Motion Tracking for Mobile, Location-Aware Applications

Candidacy Exam

Drexel Hallaway
April 5, 2004
Definitions and Scope

- **Motion tracking**
  - The sensors and computations by which a system determines either target’s:
    - Position / orientation in some Cartesian frame; or
    - Proximity to logical entity or resource(s)—“in the copy room...going up the stairs.”

- **Exclusions**
  - Motion Capture (MOCAP) of entire body pose, hand or eye tracking . . . .
  - Some mechanical systems, which seem impossible to use in a broadly mobile context.
  - Pure vision-based tracking.
Motivation

Why do motion tracking?

– To orient oneself with reference to:
  - A virtual model—view control in Virtual Reality (VR).
  - The real world:
    – Navigate with a map.
    – Enhance with virtual augmentations—including view control for virtual overlays.

– To have the free choice to share one’s pose:
  - For remote collaboration—e.g., avatar animation.
  - For personal safety—when dialing 911 on a cellphone.

Emphasis

– Self-tracking—primarily a service for the “target,” not the infrastructure or organization.

– Systems that can meet (or could approach) real-time latencies, and sub-second update frequencies.
Surveys and Filtering

- Welch 2002
- Hightower, 2001
- Welch, 1995

Inertial & Gravimetric

- Sawada 2003
- Foxlin 1998
- Newman 2001
- Priyantha 2000
- Randell 2001

Addlesee 1997

Acoustic

- Judd 1997
- Randell 2003
- Foxlin 1996
- Raab 1979

Magnetic Field

Electromagnetic Spectrum

Light Spectrum

- Golding 1999 (+temp.)
- You 1999
- Foxlin 2003
- Want 1992
- Hallaway 2003
- Welch 1999
- Hedges 2001
- Chinthammit 2003

Visible

Infrared

- Hirose 2003
- Bahl 2000
- Enge 1999
- Wang 2000
- Djuknic 2001
- Soliman 2000

Radio Frequency (RF)
Tethered?

- Some systems require wired connections.
- Mobile users—who may want to leave domain—don’t want to have to detach!

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Who “consumes” the tracking data?

- In self-tracking, the tracked user is making use of his own position / orientation.
- Some alternatives track people for managerial or organizational purposes.
- User privacy is one natural concern.

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“Inside-Looking-Out?”

- Are the sensors moving with the user?
  - The best latency characteristics.
  - Some possibility of user-local processing.
- Another usage of “Inside-Out.”

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Prepared Environment?

Ideally, a tracking system would require no environmental support.
- Some don’t.
- Others use environmental resources user didn’t set up.
- Still others require significant infrastructural investment and installation.

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## Degrees of Freedom Provided?

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<th>3DOF Orientation</th>
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### Notes
- 6DOF: 6 Degrees of Freedom
- 3DOF Position: 3 Degrees of Freedom for Position
- 2DOF Position: 2 Degrees of Freedom for Position
- 3DOF Orientation: 3 Degrees of Freedom for Orientation
- Other: Various authors and years for other applications.
Accuracy Tier?

- Accuracy requirements differ by task.
- Generally, higher accuracy costs in:
  - System price, and/or
  - Elaborate infrastructure, setup / calibration.
- Coarse systems are generally simpler, cheaper, and sometimes sufficient.

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<th>&gt; 5m</th>
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**Mechanical**

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- Soliman 2000

**Radio Frequency (RF)**
Fiberoptic Gyroscope (Sawada, et al., 2002)

- Francis Harress (1911) and Georges Sagnac (1913)—the “Sagnac Effect.”
- FOGs: phase shift $\rightarrow$ rate of rotation around axis.

$$\phi_s = \frac{2\pi LD}{\lambda c} \Omega$$

100m FO coil
Fiberoptic Gyroscope (Sawada, et al., 2002)

- Heading accuracy (drift) spec 1°/hr (σ), actually less.
- Pitch and roll accuracy specified at +/-0.5°, actually <0.1°—but done with a three-axis rate table . . . no lateral accelerations!!
Add Earth’s Magnetic Field
Dead Reckoning (Randell 2003)

