Spatial Computing for Swarms

Jacob Beal
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Agenda

- Spatial Computing
- Survey of Existing Approaches
- Proto & Amorphous Medium
From one robot, to many
From one robot, to many
From one robot, to many

Robotic density is currently very low, but…
Networked devices are filling our environment...
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Networked devices are filling our environment...

How do we program aggregates robustly?
Spatial Computers

Robot Swarms

Biological Computing

Sensor Networks

Reconfigurable Computing

Cells during Morphogenesis

Modular Robotics
More formally...

- A spatial computer is a collection of computational devices distributed through a physical space in which:
  - the difficulty of moving information between any two devices is strongly dependent on the distance between them, and
  - the “functional goals” of the system are generally defined in terms of the system's spatial structure
More formally...

- A spatial computer is a collection of computational devices distributed through a physical space in which:
  - the difficulty of moving information between any two devices is strongly dependent on the distance between them, and
  - the “functional goals” of the system are generally defined in terms of the system's spatial structure.

Notice the ambiguities in the definition.
Graphs

Crystalline (e.g. CAs)

Amorphous/Continuous

(w. Dan Yamins)
Graphs

Crystalline (e.g. CAs)

Amorphous/Continuous

density

space complexity

jitter

grain size

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Graphs

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spatial computing

(w. Dan Yamins)
Space/Network Duality

*How well does the network cover space?*

*What space is covered well by the network?*
Tentative Mathematical Definition

- A spatial computer is any set of n devices s.t.
  - Graph \( \{V,E\} \) with edge weights \( w(v_1,v_2) \)
  - Manifold \( M \), with distance function \( d \)
    - \( M \) is compact, Riemannian \( (may\ be\ stronger\ than\ needed) \)
  - Position function \( p: V \rightarrow M \)
  - \( w(v_1,v_2) = O(1/d(p(v_1),p(v_2))) \)

Examples: unit disc network, chemical diffusion
Example: Target Tracking

Intruder

Guard
Example: Target Tracking

Intruder

Guard
Example: Target Tracking

Intruder

Guard
Example: Search & Rescue

I've found a victim!

The rescue bots are on the way!
How can we program these?

• Desiderata for approaches:
  • Simple, easy to understand code
  • Robust to errors, adapt to changing environment
  • Scalable to potentially vast numbers of devices
  • Take advantage of spatial nature of problems
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A Taxonomy of Approaches

Spatial
  Geometry
  Dynamics
    Uniform
    Viral

Non-Spatial
  Non-Composable
A Taxonomy of Approaches

Spatial

Geometry

Dynamics

Uniform

Viral

Non-Spatial

Non-Composable
Approaches from Local Dynamics

Primitives describe only actions between devices and the neighbors they communicate with.

- Advantages: coherent and correct semantics
- Disadvantages: programmer must figure out how to marshal local dynamics to produce coherent large-area programs
(def gradient (src) ...)
(def distance (src dst) ...)
(def dilate (src n)
  (< (gradient src) n))
(def channel (src dst width)
  (let* ((d (distance src dst))
          (trail (< (+ (gradient src)
                        (gradient dst))
                  d)))
    (dilate trail width)))
Other Uniform Approaches

• LDP/MELD (CMU Claytronics group)
  • Distributed logic programs
  • Local resolution leads to long-distance properties
TOTA: Viral tuples

C = (value = “2”, color = “green”)  
P = (propagate to all nodes,  
decrease “value” for the first 2 hops then  
increase it, change color at every hop)
Other Viral Approaches

- Smart Messages (Borcea)
  - Execution migrates to nodes of interest, found via self-routing code packets

- Paintable Computing (Butera)
  - Consistent transfer, view of neighbor data
  - Code for install, de-install, transfer-granted, transfer-denied, update

- RGLL (Sutherland)
  - Code for arrival, tick, collision, departure
  - Communication via collision
Approaches from Geometry

Primitives describe large-scale geometric regions (e.g. “all devices on the left hill”)

