The Cricket Indoor Location System

Hari Balakrishnan

Cricket Project
MIT Computer Science and Artificial Intelligence Lab
http://nms.csail.mit.edu/~hari
http://cricket.csail.mit.edu

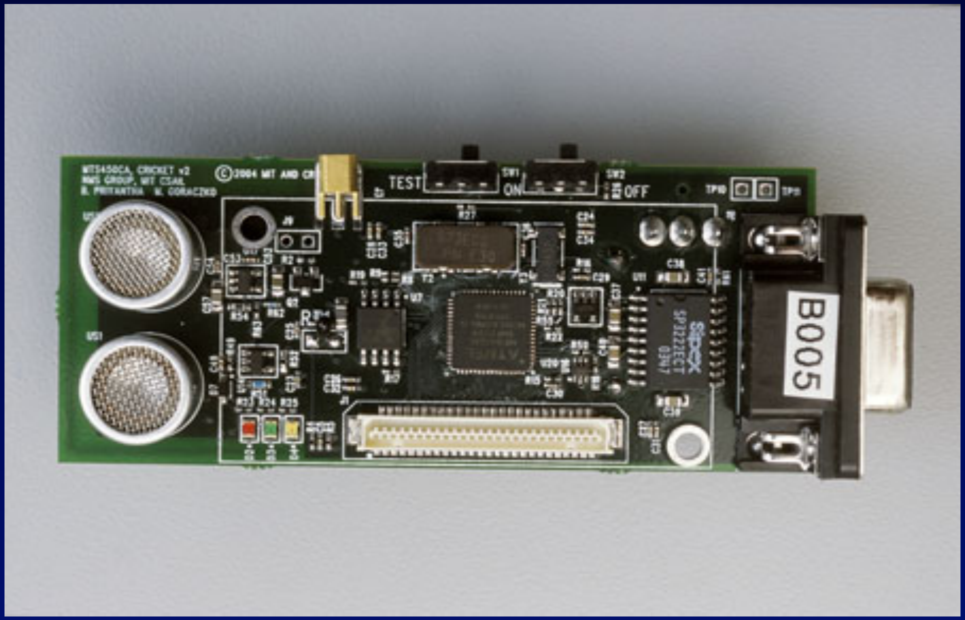
Joint work with Bodhi Priyantha and others

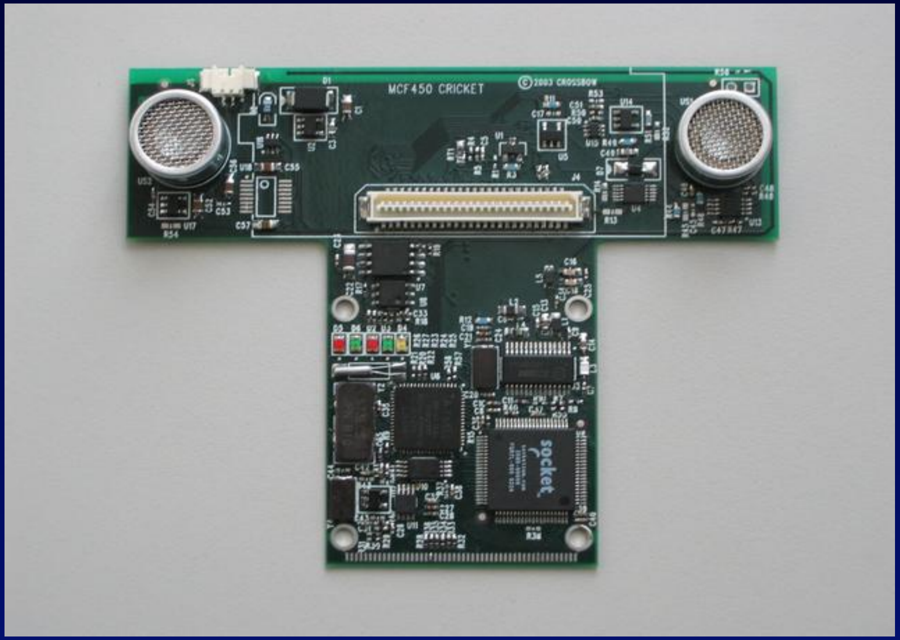
Outline

- **Some Cricket applications**
- Cricket architecture
- Distance and location estimation
- Other features, status, demo

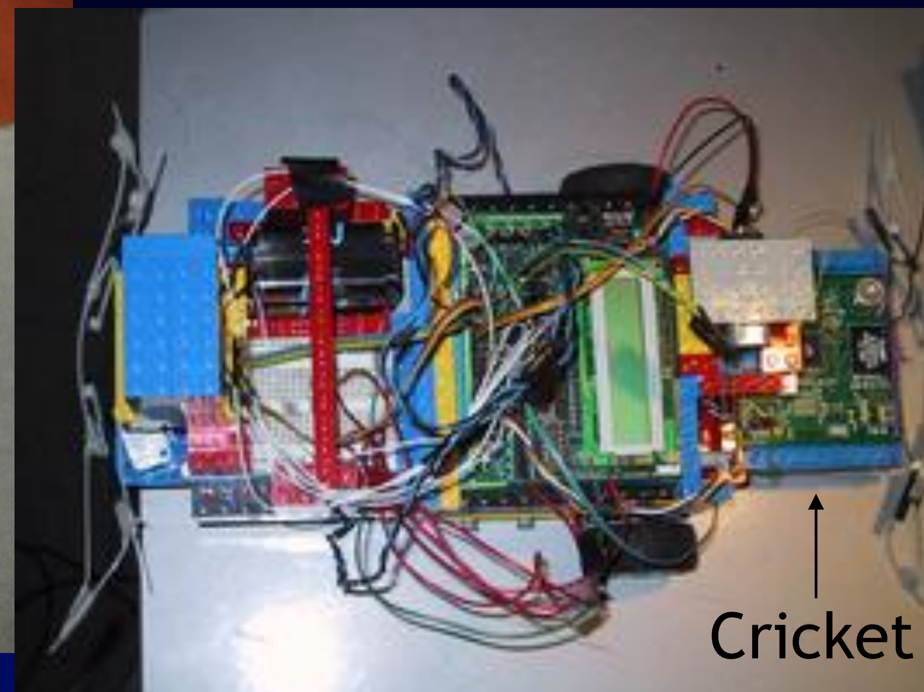
Cricket

A general-purpose indoor location system for mobile and sensor computing applications