- An idea centuries old—ancient mariners . . . .
- Randell presented 4 case studies
  - Opting for cheap sensors, but:
    - Hoping for good step detection.
    - Hoping for accurate heading.
  - Best case study “Garden Path”
    - 2-axis magnetometer taped to shoulder.
    - Two accelerometers, one on each foot.
    - Moderately sophisticated step detection.
    - 126m route tracked at 122m, $\sigma = 2.2m$. 
Dead Reckoning Module (Judd 1997)

- Foot-soldier navigation without holding compass and manually counting paces.
- Tri-axial magnetometers and accelerometers—correct compass for attitude and detect / count paces.

7x23m, plotter filled in gaps
Dead Reckoning Module (Judd 1997)

Works best in concert with GPS:
- GPS-in port.
- GPS corrects when available and accurate.
- DR fills in when not.
- Kalman filter (KF) fuses inputs and adjusts heading and step length.
Kalman Filter (Welch, Bishop, 1995)

- **Rudolph E. Kalman**
  - born Hungary 1930
  - Columbia D.Sci.; 1957
  - seminal paper 1960

- **Recursive solution** he proved optimal to the problem of discrete-data linear filtering, assuming process and measurement noise are:
  - Independent of one another
  - “white”
  - Gaussian / normal (zero-mean)
Kalman Filter (Welch, Bishop, 1995)

- Estimate a constant you can measure directly?
- Equal certainty for each measurement is just a recursive average.

\[
\bar{x}_1 = z_1
\]

\[
\bar{x}_{n+1} = \frac{n}{n+1} \bar{x}_n + \frac{1}{n+1} z_n
\]

\[
\bar{x}_{n+1} = \bar{x}_n + \frac{1}{n+1} \left( z_{n+1} - \bar{x}_n \right)
\]

“gain”  \hspace{1cm} “residual” or “innovation”
Kalman Filter (Welch, Bishop, 1995)

- Different certainties for each measurement?
- Need a “Kalman gain” to weight innovation and express filter’s variance.

\[
\hat{x}_1 = z_1, \hat{\sigma}_1^2 = \sigma_{z_1}^2
\]

\[
\frac{1}{\hat{\sigma}_{k+1}^2} = \frac{1}{\hat{\sigma}_k^2} + \frac{1}{\sigma_{z_{k+1}}^2}
\]

\[
k = \frac{\hat{\sigma}_k^2}{\hat{\sigma}_k^2 + \sigma_{z_{k+1}}^2}, \quad k \in (0,1]
\]

Kalman proved this sort of ‘k’ minimized error in the estimates—the scalar “Kalman gain.”

\[
\hat{x}_{k+1} = \hat{x}_k + k(z_{k+1} - \hat{x}_k)
\]

\[
\hat{\sigma}_{k+1}^2 = (1 - k)\hat{\sigma}_k^2
\]

Same residual . . .

Kalman gain!!
### Kalman Filter (Welch, Bishop, 1995)

**Predict state and covariance**—super-minus means a priori—using state-transition matrix $A$.

$$ \hat{x}_{k+1}^- = A\hat{x}_k $$

$$ P_{k+1}^- = A P_k A^T + Q $$

Remember $\text{cov}(p) = P \rightarrow \text{cov}(Ap) = APA^T$?

We propagate both the state and its error by $A$.

We add $Q$, the process noise covariance matrix.

$$ K_{k+1} = \frac{P_{k+1}^- H^T}{(H P_{k+1}^- H^T + R)} $$

$H$ transforms state to measurement “space”—in which, this looks a lot like the scalar $\sigma$ version before!

$$ K_{k+1} = P_{k+1}^- H^T \left( H P_{k+1}^- H^T + R \right)^{-1} $$

Since we don’t really divide matrices . . . !

$$ \hat{x}_{k+1} = \hat{x}_{k+1}^- + K_{k+1} \left( z_{k+1} - H\hat{x}_{k+1}^- \right) $$

Same as before, except on prediction, not last value…now matrix $K$, and $H$ to get $x$ into measurement space.

$$ P_{k+1} = (I - K_{k+1} H) P_{k+1}^- $$

Rather like before . . . .
Kalman Filter (Welch, Bishop, 1995)

Filter “tuning” is making good choices for process and measurement noise covariances, $Q$ and $R$.

