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Mobile Emulab: A Robotic Wireless and Sensor Network Testbed

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Need for Real, Mobile Wireless Experimentation

- Simulation problems
  - Wireless simulation incomplete, inaccurate (Heidemann01, Zhou04)
  - Mobility worsens wireless sim problems
- But, hard to mobilize real wireless nodes
  - Experiment setup costly
  - Difficult to control mobile nodes
  - Repeatability nearly impossible
- Must make real world testing practical!

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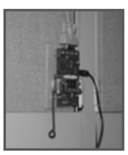
Our Solution

- Provide a real mobile wireless sensor testbed
  - Users remotely move robots, which carry sensor motes and interact with fixed motes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Key Ideas

- Help researchers **evaluate WSN apps under mobility with real wireless**
- Provide easy remote access to mobility
- Minimize cost via COTS hardware, open source
- Subproblems:
  - Precise mobile location tracking
  - Low-level motion control

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Outline

- Introduction
- **Context & Architecture**
- Key Problem #1: Localization
- Key Problem #2: Robot Control
- Evaluation
  - Microbenchmarks
  - Data-gathering experiment
- Summary

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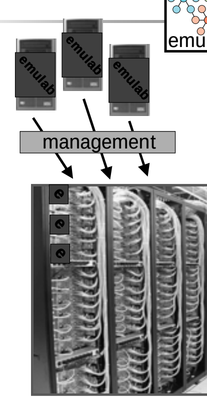
Context: Emulab

- Widely-used network testbed
  - Provides remote access to custom emulated networks
- How it works:
  - Creates custom network topologies specified by users in NS
  - Software manages PC cluster, switching fabric
- Powerful automation, control facilities
- Web interface for experiment control and monitoring
- Extended system to provide mobile wireless…



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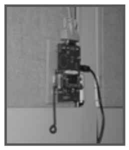
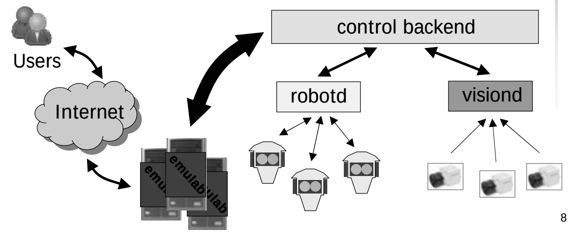
Mobile Sensor Additions

- Several user-controllable mobile robots
  - Onboard PDA, WiFi, and attached sensor mote
- Many fixed motes surround motion area
  - Simple mass reprogramming tool
  - Configurable packet logging
  - … and many other things
- New user interfaces
  - Web applet provides interactive motion control and monitoring
  - Other applets for monitoring robot details: battery, current motion execution, etc



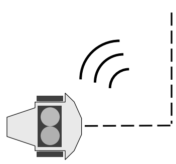
Mobile Testbed Architecture

- Emulab extensions
  - Remote users create mobile experiments, monitor motion
- Vision-based localization: *visiond*
  - Multi-camera tracking system locates robots
- Robot control: *robotd*
  - Plans paths, performs motion on behalf of user
  - Vision system feedback ensures precise positioning



Motion Interfaces

- Drag'n'drop Java applet, live webcams
- Command line
- Pre-script motion in NS experiment setup files
  - Use event system to script complex motion patterns and trigger application behavior



```
set seq [ $ns event-sequence {
    $myRobot setdest  1.0  0.0
    $program run -time 10
          "/proj/foo/bin/pkt_bcast"
     $myRobot setdest  1.0  1.0
    …
} ]
$seq run
```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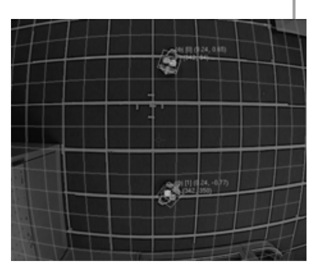
Key Problem #1: Robot Localization

- Need precise location of each robot
  - Needed for our control and for experimenter use in evaluation
- System must minimize interference with experiments
  - Excessive node CPU use
  - Wireless or sensor interference
- Solution: obtain from overhead video cameras with computer vision algorithms (*visiond*)
  - Limitation: requires overhead lighting

Localization Basics

- Several cameras, pointing straight down
  - Fitted with ultra wide angle lens
- Instance of Mezzanine (USC) per camera "finds" fiducial pairs atop robot
  - Removes barrel distortion ("dewarps")
- Reported positions aggregated into tracks
- But…



Localization: Better Dewarping

- Mezzanine's supplied dewarp algorithm unstable (10-20 cm error)
- Our algorithm uses simple camera geometry
  - Model barrel distortion using cosine function

    $loc_{world} = loc_{image} / \cos(a * w)$

    (where a is angle between optical axis and fiducial)
  - Added interpolative error correction
- Result: ~1cm max location error
- No need to account for more complex distortion, even for very cheap lenses

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Key Problem #2: Robot Motion

- Users request high-level motion
  - Currently support waypoint motion model (A->B)
- *robotd* performs low-level motion:
  - Plans reasonable path to destination
  - Avoids static and dynamic obstacles
  - Ensures precise positioning through vision system feedback

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Motion: Control & Obstacles

- Planned path split into segments, avoiding known, fixed obstacles
  - After executing each segment, vision system feedback forces a replan if robot has drifted from correct heading
- When robot nears destination, motion enters a refinement phase
  - Series of small movements that bring robot to the exact destination and heading (three sufficient for < 2cm error)
- IR rangefinders triggered when robot detects obstacle
  - Robot maneuvers around simple estimate of obstacle size