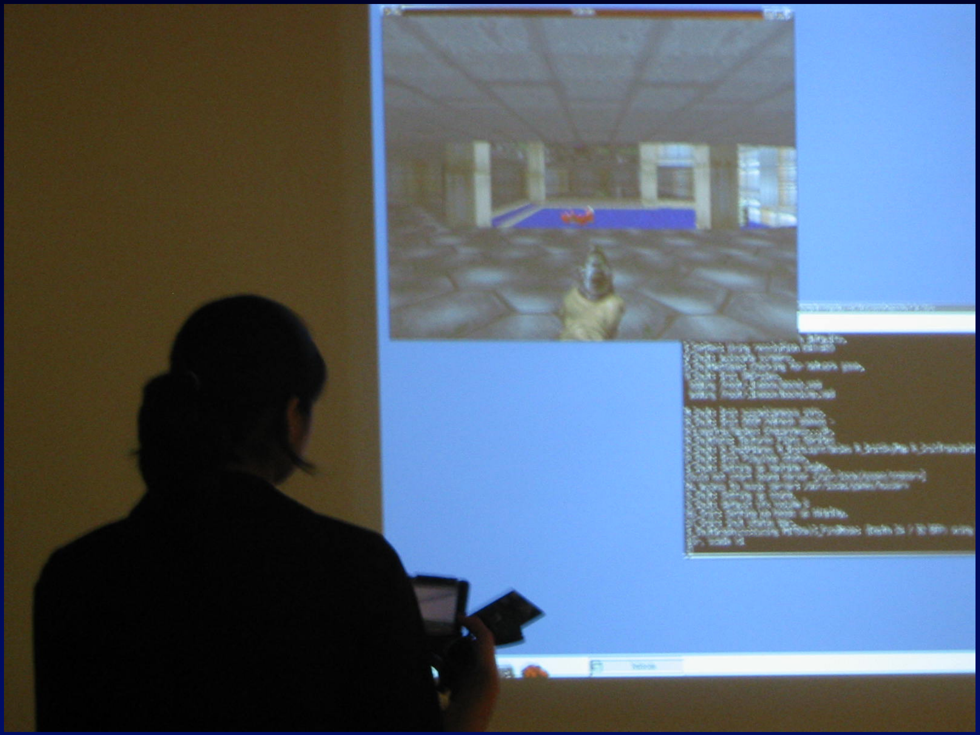




Indoor Human/Robot Navigation



Virtual/Physical Games



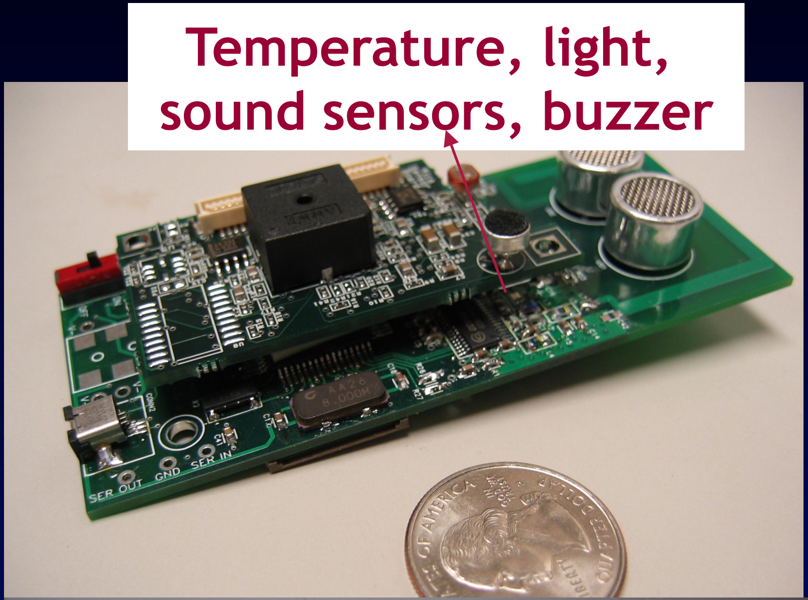
Rudolph et al., MIT Project Oxygen

Hospital Applications

Tracking patients and equipment in hospitals

Location-Aware Sensing

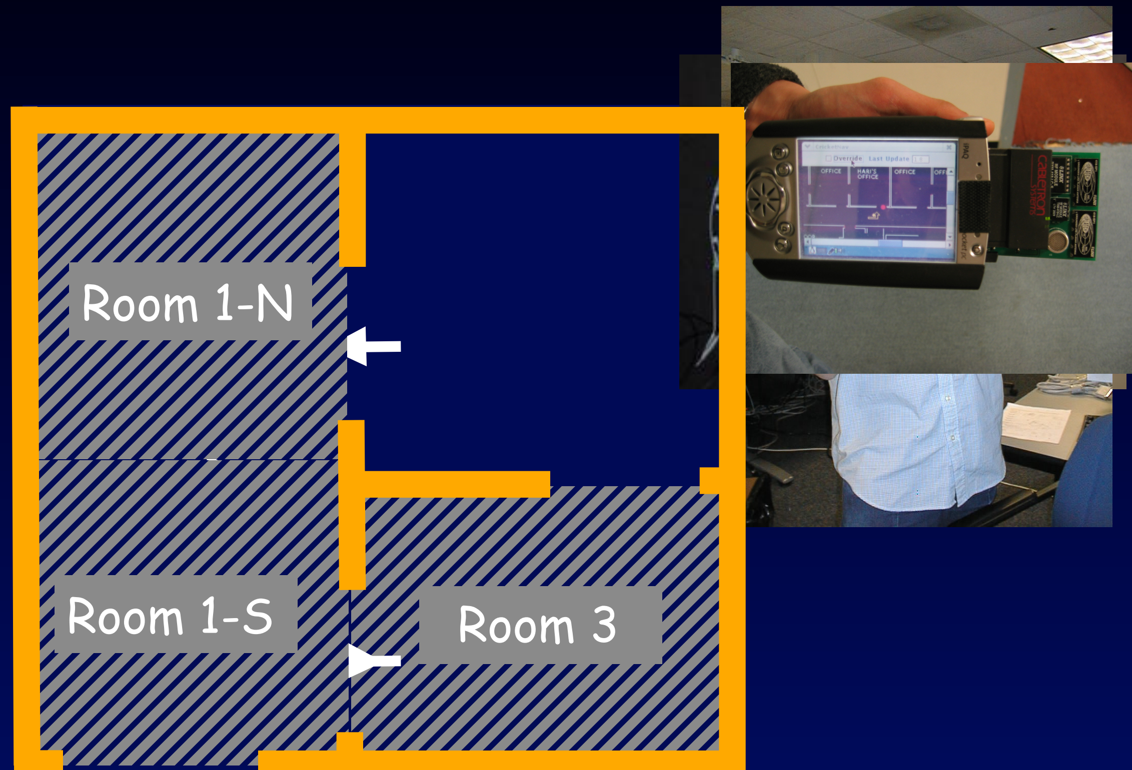
- Networked sensors enable remote monitoring and control
  - Asset tracking
  - Environmental monitoring
  - Supply chain
  - Remote actuation
- Sensor streams need to be annotated with *location*



Outline

- Applications
- **Cricket architecture**
- Distance and location estimation
- Other features, status, demo