- Advantages: coherent, easy to specify large-scale programs
- Disadvantages: generally easy to accidentally specify programs that cannot be executed correctly
Meristem formation

Turing pattern on torus

Michel, Giavitto, Spicher
Regiment

• Streaming collection of data from regions
  • Spatial primitives:
    – K-hop neighborhood
    – K-nearest nodes
  • Composition:
    – Union/Intersection
    – Map/Filter
• Distributed execution as a compiler optimization
Other Geometric Approaches

- Borcea's Spatial Programming
- EgoSpaces
- SpatialViews
- Spidey
- Abstract Regions
- Growing Point Language
- Origami Shape Language
Non-Composable Approaches

Algorithms and techniques, generally based on geometry, but not part of a system of composable parts

- Advantages: powerful spatial ideas for that are good for inclusion in code libraries
- Disadvantages: developed as stand-alone ideas, and may have limited composability
Self-Healing Gradients
Local Check-Schemes

Yamins
Other Non-Composable Approaches

- hood (Whitehouse, et. al.)
  - nesC library for interacting with neighbors
- McLurkin's “Stupid Robot Tricks”
  - Swarm behaviors intended mainly for time-wise multiplexing.
- Countless one-shot systems...
Significant Non-Spatial Approaches

- “roll-your-own” (e.g. C/C++)
- TinyDB
  - Distributed database queries for sensor networks
- Kairos
  - Distributed graph algorithms
- WaveScript
  - Distributed streaming language
  - Follow-on to Regiment w/o the spatial primitives
Summary

- Many approaches exist to programming pervasive applications for spatial computers
- Only approaches based on local dynamics currently offer predictable composition, correct execution, and spatial primitives
- Challenge: obtaining long-range coherent behavior from local dynamics
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Example: Target Tracking
Geometric Program: Channel

Source

Destination

(cf. Butera)
Geometric Program: Channel

(cf. Butera)
Geometric Program: Channel

Source

Destination

(cf. Butera)
Geometric Program: Channel

Source

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Geometric Program: Channel

Source

Destination

(cf. Butera)
Why use continuous space?

• Simplicity
• Scaling & Portability
• Robustness

(we'll come back to this in a bit...)
Amorphous Medium

- Continuous space & time
- Infinite number of devices
- See neighbors' past state

Approximate with:
- Discrete network of devices
- Signals transmit state
Computing with fields

source \( \rightarrow \) gradient \( \rightarrow \) + \( \rightarrow \) <= \( \rightarrow \) dilate

destination \( \rightarrow \) gradient \( \rightarrow \) distance

width \( \rightarrow \) dilate
Computing with fields

source

destination

gradient

distance

width

dilate

<=

+=

37

10
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Proto's Families of Primitives

**Pointwise**
- +
- Feedback
- delay
- +
- 41
- 7
- 48

**Restriction**
- restrict
- Neighborhood
- nbr
- any-hood
Modulation by Restriction

source → destination → coord

cannel

gradcast

(5, 7)
Why use continuous space?

- Simplicity
- Scaling & Portability
- Robustness

![Diagram showing 2000 devices](image1.png)
![Diagram showing 150 devices](image2.png)
Diving into the details

Let's build this up using the Proto simulator, one piece at a time...

(break to work w. simulator)
In simulation...
Example: Search & Rescue

I've found a victim!

The rescue bots are on the way!
In simulation...
Weaknesses

• Functional programming scares people
• Programmers can break the abstraction
• No dynamic allocation of processes
• No formal proofs available for quality of approximation in a composed program

*(active research on last two)*
Summary

- Amorphous Medium abstraction simplifies programming of space-filling networks
- Proto has four families of space and time operations, compiles global descriptions into local actions that approximate the global
- Geometric metaphors allow complex spatial computing problems to be solved with very short programs.
Proto is available

http://stpg.csail.mit.edu/proto.html
(or google “MIT Proto”)

- Includes libraries, compiler, kernel, simulator, platforms
- Licensed under GPL (w. libc-type exception)