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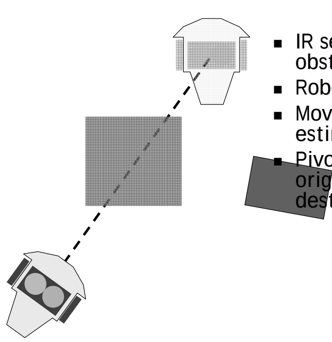
Motion: Control & Obstacles



- IR sensors “see” obstacle
- Robot backs up
- Moves to corner of estimated obstacle
- Pivots and moves to original final destination

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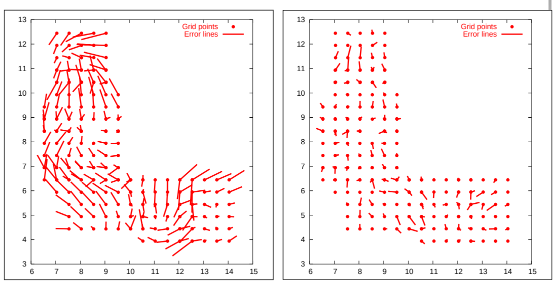
Evaluation: Localization

- With new dewarping algorithm and error correction, max error 1.02cm, mean 0.32cm

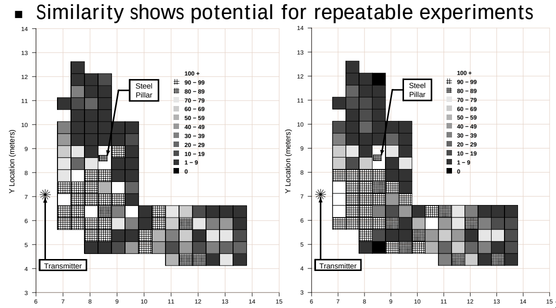


Case Study: Wireless Variability Measurements

- Goal: quantify radio irregularity in our environment
  - Single fixed sender broadcasts packets
  - Three robots traverse different sectors in parallel
  - Count received packets and RSSI over 10s period at each grid point
- Power levels reduced to demonstrate a realistic network

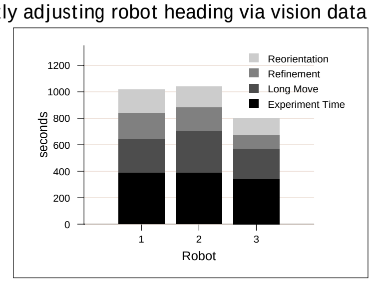
Wireless Variability (2)

- Some reception decrease as range increases, but significant irregularity evident
- Similarity shows potential for repeatable experiments



Wireless Variability (3)

- 50-60% time spent moving robots
  - Continuous motion model will improve motion times by constantly adjusting robot heading via vision data



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In Conclusion…

- Sensor net testbed for real, mobile wireless sensor experiments
- Solved problems of localization and mobile control
- Make real motion easy and efficient with remote access and interactive control
- Public and in production (for over a year!)
  - Real, useful system

Thank you!

Questions?

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Related Work

- MiNT
  - Mobile nodes confined to limited area by tethers
- ORBIT
  - Large indoor 802.11 grid, emulated mobility
- Emstar
  - Sensor net emulator: real wireless devices coupled to mote apps running on PCs
- MoteLab
  - Building-scale static sensor mote testbed

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Ongoing Work

- Continuous motion model
  - Will allow much more efficient, expressive motion
- Sensor debugging aids
  - Packet logging (complete)
  - Sensed data emulation via injection (in progress)
- Interactive wireless link quality map (IP)

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Evaluation: Localization

- Methodology:
  - Surveyed half-meter grid, accurate to 2mm
  - Placed fiducials at known positions and compared with vision estimates
- With new dewarp algorithm and error correction, max error 1.02cm, mean 0.32cm
  - Order of magnitude improvement over original algorithm

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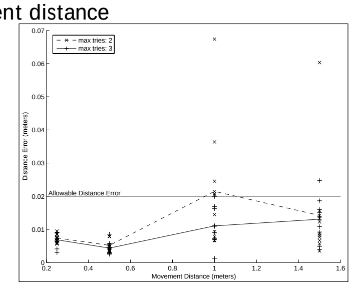
Evaluation: Robot Motion

- In refine stage, three retries sufficient
  - End position 1-2cm distance from requested position
- Accuracy of refine stage not affected by total movement distance



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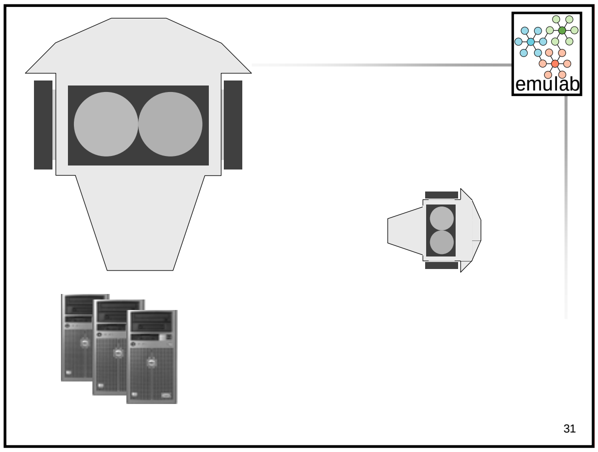
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