Cyber-physical systems – linking sensing, networking, computation and people

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sensing    networking & computation    people

Q: How are these “linked”?
Traditional data push: from sensors to people

User-driven: closed-loop “pull”
Wide range of “sensors”

- habitat monitoring
- animal tracking
- auto traffic monitoring
- video surveillance
- underwater sensing
- microclimate monitoring
- vehicle tracking in sensor field
- radar/weather
- satellite observation (EODIS)
- network traffic monitoring

in spite of differences, commonalities as well!

Overview

- introduction
- CASA: collaborative adaptive sensing of the atmosphere
  - introduction, motivation
  - testbeds
- research challenges: integrating sensors, networking, computation, people
  - system architecture
  - energy-constrained environments
    - joint sensing/communication
    - incorporating end-user utilities
- discussion: the big picture
The grand challenge

Revolutionize our ability to **observe, understand, predict** weather hazards, using sensor networks that sample the atmosphere where and when end-user needs are greatest.

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**Seismic structure response**

**Ecosystems, Biocomplexity**

**Video security, surveillance**

**Contaminant transport**

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**NEXRAD (current US system)**

- 158 radars operated by NOAA
- 230 km Doppler mode, 460 km reflectivity-only mode
- “surveillance mode”: — sit and spin

---

3 km coverage floor
NEXRAD (current US system)

Processing Algorithms

Observational Data “Push”

The Sensing Gap

Sparse, high-power radar

- *sensing gap*: earth curvature effects prevent 72% of the troposphere below 1 km from being observed
- coarse resolution
CASA: collaborative adaptive sensing of the atmosphere

CASA: dense network of low power radars:
- sense lower 3 km of earth’s atmosphere
- collaborating radars:
  - improved sensing
  - improved detection, prediction
- finer spatial resolution
- responsive to multiple end-user needs

“Sample atmosphere when and where end-user needs are greatest”

CASA: dense network of inexpensive, short range radars

- finer spatial resolution
- beam focus: more energy into sensed volume
- multiple looks: sense volume with most appropriate radars
CASA: adaptive data pull

MC&C: Meteorological command and control

Meteorological Detection Algorithms

SNR

Resource planning, optimization
data policy

End users: NWS, emergency response

CASA: End Users

(Real) end users: National Weather Service, emergency response managers, researchers
What’s needed to solve this problem?

CASA
Collaborative
Adaptive
Sensing
of the Atmosphere

NSF
Engineering Research Center

Remote sensing
Data-intensive systems
Networking
Real-time systems
Numerical prediction
Emergency management
Radar meteorology
Quantitative inversion
Climate studies
Social impact
Antenna design

core partners

Integrative, engineered systems

- focus mandated by NSF
- 3 CASA testbeds

NetRad - Storms
Urban Flooding

Tornado Alley, SW Oklahoma
Brays Bayou, Houston

Project Year
1 2 3 4 5 6 7 8 9 10

Off the Grid – resource constrained
Oklahoma 4-Node Test Bed

Spring 2007 storm season:

4/10/07: first CASA data citation by NWS

5/8/07: circulations in testbed

Note: not policy
April 10, 2007 Elevated Super Cell

CASA’s Adaptive Sector scanning at multiple elevations from 1 to 14 degrees, 40 sec. sector scan

ground truth verification (NEWS9)

CASA IP1 view: May 8 event

KLWE at 1.0 deg elevation, 21km range (~200m AGL)

7:26pm  7:28pm  7:32pm  7:34pm  7:36pm  7:38pm  7:39pm

... corresponding NEXRAD view

7:28pm  7:34pm  7:39pm
Movie: NetRad in operation

May 14, 2009

Off-the-Grid Test Bed

- no reliance on infrastructure
- solar/battery-operated nodes
- multi-antenna multi-hop 802.11 directional antenna

Topology of the MA OTG testbed
Prototype OTG Node

- 4 kW (incoherent) Marine Radar
- Low power embedded PC
- 60 W solar panel
- 110 Ah battery

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Our architectural worldview

application-layer functionality, control, protocols

IP backplane

middle age: a narrowing mind, a widening waist

Youthful, IP "hourglass"  Internet at middle-age: lovehandles?