Scalar $R$ is 1 on left, and 0.0001 on right . . . .
Sometimes we can’t measure enough to do a complete state estimate in a given moment.

Waiting for the rest → false “simultaneity assumption.”

Greg Welch coined the term “SCAAT” (single constraint at a time) to describe a using a KF with:

- Different observation matrix $H$ at each step to “strip down” the state to the element(s) measured now.
- $H$ also masks the parts of the covariance and gain matrices the measurement(s) should effect.

Assuming all needed measurement “types” arrive often enough, the filter still converges, and arguably more rigorously.
Can we use KFs on non-linear processes?

The Extended Kalman Filter (EKF) does just that—in an approximate, not theoretically optimal, but often very useful way:

- We use our non-linear process-transition function $f$, where before we had matrix $A$.
- A possibly non-linear observation function $h$ replaces matrix $H$.
- We “linearize” $f$ and $h$ into Jacobian matrices.
- Jacobians propagate the covariance matrices of the filter like $A$ and $H$ before.
- Jacobians are defined by the developer, but get evaluated at each step as a local, linear approximation of the effects of their related functions.
Kalman Filter (Welch, Bishop, 1995)

\begin{align*}
x_k &= f(x_{k-1}, w_{k-1}) \\
z_k &= h(x_k, v_k) \\
\tilde{x}_k &= f(\hat{x}_k, 0) \\
\tilde{z}_k &= h(\tilde{x}_k, 0)
\end{align*}

Vectors \( w \) and \( v \) are process and measurement noise vectors, whose covariance matrices we saw before as, respectively, \( Q \) and \( R \).
Kalman Filter (Welch, Bishop, 1995)

\[
\hat{x}_k^- = \tilde{x}_k = f(\hat{x}_{k-1}, 0)
\]

\[
P_k^- = A_k P_{k-1} A_k^T + W_k Q_{k-1} W_k^T
\]

\[
K_k = P_k^- H_k^T \left( H_k P_k^- H_k^T + V_k R_k V_k^T \right)^{-1}
\]

\[
\hat{x}_k = \hat{x}_k^- + K_k \left[ z_k - h(\hat{x}_k^-, 0) \right]
\]

\[
P_k = (I - K_k H_k) P_k^-
\]

Note that the covariances of noise are now bracketed in Jacobians to propagate their effects—since \( f \) and \( h \) depend on \( w \) and \( v \), respectively, but those values were set to their zero expectations . . . .
Inertial Head-Tracking (Foxlin 1996)

Problem: Drifty gyros and sloshy, fluid inclinometer . . . how to get better results?

Answer: In addition to the 3D orientation state, model the gyro drift/bias as “state” . . . figure out how to correct drift with inclinometer . . . .
Inertial Head-Tracking (Foxlin 1996)

Doesn’t do the conventional, direct Kalman filter (KF)

Rather, a Complementary KF
Inertial Head-Tracking (Foxlin 1996)

- Filter measurement is the sloshy inclinometer and compass inputs.
- Measurement noise covariance $R$
  - Running value for “still time” $\tau$.
  - $\sigma_v = 1 / (1 + 400\tau)$ but if $\sigma_v < 0.01$ then $\sigma_v = 0.01$.
  - Compass gets higher variance.

$$R = \begin{bmatrix} \sigma_v^2 & 0 & 0 \\ 0 & \sigma_v^2 & 0 \\ 0 & 0 & \sigma_v \end{bmatrix}$$
Inertial Head-Tracking (Foxlin 1996)

KF disabled (no residual gain)

KF enabled (gain driven by “stillness”)
Indoors with Cheap Sensors (Golding 1999)

- Indoor, unprepared environment.
- Cheap sensors worn by user:
  - Tri-axial accelerometer and magnetometer.
  - Fluorescent light detector.
  - Temperature sensor.
- Bayesian inferential approach
  - Training on “locations” builds sensor distributions.
Indoors with Cheap Sensors (Golding 1999)

- Tracking samples sensors at 20Hz:
  - Sensor states, previous probability + Bayes’ Rule
- Results:
  - Before “cooking” z-accel-variance, 52% errors!
  - After, 2% error rate, though variance takes longer to respond.