Location = Space, Position, Orientation

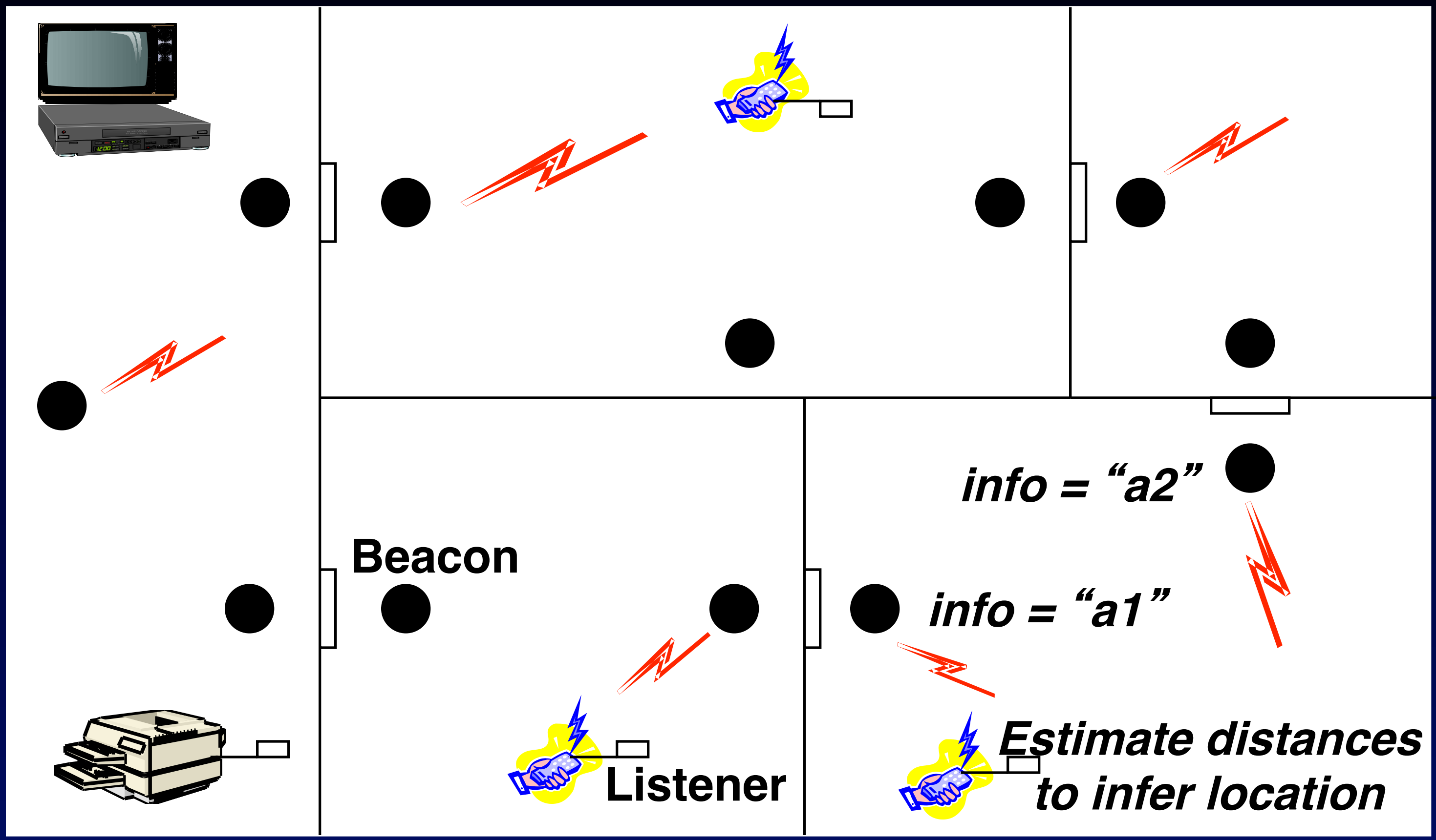


- Space: Rooms, parts of rooms
- Position: (x, y, z) coordinates
- Orientation: Direction vector

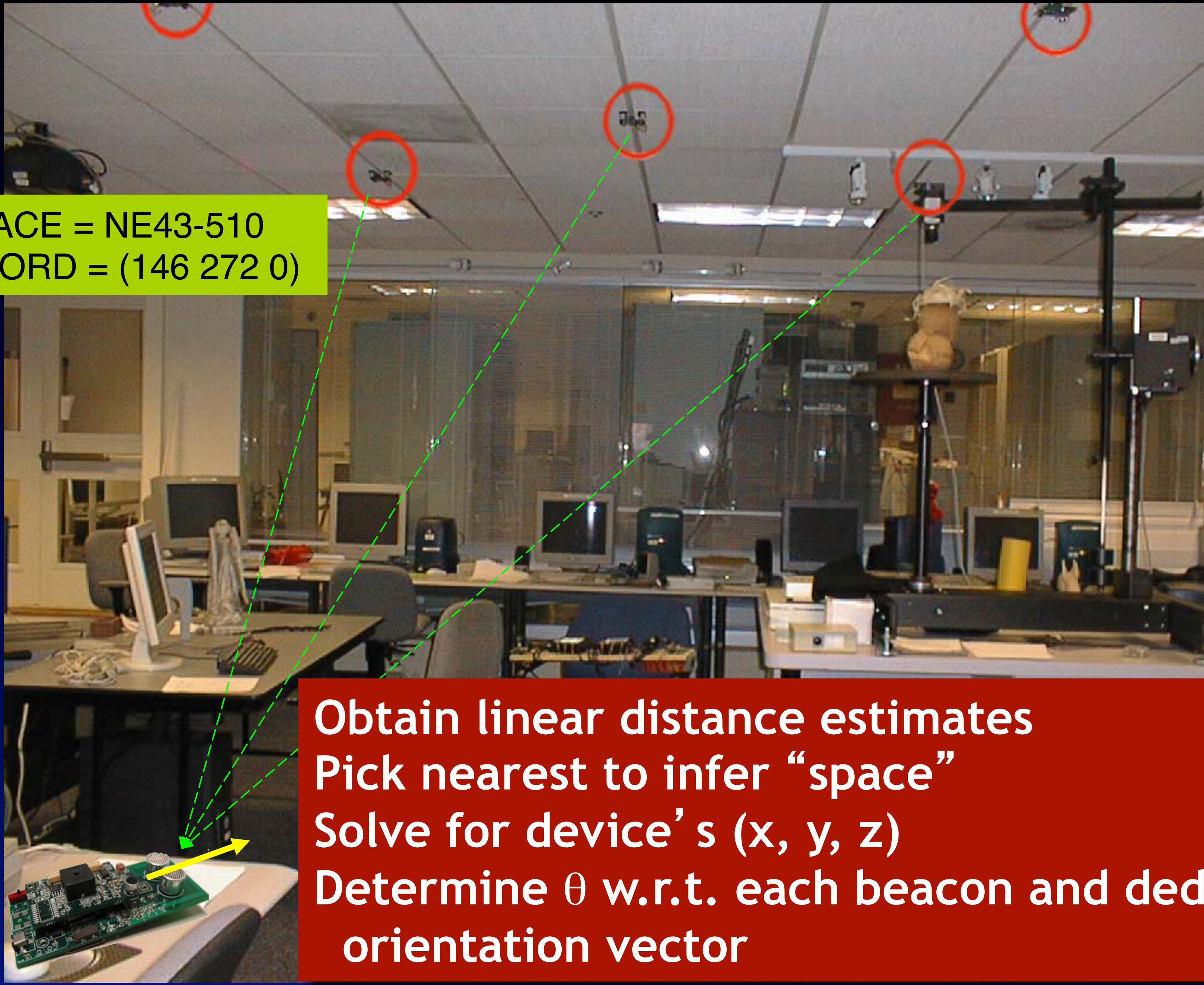
Design Goals

- Must work well indoors
- Must scale to large numbers of devices
- Should not violate user location privacy
- Must be easy to deploy and administer
- Should have low energy consumption