<table>
<thead>
<tr>
<th>Applications</th>
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<tbody>
<tr>
<td>TCP UDP</td>
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<tr>
<td>IP</td>
</tr>
<tr>
<td>Eth token</td>
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Middle-aged Internet: losing the hourglass?
Middle-aged Internet: *keeping* the hourglass!

Middle age: a expanding mind, a slim waist

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Architecture overview

1 Mbps (moment)
100 Mbps (raw)

30 sec. "heartbeat"

SNR data, policy

Resource planning, allocation

MC&amp;C: Meteorological command and control

Meteorological Task Generation

End users: NWS, emergency response
Meteorological Command and Control (MC&C)

Time sensitive: decouple ingest from command generation

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Optimal joint sensing/routing in energy constrained environments

- energy expenditures: sensing, send/receive data
- each node must determine:
  - $s_i$: sensing (data generation) rate,
  - $X_{ij}$: how to route sensed data towards sink, subject to power constraints
- node decision affects others: sensed data must be sent
Goal: maximize utility of received data

System-wide utility function

\[ U = \sum_i U_i(s_i) \]

- \( s_i \): node \( i \) sensed and delivered data rate
- \( U_i(s_i) \): utility of node \( i \) data.
  concave, increasing function

Optimization problem formulation

\( S \): sensing rates; \( X \): routing
\[ \max_{s, X} \text{ network utility } U(s) \]
\text{s.t.}
1. \( J(s, X) = 0 \)
2. \( F(s, X) \leq C \)
3. \( p(s, X) \leq P \)

- flow conservation
- routes \( X \) satisfying sensing rates \( s \)
- link rates limited by capacities
- demand feasibility
- power usage limited by available power
- power feasibility
Mapping from sensing/routing problem to routing problem

\[ S_i = \max(s_i) \]

Algorithm:
- receive marginal utility information from downstream nodes
- change flow rates to downstream to balance marginal utility
- compute own marginal utility wrt upstream flow, send upstream

Distributed optimization

- convergence proof, step-size requirements, evaluation

Simulation scenario

CASA student testbed
- energy collection rate: 7-13W
- X-band radar-on power: 34W
- radar-on rate 1.5Mbps
- link-on trans power: 1.98W
- link-on receive power: 1.39W

$$U_i(s_i) = -w_i s_i^{-0.5}$$
$$U = \sum_i U_i(s_i)$$

Energy balance for different energy harvest rates

Optimal joint sensing/routing: many open questions!

- in-network computation (data fusion)
  - data flow no longer conserved!
- considering battery recharge/drain
- implementation, measurement
  - point-point directional links
  - end-end system

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What do end-users want?

- **understand**: research data
- **predict**: give advance warning
- **respond**: using current/recent data

not always achievable simultaneously!

Incorporating end-user utilities

- 1 Mbps (moment)
- 100 Mbps (raw)
- 30 sec. "heartbeat"
Optimizing radar scans: incorporating end user considerations

Where to point?

Find \textit{configuration} that optimizes utility at time step \(k\):

\[
J = \max_{\text{configurations}, C} \sum_{\text{tasks}, t} U(t, k)Q(t, C)
\]

Utility – "how important" is task \(t\) to the users at time \(k\)?

\[
U(t, k) = \sum_{\text{groups}, g} w_g U_g(t, k)
\]

Quality – "how good" is scanning configuration \(C\) (distance, coverage, # radars) for task \(t\)?

Optimizing radar scans: architecture!

