Doursat, R. (2007) Embryomorphic engineering: How to design hyper-distributed architectures capable of autonomous segmentation, rescaling and shaping. *Unconventional Computation Conference*, March 21-23, 2007, Los Alamos National Laboratory (LANL) and Santa Fe Institute (SFI), Santa Fe, NM.

Embryomorphic Engineering: How to Design Hyper-Distributed Architectures Capable of Autonomous Segmentation, Rescaling and Shaping

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Abstract— Exploding growth in hardware components, software modules and network users forces us to find an alternative to rigidly designing computational systems in every detail. Future progress in information and communication technologies will depend on our ability to, instead, "meta-design" mechanisms allowing those systems to self-assemble, self-regulate and evolve. Such decentralized, autonomous systems are already pervasive in nature and called "complex", although they are often less costly, more efficient and even simpler than intelligently designed, centralized systems. Complex systems are characterized by the self-organization of a great number of small, repeated elements into large-scale patterns, where each element may itself obey the dynamics of an inner network of smaller entities at a finer scale (microprogram). The new engineering challenge is to "guide" this self-organization, i.e., prepare the conditions and mechanisms favorable to a robust and reproducible—as opposed to random—pattern formation process (macroprogram). Yet, at the same time, it is also to let the parameters of this process evolve in order to freely generate innovative designs. Finding efficient systems requires matching loose selection criteria with productive variation mechanisms. The first point concerns the openness of the designers to "surprising" outcomes; the second point concerns the intrinsic ability of complex systems to create a "solution-rich" space by combinatorial tinkering on highly redundant parts. Embryogenesis, the development of an entire organism from a single cell, provides the most striking example of self-organization guided by evolvable genetic information. This work presents an original model of artificial *embryomorphic* system growth. A virtual organism is represented by a mass of cells that proliferate, migrate and self-pattern into differentiated domains. Each cell contains an internal gene regulatory network Γ (composed of modular subnetworks G_0, G_1, ...) and acquires specific gene expression identity by interaction with neighboring cells. Different identities I_1, I_2, ... trigger different cell behaviors, which in turn induce new identities. The final organism's architecture depends on the detailed interplay between the various rates of cell division and movement, propagation of genetic expression and positional information. Ultimately, on this score of "theme and variations" (developmental laws and parameters), evolution will be the player. In possible hardware applications of this model, nano-units containing the same instructions could self-organize without the need for reliability or precise arrangement as in traditional VLSI. In software or network applications (servers, security, etc.), a swarm of small-footprint software agents could diversify and self-deploy to achieve a desired level of functionality. In all cases, embryomorphic architectures suggest a "fine-grain" approach to systems design, i.e., one based on hyper-distributed collectives of a great number of very simple and relatively ignorant cloned elements.