<table>
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<td>2.1 secs</td>
<td>10.5</td>
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Inertial / Dead Reckoning Summary

Huge advantages:

- No environmental preparation.
- Mobile, self-contained.
- Often high update rates.
- Closest thing to a “Silver Bullet” we’ll likely find!
- Self-tracking—no privacy concerns.

Huge problem: Without something absolute to correct them, all truly inertial systems drift.
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Active Floor (Addlesee 1997)

- Mechanical / gravimetric tracking of walkers.
- Load cells at corners of floor tiles.
- Measure vertical component of Ground Reactive Force (GRF).
- Hidden Markov Models try to “recognize” walker.
Active Floor (Addlesee 1997)

- 15 subjects:
  - 20 signature steps each.
  - 10 for training, 10 for testing HMMs.

- Best results (Young’s HTK: HMM Toolkit):
  - Using 7 states, 25 samples / observation, 2-sample overlap.
  - Missed only 13 out of 150 test identifications.

- But, normalizing signatures for weight increased the errors to 50%+!
The “Cricket” (Priyantha 2000)

- World-affixed beacons
  - simultaneous RF and ultrasonic chirp.
  - No central scheduling—randomized either side of 0.25s.
  - Under $10 each, range of ~30’.

- RF carries string for network lookup in Intentional Naming Service (INS)
  - Map
  - Resources

- No central admin, except the INS in this implementation.
The “Cricket” (Priyantha 2000)

- Listeners with RS-232 to mobile.
  - also <$10
  - single-chip RF receiver
  - single-chip tone-detector circuit
- Range from acoustic TOF.
- To determine closest Cricket—proximity.
- How to get closest proximity?
  - Maintained trailing buffer of chirps.
  - Static case: MinMean and MinMode both better than Majority.
  - Dynamic case: MinMode somewhat better than MinMean.
- Can distinguish ~1ft. past baseline between beacons as near as 4’ apart.
Acoustic-Inertial Hybrid
The “Bat” (Newman 2001)

- Infrastructure polls each bat via Wi-Fi (20ms slots).
- Mobile Bat replies with ultrasonic chirp.
- System
  - measures TOF to ceiling receivers.
  - Trilaterates a position—within 3cm, 95% of the time.
- Mobiles get state through CORBA object over network.
- HMD / AR and PDA versions . . . .
The “Bat” (Newman 2001)

**HMD / AR version**
- Helmet, 3 Bats 1 inertial orientation tracker.
- gets consecutive slots for 3 chirps.
- Orientation from 3 positions if coherent.
- Only 2-3 updates per second *from system.*
- Inertial tracker can give 100Hz.
- Fuses inertial tracker—and all updates—using SLERP.

**PDA “Bat Portal”**
- One Bat on Compaq iPAQ.
- Another Bat around neck.
- Head-to-iPAQ ray drives display.
“Constellation” (Foxlin 1998)

- Idea behind IS-600 and IS-900.
- Transponder ultrasonic beacons at modeled poses (typically ceiling).
- Ultrasonic Receiver Modules (URMs) worn by mobile user
  - Excite ceiling transponders with unique IR codes.
  - Time transponder’s chirp TOFs for ranges.
  - arrivals at mobile $\rightarrow$ 0 latency.

Figure 1: General idea of the Constellation$^\text{TM}$ system

Figure 2: Schematic overview of hardware
“Constellation” (Foxlin 1998)

SCAAT EKF fuses inertial inputs with ranges

- Predicts each range.
- Receiver only gated "open" around prediction.
- Throws out suspicious deviations.
- Scalar range → no matrix inversion.