Find \textit{configuration} that optimizes utility at time step \(k\):

\[
J = \max_{\text{configurations}, C} \sum_{\text{tasks}, t} U(t, k)Q(t, C)
\]

- separation of "how important," \(U(t, k)\), from "how good," \(Q(t, C)\)
- \(U(t, k, Q(t, C))\) would have been possible but:
  - complex to solve
  - complex to specify and update \(U(t, k, Q(t, C))\)
  - "stovepipe" design
How to define “how important”: $U_g(t,k)$

- user values for detected weather features

<table>
<thead>
<tr>
<th>Event</th>
<th>Location</th>
<th>Prior Information available</th>
<th>NWS utility $W_r=0.4$</th>
<th>EM utility $W_r=0.3$</th>
<th>Researcher utility $W_r=0.2$</th>
<th>Vieux utility $W_r=0.1$</th>
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<td>1</td>
<td>4</td>
<td>1</td>
<td>5</td>
<td>1</td>
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<tr>
<td>Mesocyclone</td>
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<tr>
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</table>

How to define “how important”: $U_g(t,k)$

- “naturally”: group-sensitive utility for each feature (tornado, wind shear, hail core) scanned
- … and the survey says…..

User feedback:
- NWS: want “mental movie” scanning “areas of interest” at regular intervals
- need context: scan areas around features (storm cell)
- want to joystick system
  (want their own network)
User Utility Rules (revised)

- **interval-based preferences**: “do X every Y time units”
- utility considers both objects, time

<table>
<thead>
<tr>
<th>Rules</th>
<th>Rule trigger</th>
<th>Sector Selection</th>
<th>Elevations</th>
<th># radars</th>
<th>Contig.</th>
<th>Sampling interval</th>
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<td>NWS</td>
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<tr>
<td>N1</td>
<td>time</td>
<td>360</td>
<td>lowest</td>
<td>1</td>
<td>Yes</td>
<td>1 / min</td>
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<tr>
<td>N2</td>
<td>storm</td>
<td>task size</td>
<td>lowest</td>
<td>1</td>
<td>Yes</td>
<td>1 / 2.5 min</td>
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<tr>
<td>EMs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E1</td>
<td>time</td>
<td>360</td>
<td>lowest</td>
<td>1</td>
<td>Yes</td>
<td>1 / min</td>
</tr>
<tr>
<td>E2</td>
<td>reflectivity over AOI</td>
<td>task size</td>
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<td>1</td>
<td>Yes</td>
<td>1 / min</td>
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<tr>
<td>E3</td>
<td>velocity over AOI</td>
<td>task size</td>
<td>lowest</td>
<td>2+</td>
<td>Yes</td>
<td>1 / 2.5 min</td>
</tr>
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Virtualization: enabling the end user

- **virtualization** of computing, communication, and sensing resources

- **each** user:
  - sees “standalone” sensor network
  - can modify, download, execute, experiment with own code
  - implements user-specific service outside (architecturally above) infrastructure provider

Virtualization: making end users happy

Instead of this...

...this system view
Virtualization: enabling end user

Why virtualization?

- users want programmability/resources at *in-network* nodes: computing over local data, storage
  - good application: avoid active networking redux
- challenges: virtualizing sensing resources:
  - **sharing**: sensed data from one user usable by another (unlike bandwidth, computing)
  - **admission control**: mediating among different users with different priorities
    - partially satisfiable user requests? (negotiate?)
    - time-vary allocation of resources?
    - priorities among users (policy)?
Sensor Virtualization Architecture

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Q: How are these “linked”? 

The really big picture

- importance of the user
  - “It’s the end-user, stupid”
  - “It’s the application, stupid”
  - “It’s the network, stupid”

of course, not everyone agrees …. 

Verizon product, 2009
The *really* big picture

- importance of user requirements
  - “It’s the user, stupid”
  - “It’s the application, stupid”
  - “It’s the network, stupid”

- architecture (as opposed to stovepipe) for embedding user requirements?
  - sensor networks
  - content distribution
  - special-purpose overlays

Architecture: stovepipes or layers?
Architecture: stovepipes or layers?

CPS/sensor networking: where are we?

[adapted from Hluchyj 2001]
The end
thanks!

?? || /* */