but also storage (management) of all kinds of objects – even in small apartments.
From Research targeted at **type III** *artefacts*	
Artefacts that are capable of mind-body co-evolution and may adapt over a finite period of time to arbitrary enviroments (ultimate goal of the Factor-10 developments).	Unlimited range of applications. From microscale (e.g. use inside blood-vessels) to creatures of animal-like shape up to free-form structures with intelligent behaviour and distributed sensing (e.g. for house or road construction purposes) to symbiotic human-artefacts use (e.g. for increasing stamina, cognitive skills, etc.).
From Ongoing Basic Research	
In-depth understanding of the neural basis of human sensorimotor and cognitive processes and their development, the interaction of sensor/motor skills and the way mind and body interact during their respective development.	Researchers can simulate development (e.g. development of senses on fixed bodies and/or co-evolution of mind and body on growing structures) in a much more realistic way by using artefacts and test hypotheses on them; depending on the level of modelling-granularity as a supplement to animal experiments (in the long run possibly leading to a reduction of the need to carry out such experiments).
Basic Technologies in the field of: materials research, optoelectronics, sensors, actuators, information processing, …	Industrial Automation Companies, Telecommunication Companies, new companies of still unknown profile.

Table 4.1: Application areas and users of direct and spin-off results from research under the umbrella of Factor-10.