Nature inspired robustness

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There are many things in nature which we can admire from the engineering point of view and which gave rise to appropriate strategies for industrial products. One examples are the self-peeling of underwater shells which was the blueprint for ship paint which avoids the increasing heavy burden of creatures attaching to the hull of the ship and increasing propagation energy consumption. Another one is the analysis of earwax which offered blueprints for a spectrum of fungicides and anti-bacterial substances.

1 Nature inspired robustness principles

These attempts give rise to completely new products, whereas this initiative aims for a certain aspect which can be observed in natural systems: the intrinsic stability and robustness of the solutions obtained. One examples is the walking mechanism of humans: Although all parts in this mechanism, the muscles, the bones and the sensory tissue are growing throughout childhood, people are continuously able to walk. Which robotic system maintains its function correctly although the length of the manipulator components, the force of the motors and the sensors are constant changing? The solution to this is one of the nature inspired principles for technical systems.

There are several aspects of "robustness":

1. One major aspect is in the sense of "fault-tolerant". This means that random faults or accidents in the considered system should not propagate and should not impede the desired system functions too much.

2. The second aspects means "stability" in a system inherent way. This means that the system should not be deviated by noise or random input, even if its internal components are slightly changed.

These two properties can be observed for a variety of biological systems. They are both involved for the case of mutations or accidents of the biological subjects and are essential for the survival of the genes. What can we learn by nature ? Here I see the following principles which can not only be implemented in products, but should also be reflected in models of the biological systems:

a) There are a multiple of similar effects, all going in the same direction in parallel. If one fails, the others may continue. This can be compared to the classical parallel redundancy in fault tolerance theory. An example for this are the muscle fibers all effecting in parallel on one bone. If one cracks, the others will continue to function.
   Another example is the group encoding of the muscle enervation: Here, the fibres receive almost the same input, but slightly deviate compared to the neighbour. This results in a very precise mechanical control which continues, even when some of the muscle fibres are degraded. The control resolution of the muscle fiber bundle will be smaller, but the movement will continue.

b) There is an adaptive feedback in the system which allows a broad range of the parameters involved without changing system behaviour too much. An example for this is the human walking cited above. Here, the intrinsic system behaviour compensates the large varying effects of bone and tissue growth.

These two ideas can be applied also on models.

2 Model robustness

Let us regard for instance a dynamic model of infection and septic shock. On one hand, it is well known that in the immune reaction on infection a myriad of substances are involved which can be ordered in certain ways, e.g. by their proinflammatoric or contrainflammatoric effects. They can be described by similar biochemical pathways based on gene expression data, see [Guthke2003]. Blocking only one of the involved reactions did not change the whole system: Also the septic shock with its high associated mortality is not impeded. Thus, all models describing these pathways have to reflect the parallelism of these similar pathway dynamics.

On the other hand, generic models based on ordinary differential equations for one pathway heavily depend on their parameters. The parameters can be adapted very widely for a set of measured data, giving a “million model space” (Constantin 2005). Although these systems approximate the measured data very close, they behave completely different outside the defined ranges: The model is not robust in respect to its parameters.

In contrast to this, all living beings are subject to mutations. The corresponding infection fighting system have to be robust in its parameters in order to function in most of the species.

Therefore, in order to make our modelling more realistic we have to incorporate the natural robustness features. How? We might let us inspire by nature to increase model robustness by the following means:

1) *Behaviour robustness by parallelism*: Instead of modelling only one pathway, we have to model a bundle of it. This might be done by several versions of the principal same system behaviour, using the same state variables. If one of the pathway models have flaws due to strange parameter behaviour, the others will continue to operate and try to average it out.

2) *Parameter robustness by feedback*: Complement the differential equations by additional feedback terms which stabilize the system without altering the system behaviour too much.

An example might illustrate the ideas.

3 A simple example

Let us assume that we have a simple state control mechanism, for instance a sensor-effector system.

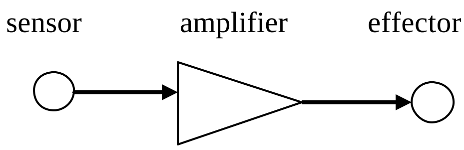

Fig. 3.1 A simple amplification system example

The effect y of the sensor input x depends heavily on the amplifier factor A. If the parameter A varies, also the output

$$y = Ax$$

varies. Since the fabrication of an electronic amplifier is subject to many random fluctuations in the chip process, the amplification factor A can not be controlled very precisely in practice. This fact corresponds to the random variations in the chemical processes of living beings:

small chemical variants cause different solvability and therefore different concentrations in the body.
How does the engineer solve this problem? By adding feedback the amplification factor becomes stable: If we add a negative feedback line from the output by a weight $k < 1$ to the system, see Fig. 3.2, we get as sum

$$y = Ax - kAy \qquad \text{or} \qquad y(1+kA) = Ax \tag{3.1}$$

Therefore, we get a new amplification factor by

$$y = A/(1+kA)\,x = A'x \text{ with } A' = \frac{1}{1/A + k} \tag{3.2}$$

This new amplification factor A' is special: in the limit for big $A \rightarrow \infty$, it just becomes 1/k which is constant, independent of the genuine amplification factor A. Therefore, the system function is provided independent of all random variations in the chip production process; it has become robust by negative feedback. The robust system is shown within the dotted lines.

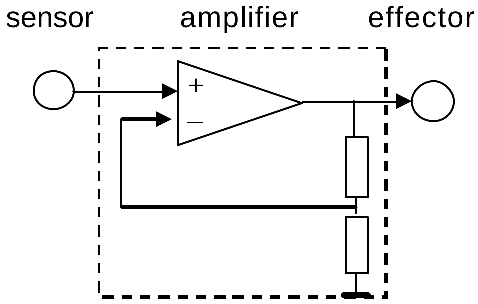

Fig. 3.2 Including a feedback line in amplification

Nevertheless, if the amplification is decreased under the coefficient 1/k even this system will fail, i.e. large system variations can not be handled. Here, parallel redundancy might come into hand in order to increase the robustness. If we conceive several robust systems in parallel with the same input and output, we will get the following robust control scheme.

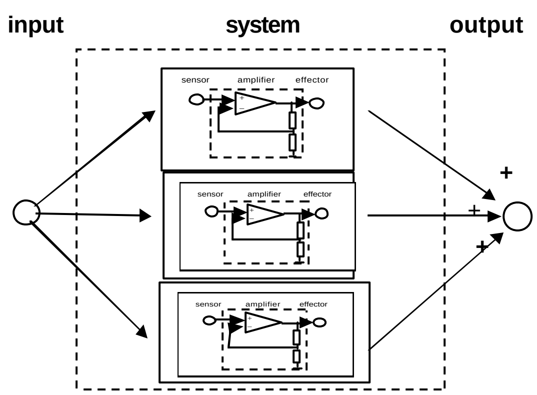

Fig. 3.3 Parallel systems for robust control

This example shows us what "nature inspired robustness" may be. Nevertheless, the detailed development for more complicated systems of differential equations is still an open issue and should be subject to research.