Cricket Architecture

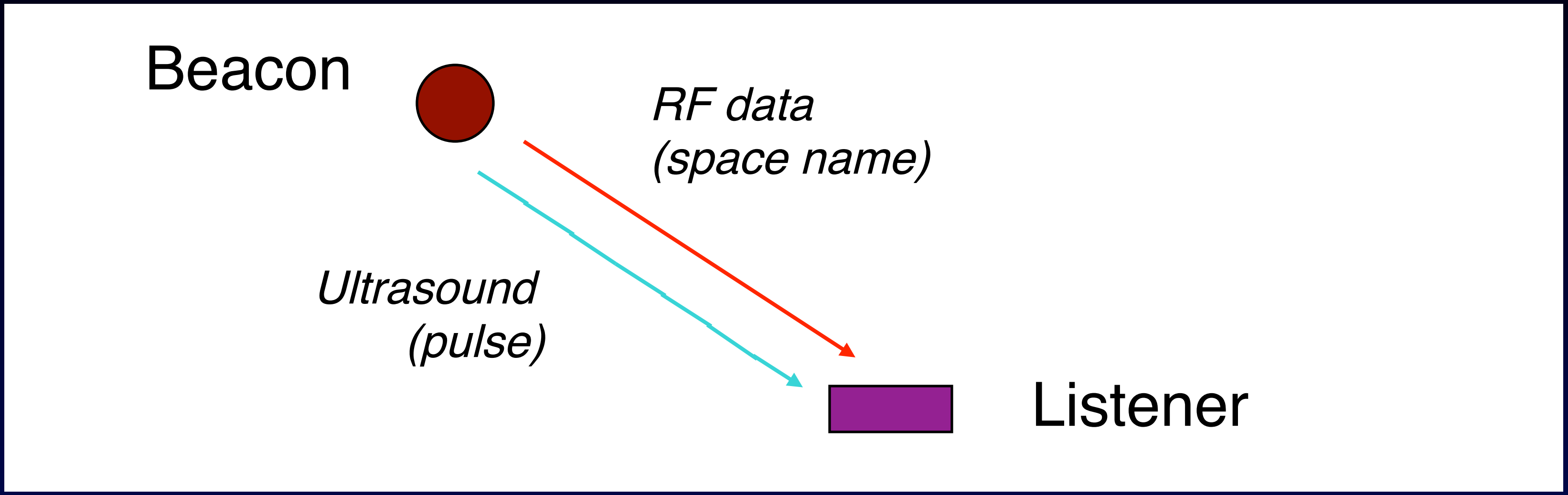


Passive listeners + active beacons scales well, helps preserve user privacy
Decentralized, self-configuring network of autonomous beacons



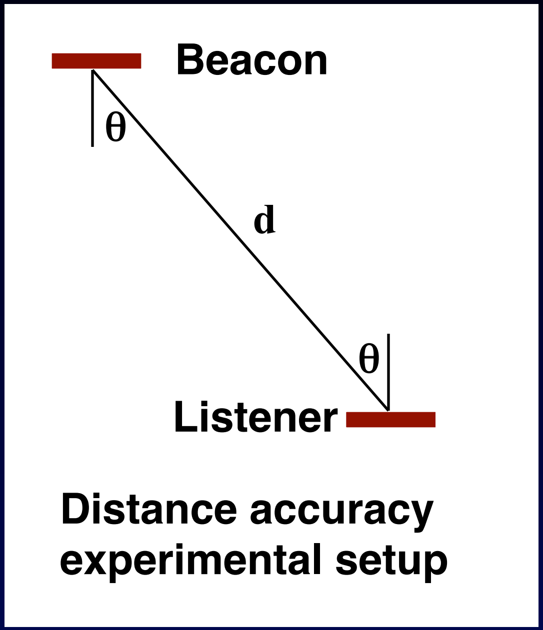
Obtain linear distance estimates
Pick nearest to infer “space”
Solve for device’s (x, y, z)
Determine θ w.r.t. each beacon and deduce orientation vector

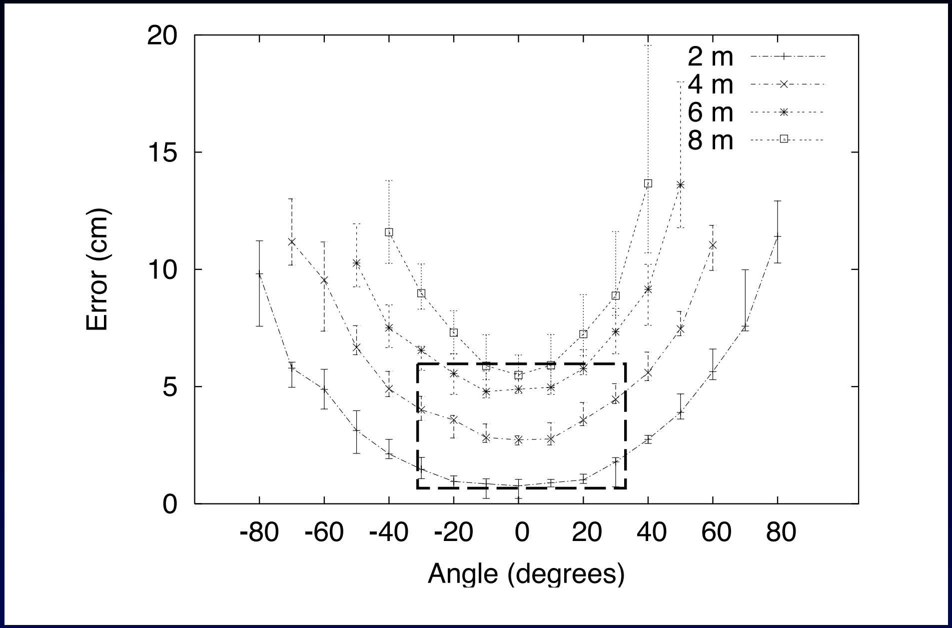
Determining Distance

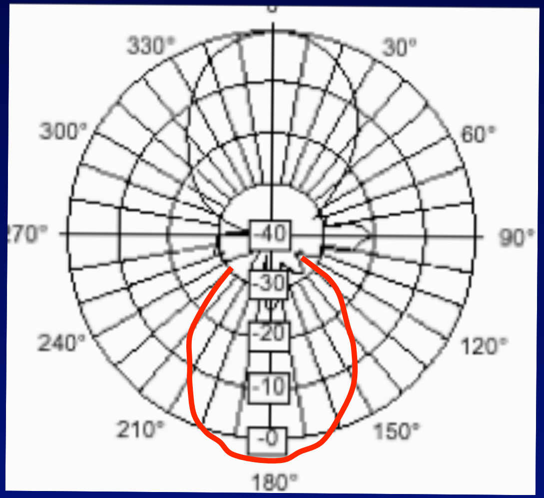


- The listener measures the time gap between the receipt of RF and ultrasonic (US) signals
  - Velocity of US << velocity of RF

Distance Measurement Performance

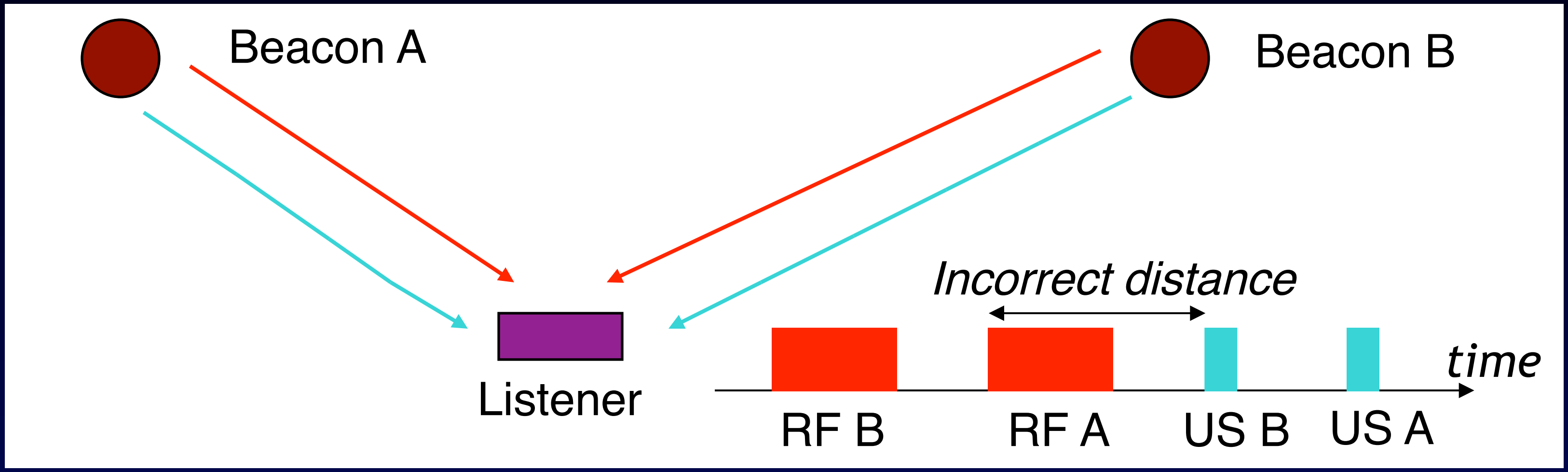






- Error increases with *d* and θ
  - Signal gets weaker with increasing *d* and θ
  - Takes longer to detect at listener
  - Errors are on the order of US wavelength