Error sources:
- Beacons' positions mis-modeled.
- Air temperature alters sound propagation vs. model.
- Constant-time delays in beacons/URMs (part-to-part variations).
- Transducers in beacons/URMs off axis.

Simulation accuracy (2m below): 2.5mm; more like 1.5mm with corrections for systemic sources above.
Acoustic Tracking Summary

**Advantage:** An absolute reference with outside world, without physical connection to it.

**Requirements:**

- Something to show when sound left source.
  - In-Out: Mobile Bats chirp upon RF poll (more latency).
  - Out-In, or time reference (less latency):
    - Constellation: stationary beacons chirp upon mobile IR poll.
    - Randell’s low-cost system had 4 stationary beacons chirp at equal intervals after RF “clock ticks.”
    - Cricket chirps and emits RF simultaneously.

- A line of sight from beacon to sensor.
- No jangling keys! ;-)
### Surveys and Filtering

- Welch 2002
- Hightower, 2001
- Welch, 1995

### Inertial & Gravimetric

- Sawada 2003

### Acoustic

- Foxlin 1998
- Newman 2001
- Priyantha 2000
- Randell 2001

### Mechanical

- Addlesee 1997

### Magnetic Field

- Judd 1997
- Randell 2003
- Foxlin 1996
- Raab 1979

### Electromagnetic Spectrum

#### Light Spectrum

- Golding 1999 (+temp.)
- You 1999
- Foxlin 2003

#### Visible

- Want 1992
- Hallaway 2003
- Welch 1999
- Hedges 2001
- Chinthammit 2003

#### Infrared

- Hirose 2003
- Bahl 2000
- Enge 1999

#### Radio Frequency (RF)

- Wang 2000
- Djuknic 2001
- Soliman 2000
Indoor Magnetic Tracking (Raab 1979)

- Imposed magnetic fields:
  - Sequentially.
  - Around source axes x, y and z.
  - One time-slot un-imposed, for room’s ambient field.

- Each field evokes current in the 3-coil sensors.

- Currents modeled as series of frame rotations on a range-attenuated dipole vector.

- 3 coil currents (ambience) X 3 fields, solves 6DOF sensor pose.

- Solution reduces to 9 equations, 6 unknowns, using:
  - Last estimate and deltas presumed small.
  - Small-angle theorem approximations.

\[
H_{\rho} = \frac{M}{2\pi\rho^3} \cos \zeta
\]

\[
H_{\rho} = \frac{M}{4\pi\rho^3} \sin \zeta
\]
Indoor Magnetic Tracking (Raab 1979)

Huge STRENGTH: Unaffected by physical occlusions like the human body! No line of sight requirement!

WEAKNESSES:
- Field strength diminishes with the CUBE of range—these tend not to work beyond 10’, if that.
- Gradient of field strength diminishes with the FOURTH power of range
  - resolution / granularity diminishes as a result: a 1cm motion near the source has much more ratio effect than the same motion further away.
  - A/D converters only have so many bits . . . .
- Metal or other non-earth magnetic sources introduce distortions. DC versions help in some cases, but not in others.

Amusing CAVEAT: Symmetry of fields creates a hemispherical ambiguity—another pose, exactly opposite the current one—where the sensor would have identical readings.
### Surveys and Filtering
| Welch 2002 | Hightower, 2001 | Welch, 1995 |

#### Inertial & Gravimetric
<table>
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#### Acoustic

#### Mechanical

#### Magnetic Field

#### Electromagnetic Spectrum

#### Light Spectrum
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#### Radio Frequency (RF)
|---|---|---|
Active Badge (Want 1992)

- Badges emit IR every 15s
  - encoding a unique ID
  - unsynchronized—cheap components → clock drift and few collisions.

- Custom, inexpensive network
  - controller can poll up to 128 sensors
  - controllers can be aggregated through computer networks for scale-up.

