Functional Blueprints: An Approach to Modularity in Grown Systems

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Engineering Systems that Grow

- Robustness to faults, variation
- Long lived infrastructure
- Assistive design
- Synthetic biology

But building a static blueprint is hard already...

Why doesn't growth injure animals?



Many interlinked systems

- Muscles, bones, blood, lungs, kidneys, etc...
- How is growth synchronized?
 - Not like building a house!

Consider Osgood-Schlatter's disease ...

Hypothesis: Functional Blueprints

- Not "what" but "why"
 - Register stress when functionality degrades
 - Homeostatic rules for relieving stress
 - Ratios, structure determined dynamically
- When uninhibited, a prime attribute grows
 - Stress develops in other systems, inhibiting prime
 - Homeostatic acts develop, destress linked systems
 - Secondary, tertiary links are stressed, cascading growth

Incremental integration through growth!

Example: Vascular System





Oxygen-starved cells signal capillary to leak



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Metric: oxygen, elastic stress

Homeostasis: leaking, vessel grow/shrink

Functional Blueprint

- 1. Functional behavior that degrades gracefully
- 2. Metric for degree and direction of stress
- 3. Incremental growth program for stress relief
- 4. Program to construct minimal initial system

Stress as an Integration Signal



- Bone growth→muscle stress
- Muscle growth→vascular stress
- Vascular growth→kidney stress
- Kidney growth→equilibrium
 - Bone growth re-enabled



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Viable Adjustment Theorem:

Consider a system S, for which every subsystem has a functional blueprint, and let X and Y be subsystems of S. For any given configuration c_s , if $v_x(c_x) > 0$, then there exists a $\delta > 0$ such that $c'_s = i_{Y,\epsilon,d}(c_s)$ has $v_x(c'_x) > 0$ for every d and $\epsilon \leq \delta$.

- Meaning: graceful degradation lets incremental independent subsystem changes be viable.
- Implication: it is possible to create stress-based navigation through design space.

A (Cartoon) Simulation of Tissue Growth

- Tissue maintains homoegeneity by cell motion, cloning, apoptosis
- Vascularization grows toward underserved regions, keeping branching factor limited
- Composed form:
 - tissue grows only when well served by vascularization
 - vascularization stimulated by tissue growing to develop underserved regions

Proto: Computing with Fields



Growth via Density Maintenance



proto -geometry 480x480 "(mov (cell-density 1 0 0.1))" -m -s 0.1 -n 10 -rad 2 -dim 500 500 -dist-dim -5 5 -5 5 -l

Vascularization



```
(def vascularize-mod (source active serv-range p)
 (rep (tup vessel served parent)
      (tup source source (if source (mid) -1))
      (mux source
       (tup 1 1 - 1)
       (let ((service
              (< (gradient vessel) serv-range))</pre>
             (server (gradcast vessel (mid)))
             (children (sum-hood (= (mid)
                        (nbr parent))))
             (total-children (tree-children parent)))
         (radius-set
          (mux vessel
           (* 0.5 (sqrt (+ 1 total-children))) 2))
         (mux vessel
          (mux (or (muxand
                     (any-hood
                     (and (= (nbr (mid)) parent)
                           (> (nbr children)
                            (mux (nbr source) 6 3))))
                     (not (any-hood
                           (< (nbr total-children)</pre>
                              total-children))))
                   (not (any-hood
                          (and (nbr vessel)
                           (= (nbr (mid)) parent)))))
               (tup 0 1 -1); discard vessel
               (tup 1 1 parent)) ; keep vessel
          (mux (muxand active
                (or (sense 2)
                 (muxand (any-hood (nbr vessel))
                  (muxand (dilate (not served))
                                   serv-range))
                           (< (rnd 0 1) p))))
               (tup 1 1 server)
               (tup 0 service -1)))))))
```

Gradual Degradation



Vascularization/Density Co-Regulation

```
(def tissue (src pd pv)
(let ((v (vascularize src 50 pv)))
 (if (not src)
      (mov (cell-density (2nd v) 0 pd))
      (tup 0 0 0))
      (drawvasc v)))
```



proto -geometry 480x480 "(tissue (= (mid) 0) 0.1 0.02)" -m -s 0.1 -n 10 -rad 2 -dim 300 300 -dist-dim -5 5 -5 5 -l -sv -fixedpt 0 0

Vascularization/Density Co-Regulation



Modulation of Composed System



```
(def growf (src vlim)
(let ((grow (in_bounds)))
       (kill (not (out_bounds)))
       (v (vascularize-mod src
           (or (not vlim) (vin_bounds))
           50 0.02)))
(if (not src)
       (mov (cell-density
              (and (or vlim grow) (2nd v))
                 (and kill (not vlim)) 0.1))
       (tup 0 0 0))
       (drawvasc v)))
```

proto "(growf (= (mid) 0) 0)" -m -s 0.1 -n 10 -rad 2 -dim 500 500 -dist-dim -5 5 -5 5 -l -sv -fixedpt 0 0

System Decoupling



proto -geometry 480x480 "(growf (= (mid) 0) 0)" -m -s 0.1 -n 10 -rad 2 -dim 500 500 -dist-dim -155 -145 -155 -145 -l -sv -fixedpt -150 -150 proto -geometry 480x480 "(growf (= (mid) 0) 0)" -m -s 0.1 -n 10 -rad 2 -dim 500 500 -dist-dim 45 55 145 155 -l -sv -fixedpt 50 150 proto -geometry 480x480 "(growf (= (mid) 0) 1)" -m -s 0.1 -n 10 -rad 2 -dim 500 500 -dist-dim -5 5 -45 -35 -l -sv -fixedpt 0 -40

Contributions

- Functional blueprint framework
- Theoretical capability for systems integration using functional stress as coordinating signal
- Tissue growth model demonstrates how functional blueprints support modularity