Multiple Beacons Cause Complications



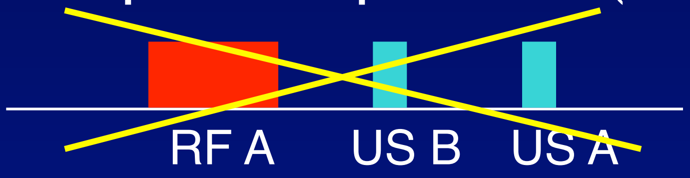
- Beacon transmissions are uncoordinated
- Ultrasonic pulses reflect off walls

These make the correlation problem hard and can lead to incorrect distance estimates

Solution: Beacon interference avoidance + listener interference detection

Solution (Part 1): Beacon Interference Avoidance

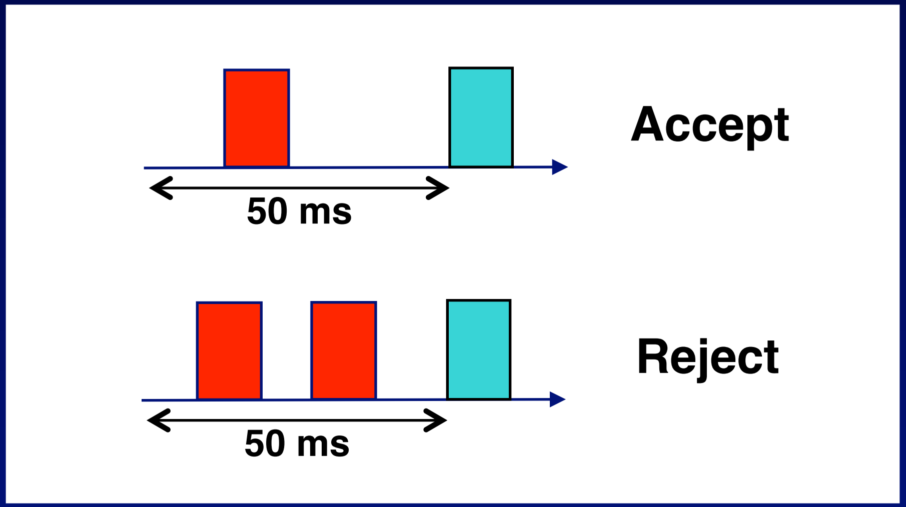
- Use carrier-sense + randomized transmission at each beacon
  - Listen-before-transmit
  - Delay for random time in [T1, T2], then xmit
- Engineer RF range to be > 2x US range (approx.)
- Idle time between beacon chirps to allow US signal to "die down" (50 ms)
  - Upon hearing any RF xmission, delay for 50 ms
- Result: No "US interference" pattern possible (if carrier sense works)



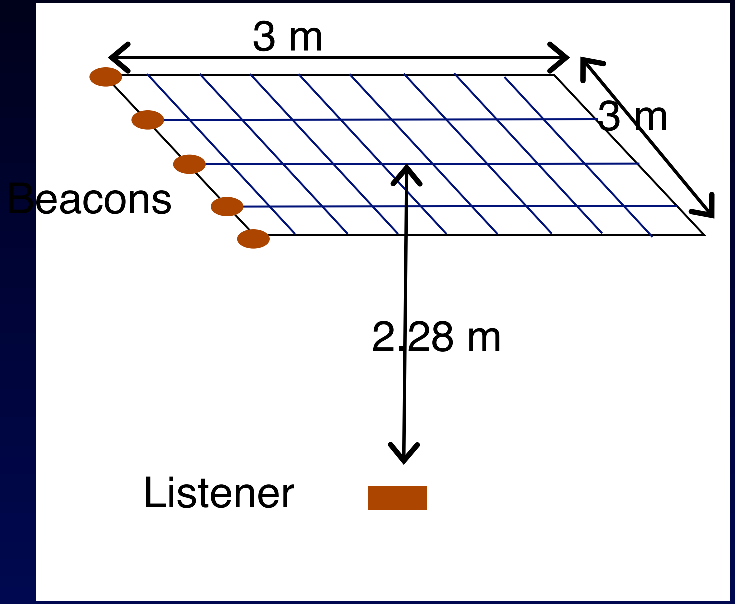
Solution (Part 2): Listener Interference Detection

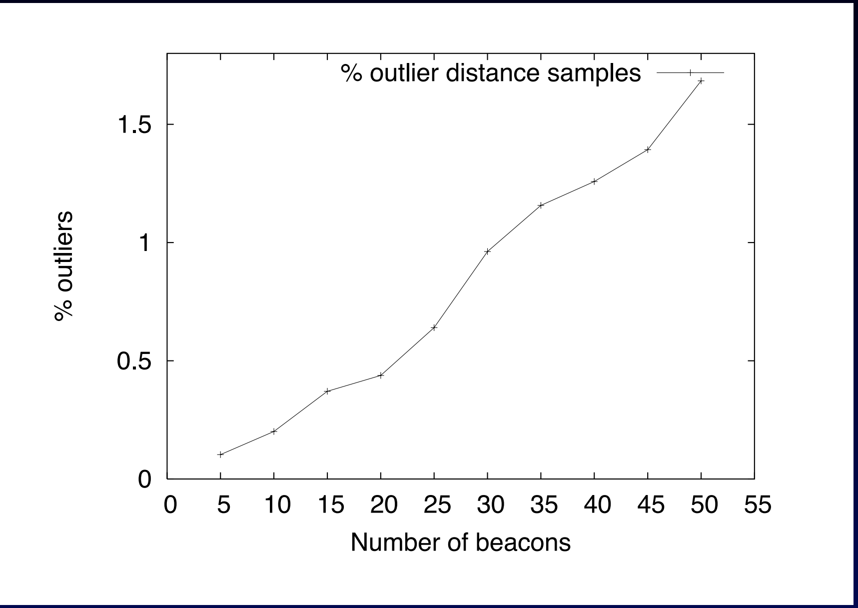
- "RF interference" still possible

- Solution: Listener counts the number of RF messages during 50 ms before US signal
  - Only one RF? Then, accept
  - More than one? Then, reject



Beacon Interference Detection/Avoidance Performance





- Outliers (>5% error) caused by:
  - RF vagaries: dead spots, fading, imperfect carrier sensing
  - Ultrasonic noise: Jangling keys, faulty lights
- Hence, position estimators need to handle outliers

Space Estimation

- Static outlier detection: MinMode algorithm
- Find mode of each beacon's measured distances over recent time window
- Space = beacon with smallest mode