- Stationary sensors buffer up to 20 most recent “sightings” between controller polls.

- System infers coarse proximity from Badge “hits,” and caches recent history.
Active Badge (Want 1992)

- Receptionist immediately loved system.
- Staff grudgingly tried it 2 weeks then voluntarily continued—raise privacy concerns!
- At least three more installations by the time of the paper.

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12.00 1st January 1990
Coarse, Inexpensive IR (Hallaway 2003)
Coarse, Inexpensive IR (Hallaway 2003)

Green: “Intersections” Fragment

Red: “Intersections and Subtractions” Fragment

Blue: “Ellipse of Confidence” around estimate
Coarse, Inexpensive IR (Hallaway 2003)

Red: IR tracker
Blue: InterSense IS-900 “ground truth”

3m
4.5m
Ca. 1 m position accuracy
Ca. 1 s temporal lag

Coarse, Inexpensive IR (Hallaway 2003)
IR Beacon Summary

Want

– Sensors outside:
  - System tracks users.
  - Users initially worry about privacy.
– Target proximity (which room).

Hallaway

– Sensors inside:
  - Mobile user tracks himself.
  - Could protect privacy.
– Coarse Cartesian target position (2D) and orientation (1D).
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Constellation$^{3Di}$ (Hedges 2001)

- Transmitters spin ~40rps
  - Sweeping volume with two angled, planar fans of IR laser
  - Emitting an omnidirectional strobe timing reference.

- Receivers:
  - Sensors are IR-filtered diodes that “see” the fan and strobe “hits.”
  - Board firmware sorts “hits”
    - What transmitter.
    - Which fan or strobe.
    - Temporal basis.
  - Board outputs transmitter-frame angle pair at which fan hits occurred.
Constellation$^{3Di}$ (Hedges 2001)

Software:
- Initially calibrates transmitters
  - Into global reference frame.
- During positioning, calculates rays along which sensor(s) must lie
  - Using known transmitter parameters--fan angles, etc.
- Resolves bundles of rays into closest position in global frame.

Performance: millimeter-level positional accuracy—in the static model, averaging out noise over 2 seconds.
Virtual Retinal Display shares “aperture” with tracker:

- Constant IR “dot” added to visible scan.
- Beam splitter reflects IR component out, and visible light into the eye.
- IR is always collinear with visible ray scanning the retina.
- Sensors in environment.
Structured Light Summary

**Constellation**

- **3Di**
  - Sensors “inside” on tracked user:
    - Can be untethered for mobility.
    - Can protect privacy of the tracked.
  - Volume of tracking is large and constant, given setup.

**SARSDT**

- Sensors “outside” in the environment:
  - Display must be tethered to system for tight synchronization.
  - Volume where tracking occurs at any given moment is the 16.5x6.5° FOV of the VRD!
    - For decent coverage, walls would have to be “carpeted” with sensors.
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HiBall (Welch, Bishop, et al., 1999)

- Dodecahedral device
  - 6 heavily IR-filtered, fixed-focus lenses.
  - 6 LEPDs—fast!

- Ceiling instrumented with IR LEDs.

- 2kHz updates; <1ms latency; <0.2mm and 0.02 degrees noise.
HiBall (Welch, Bishop, et al., 1999)

**Estimation cycle:**
- Random choice of one of 26 FOVs.
- Flash least-recently used LED in the ceiling projection of its LEPD.

**SCAAT EKF**
- Separate KF state for each LED appended to tracking KF.
- Predict image-plane projection of LED.
- Apply gain to residual of measurement.
- Update LED calibration along with tracking estimate.
- Save LED corrections to its own filter.
VIS-Tracker (Foxlin 2003)

- InertiaCube with 1/3” CCD.
- CCD exposure and transfer takes 40+ms, but allows for absolute correction.
- InertiaCube updates every 8ms, based on 1920Hz sampling.
- **Accuracy on the order of 1cm during walking.**
Outdoor Orientation (You 1999)

- Calibrating, controlling or modifying the outdoors is unrealistic.
- Outdoor views are often at long ranges, affected:
  - greatly by orientation.
  - little by small changes in position.
- Outdoor orientation tracking in unprepared environment?
  - 3 rate gyros—sampled at 1kHz.
  - Compass and tilt sensor.
  - Sony camera.
Outdoor Orientation (You 1999)

- Compass fused with gyros:
  - 16Hz vs. 1kHz updates \(\rightarrow\) compass corrections 92ms into past.