Position Estimation

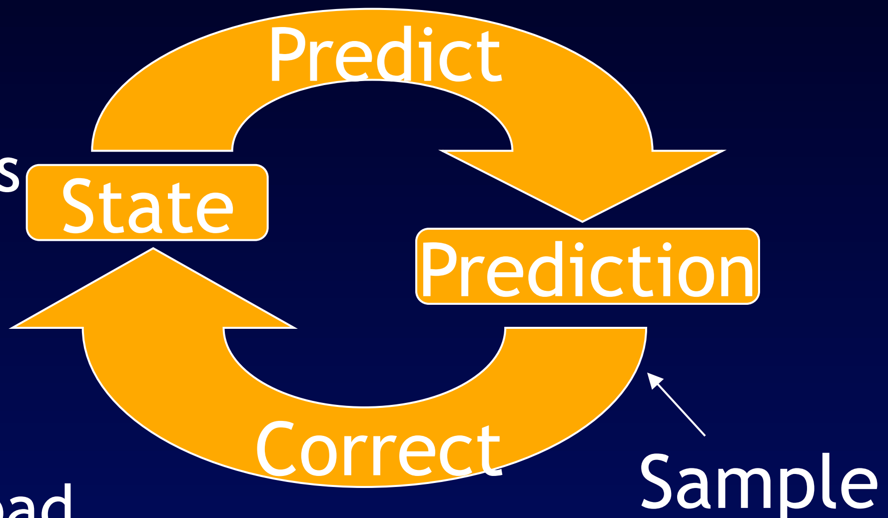
- Static case is easy (lateration)
- Mobile case is harder

$$f : \begin{bmatrix} t_1 & d_1 & p_1 \\ t_2 & d_2 & p_2 \\ \vdots & \vdots & \vdots \\ t_n & d_n & p_n \end{bmatrix} \longrightarrow \Re^3$$

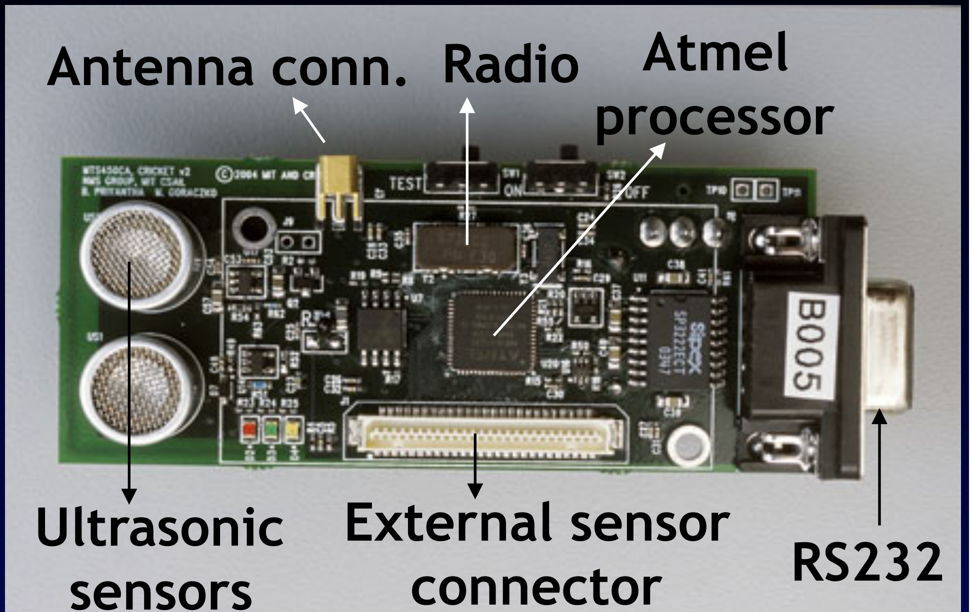
Samples — Position estimate

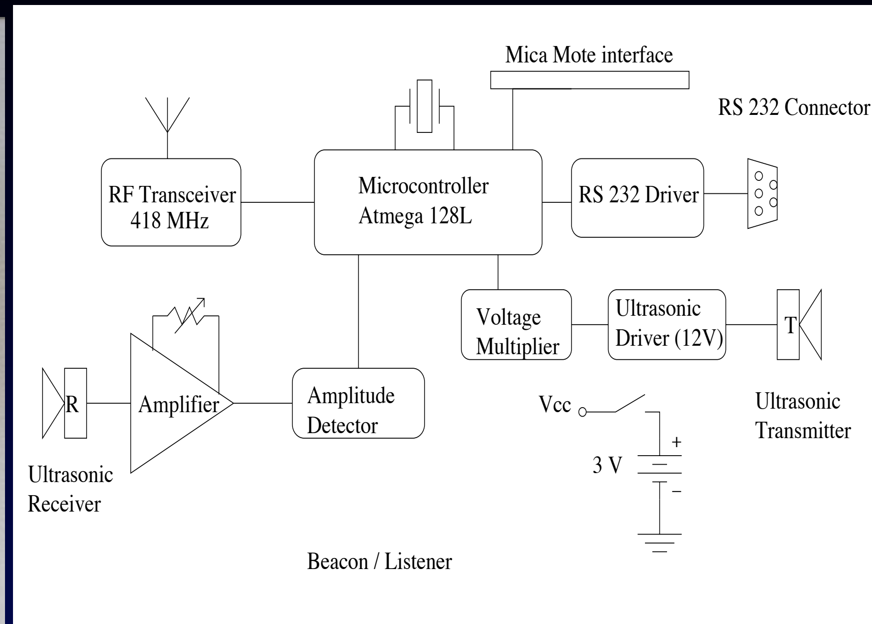
Listener: Extended Kalman Filter

- Single-constraint-at-a-time Kalman filter (similar to Welch et al.)
- Handle non-Gaussian errors
- Cope with bad state
- If prediction consistently bad, then reset by active chirp



Prototype

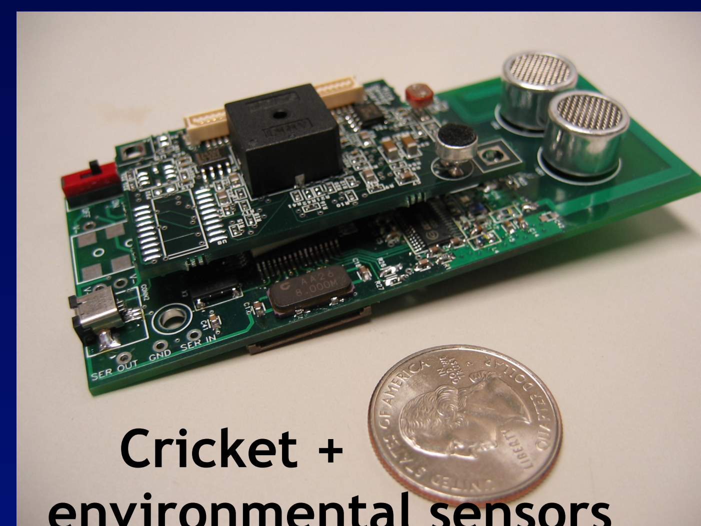




Distance accuracy: 1-5 cm
Position accuracy: 10-15 cm
Orientation accuracy: 3-5 degrees

Beacon power consumption: 1.5 mA @ 2.7 V
Two AA batteries last 6-8 weeks

Embedded software in TinyOS
Commercially available



Demo: Tracking a Moving Robot with Cricket

Other Features of Cricket

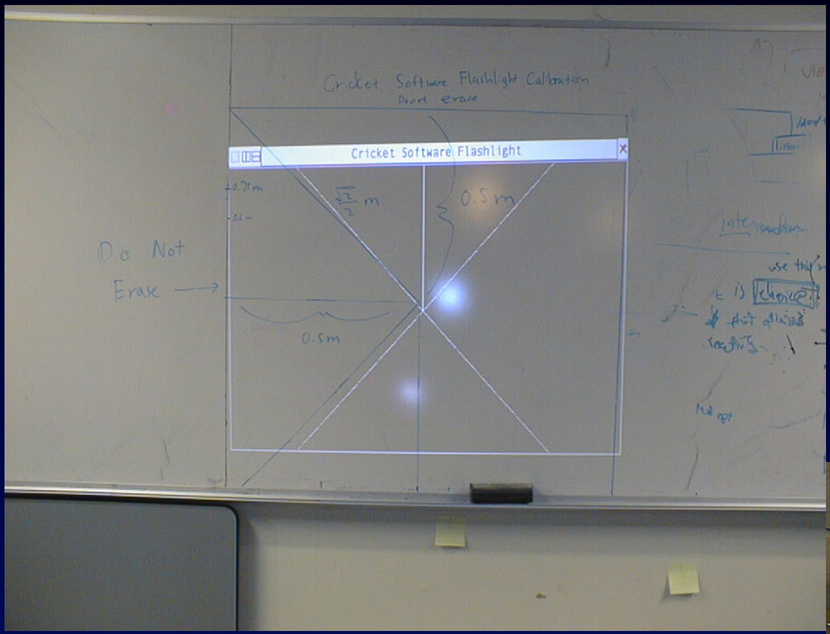
- Orientation
  - Listener ultrasound array for differential distances
- Filtering and tracking algorithms
- Reducing energy consumption
  - Sleep/wakeup scheduling and hardware optimizations
- Health monitoring and maintenance
- Location API

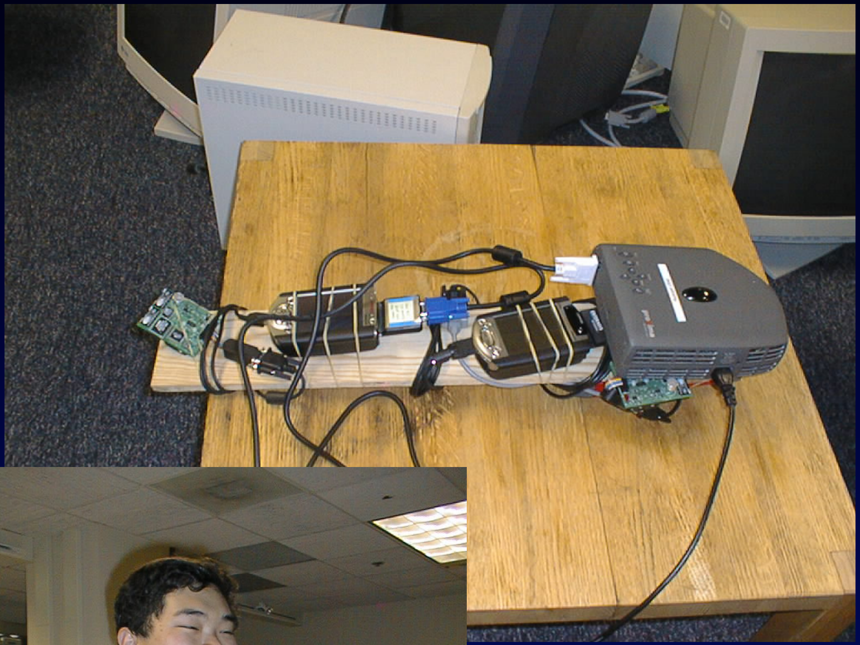
Conclusion

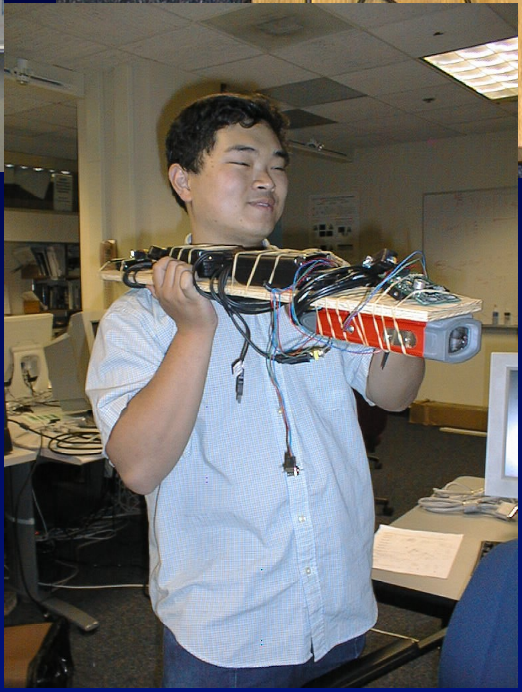
- Key ideas in MobiCom 2000 paper
  - Active beacons, passive listener
  - Notion of *space* as distinct from position
  - Distributed coordination
  - Handling noise in distance estimates
- Cricket provides location information for mobile & sensor computing applications
  - Accurate space, position, orientation
  - Designed for both handheld and sensor apps
- Passive mobile architecture is scalable and helps preserve user privacy
- Hardware commercially available; software open-source