- Camera-inertial fusion:
  - Camera maintains set of world points / features.
  - Inter-frame pixel velocities correct inertial system, based on inertially projected pixel velocity:

\[
\Delta \omega = A^{-1}(x^I - x^C)
\]

Registration error averaged 4.27 pixels over sequence, or \(~0.4^\circ\)!
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RFID for Deaf-Blind (Hirose 2003)

- Problem: Leading and tracking the deaf-blind.
- 1349 active, battery-powered RFID tags:
  - embedded in 1700m² floor.
  - emitting unique IDs at 5Hz.
  - ~1.2m range to antennae.
- Worn antenna vest.
RFID for Deaf-Blind (Hirose 2003)

- N new readings $\Rightarrow$
- $\sigma = \sim 0.4m$, recording positions at 10Hz.

\[
x(t) = \frac{1}{n+1} \left\{ x(t-1) + \sum_{i=1}^{n} u_i \right\}
\]
“RADAR” Wi-Fi Location (Bahl 2000)

- Wireless NIC drivers expose:
  - Signal strength (SS)—correlated well with range.
  - Signal-to-noise ratio (SNR)—did not.

- Multiple base stations → trilateration on ranges.

- Empirical strategy:
  - Sample environment, building table of (mean) tuples: position, direction, station, SS, SNR.
  - Track by using table match(es) closest in SS space.
  - Got best results [median error 2.5m] using 2-4 multiple-nearest-neighbor tuples, and the maximum of the four directions’ SS (vs. single nearest neighbor and worst-case direction).
“RADAR” Wi-Fi Location (Bahl 2000)

Radio Propagation Model:

\[ P(d) = P(d_0) - 10n \log\left(\frac{d}{d_0}\right) - \begin{cases} 
  nW \cdot WAF : nW < C \\
  C \cdot WAF : nW \geq C 
\end{cases} \]

- Tests found \( C = 4 \), \( WAF = 3.1\text{dBm} \), and \( \Rightarrow \)
- Median results were not that much worse than empirical, 4.3m median error.
- Saves hugely on preparation, if you have a map and an algorithm to compute wall intersections.
Global Positioning System (Enge 1999)

- **Simple Position:**
  - Data message includes satellite time.
  - 4+ satellites → 4+ equations, 3 unknown ranges, 1 unknown clock offset. Solved clock offset gives approximate transit time.
  - Receiver knows pseudorandom noise (PRN) Coarse/Acquisition (C/A) spread-spectrum code modulated on signal.
  - Autocorrelation of its own C/A copy has a sharp peak.
    - Refines transit time mod 1ms.
    - Ideally yields meter-level ranging.
Simple *Velocity*:
- Another loop monitors carrier phase and Doppler shift.
- Doppler shift is satellite-receiver velocity projected on line of sight.
- Four such velocities, and known satellite positions, allow ground velocity calculation.

Precise UTC *time* is just the bias-corrected receiver time plus leap-seconds that differentiate GPS time from UTC.
Global Positioning System (Enge 1999)

GPS precision depends on:

- Geometry (GDOP)
  - The more orthogonal the ranges used, the more accurate the fix.
- Number of satellite ranges available.
- Ionospheric and tropospheric distortions of the velocity of light.
Augmentations to GPS reduce error further.

- Differential (DGPS): land-based radio stream of error corrections gives \(~1\text{m}\) accuracy.
- Real-Time Kinematic (RTK)
  - specialized receiver monitors \textit{carrier} phase.
  - Phase offset is good, but which wave iteration?
  - Land-based radio stream helps resolve integer ambiguity.
  - Upon convergence, yields precision of \(~5\text{cm}\).