http://cricket.csail.mit.edu/

Pose-Aware Applications



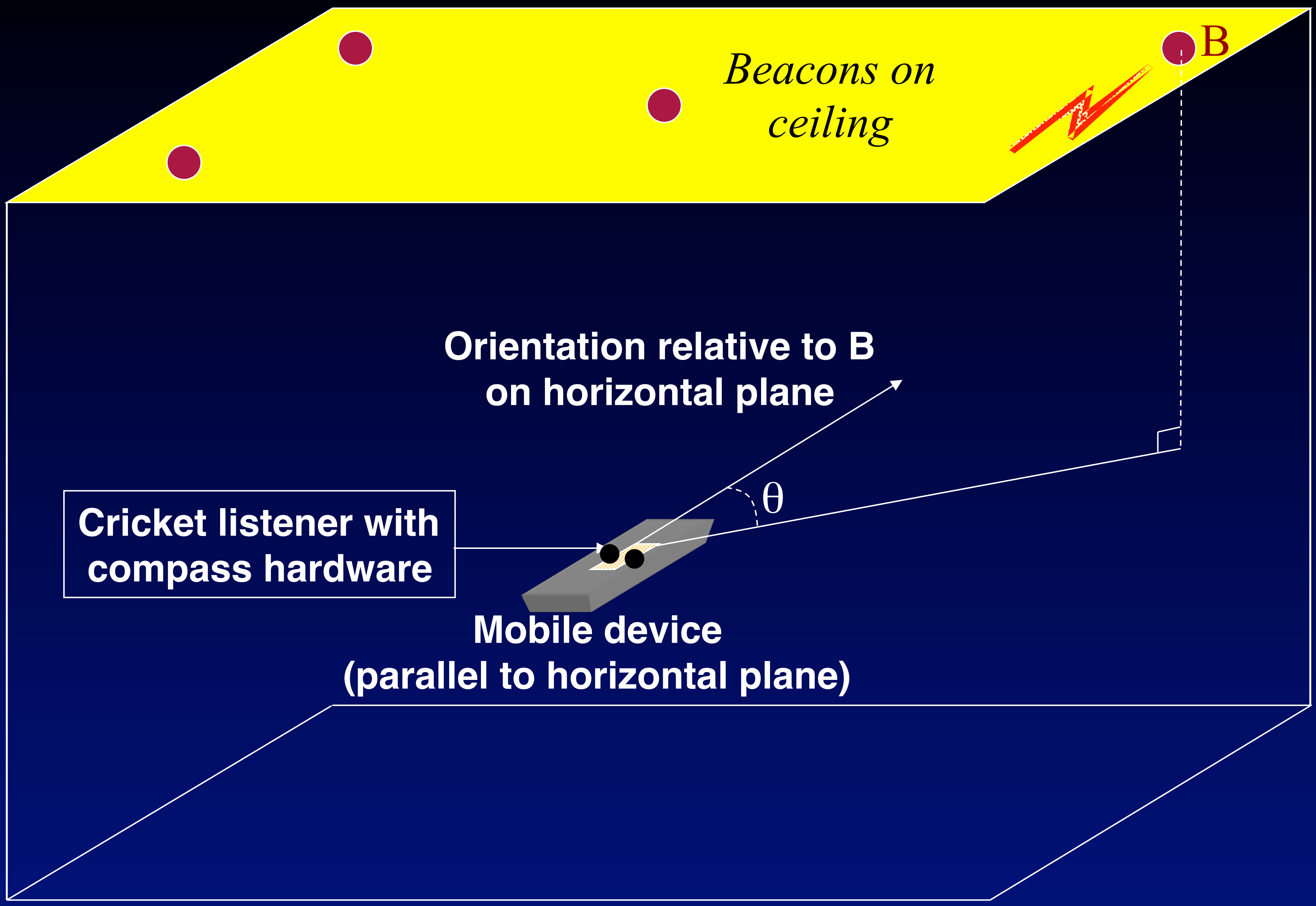




Software flashlight & marker

Teller et al., MIT Project Oxygen

Orientation



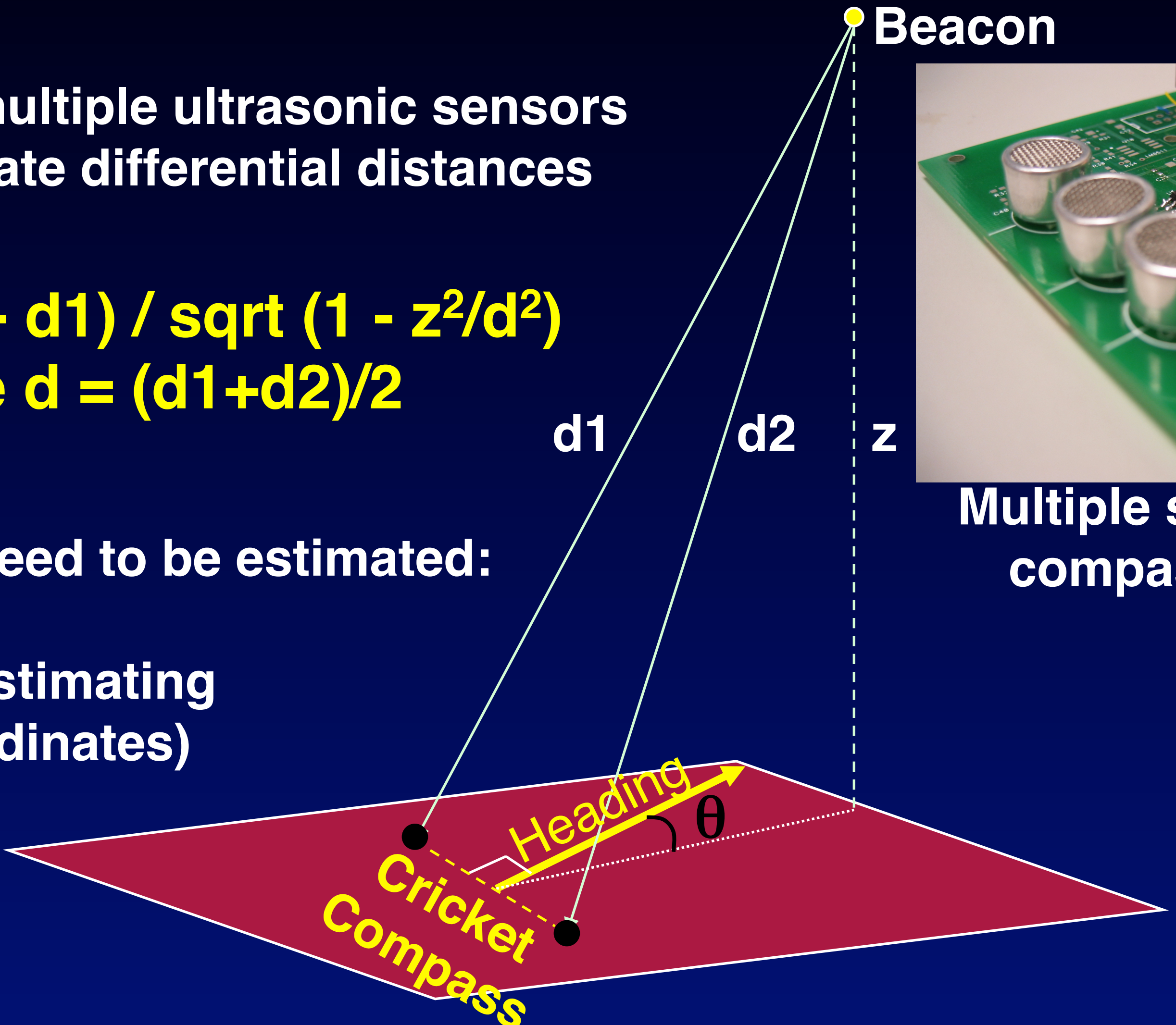
Orientation using Differential Distance

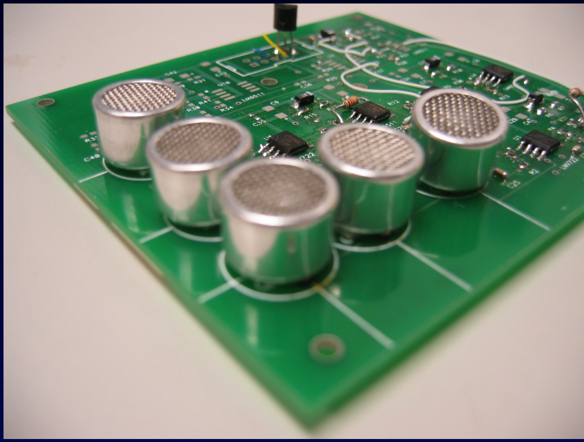
Idea: Use multiple ultrasonic sensors and estimate differential distances

$$\sin\theta = (d2 - d1) / \mathrm{sqrt}\,(1 - z^2/d^2)$$
$$\text{where } d = (d1+d2)/2$$

Two terms need to be estimated:

1. d2 – d1
2. z/d (by estimating coordinates)



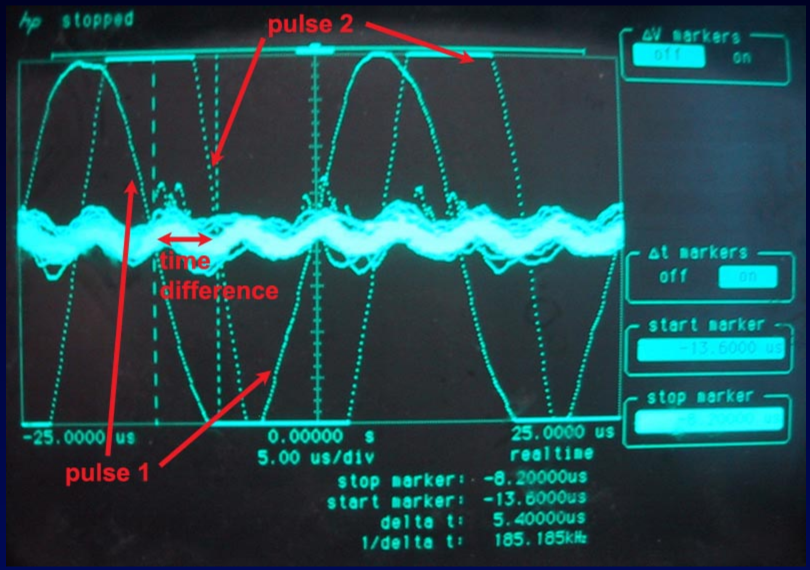


Multiple sensors on compass board

Use phase difference

Differential Distance Estimation

- Problem: for reasonable values of parameters (d, z), (d2 - d1) must have 5 mm accuracy
  - Well beyond all current technologies!



$\phi = 2\pi\,(d2 - d1)/\lambda$

Estimate phase difference between ultrasonic waveforms!