- WAAS: \textit{Geosynchronous} satellites over US:
  - Are themselves serving as additional pseudoranges.
  - Broadcasting differential corrections.
  - Yielding \(~1\text{-}3\text{m}\) accuracy—FAA approved for many landings now.
Cellular / PCS

E-911 Legislation

- Since October 1, 2001:
  - Networks must be able to locate all cellphones:
    - 95% within 300m.
    - 67% within 100m.
  - Cellphones with ALI (automatic location identification):
    - Must be available, and 50%+ of activations.
    - 95% must be locatable within 150m.
    - 67% must be locatable within 50m.

- Since October 1, 2002, 95%+ of cellphone activations must be ALI-capable units.
How are networks accomplishing this?

- Can’t forbid use of old handsets.
- Angle of arrival (AOA) to towers.
  - Requires carefully calibrated antenna array.
  - Even then less definite a solution.
- Time of arrival (TOA) or Time difference of arrival (TDOA) to towers.
  - Requires tight time synchronization.
  - CDMA already has such synchronization.
  - GSM / TDMA networks can use various strategies.
- Multipath / RF “fingerprinting” of locations in database.
- Providing GPS-capable handsets with Assisted GPS.
Assisted GPS (AGPS)

- These handsets have a full or partial GPS receiver.
- Conventional receivers take minutes to establish fix on weak satellite signals:
  - Uncertain frequencies (Doppler)
  - Uncertain PRN C/A code phase.
- AGPS networks send GPS acquisition data over the air
  - lowers GPS acquisition time to seconds—or less.
  - Allows acquisition of lower-powered signals that with a conventional receiver—some are using language about indoor GPS acquisition.
gpsOne™ (Soliman 2000)

How else can networks help GPS? By treating towers as pseudolites.

Qualcomm’s CDMA strategy is already:
- Precisely time-synchronized.
- On GPS time.

Figure 1: RTD measurements at serving base station

Figure 2: RTD to other base stations
gpsOne™ (Soliman 2000)

\[ \sigma = 19\text{m}, \text{ just resolving clock} \]
\[ \sigma = 88\text{m}, \text{ clock fix, plus extra range} \]
\[ \sigma = 139\text{m}, \text{ clock fix and two extra ranges} \]
Radio Frequency Analysis

- **RFIDs** provide close-range proximity detection:
  - In sufficient densities even Cartesian tracking can happen.

- **Wi-Fi lateration** useful but coarse:
  - Might be interesting to hybridize it with, say, inertial techniques.

- **GPS** is proven and *improving* technology:
  - Removal of SA, and the emergence of WAAS are significant!
  - Poor reception areas will be ever with us, though.

- **Given convergence trends,** cellphone tracking offers interesting possibilities, but:
  - Will positioning data be ported to expert users of phones?
  - Will network operators merely sell location-specific services—
    even advertisements?
The future of tracking in the marketplace of the “common man” will likely:

- Leverage techniques that:
  - Require no environmental preparation; or
  - Take advantage of infrastructures already in place.
- Not offer anything like the “state of the art” we like to expect in our professional laboratory settings.
- Require using multiple strategies in parallel or sequence for:
  - Broad mobility; and
  - Continuous coverage.
- Benefit hugely from the increased quality of hybrid combinations over standalone techniques.
Closing Ponderings

As a result, several lines of research look promising and useful:

- Investigating hybrid strategies not already “done to death.”
- “Meta-tracking” strategies to
  - Manage multiple tracking technologies;
  - Coordinate “handoffs” between them over transitions; or
  - Filter their simultaneous usage; and
  - Maintain some technology-global sense of variance.
- Adaptive UIs that
  - Make the most productive choices about how to present information, given current services and their accuracies;
  - Don’t “promise more than they are delivering” in real time, in terms of accuracy of location awareness.
  - Do give intuitive cues to users about the extent that the current system’s state can be trusted.
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