Mobile Sensing: Leveraging Mobile Phones to Support Personal, Community, and Participatory Sensing

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CENS Urban Sensing collaborators also include: Mark Allman, Dana Cuff, Jerry Kang, Vern Paxson, Fabian Wagemister,
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Many critical issues facing science, government, and the public call for high fidelity and real time observations of the physical world.

Embedded sensing systems:

reveal the previously unobservable

help us understand and manage interactions with physical world, scarce resources, and one another.
Embedded networked sensing is revealing previously unobservable phenomena

**Embedded** in the physical environment

**Networked** to share information/adapt

**Sensing as in measurement**

- **Handheld Sensing**
  - human participation, reality checking, etc.

- **Remote Sensing**
  - Overlaying the “big picture” on local events

- **Robotic Mobility**

- **Static Sensing**
  - Stationary sentinels, continuous in time
Lessons from the field 2002-2008

Early themes
- Thousands of small devices
- Fully autonomous systems
- Specially-designed and deployed hw

New themes
- Systems of heterogeneous devices
- Humans and models in the loop
- Leverage available devices
Interactive systems take advantage of human observation, actuation, and inference

- Analogous to MRI technology
- Expands the types of sensors that can be used
- Leverages many data sources and models: remote sensing, geographic information system, ...
From ecosystems... to human systems

Automatically-generated, geocoded, data streams from individuals promises to make visible human concerns that were previously unobservable... or unacceptable

Urban sensing applications will leverage the millions of mobile-phone location, acoustic, image and bluetooth-connected sensors, as well as proliferation of geospatial and mapping data and tools
Imagine if….

Our everyday cell phones would alert us when we are exposing ourselves to unhealthy environmental conditions, just as they now alert us to traffic jams on the highway.
Mobile Sensing

Enabled by $2 \times 10^9$ mobile phone users, increasingly with:
- Digital imagers, location (GPS, cell tower), bluetooth connected sensors
- Automatic-geocoding of data
- Programmed, user-initiated, or server-initiated capture
- Server-side processing and presentation of personal data

Motivated by $6 \times 10^9$ people on planet earth and their concerns...
- Individual health and wellness
- Public health, urban planning, epidemiology
- Civic concerns (transportation, safety, culture...)
- Resource management
Neighborhood Walkability for Urban Planning

Kim, Kim, Petersen, Arab, Burke, Estrin, Goldman...
Exposure Assessment

Personal Environment Impact Report

How I interact with the environment...

GPS data from a Nokia mobile phone is used to derive the following results.

- **Impact**
  - Rank 3 of 5 friends.
  - Me: 4.60
  - Friends: 4.60

- **Exposure**
  - Rank 5 of 5 friends.
  - Me: 87.76
  - Friends: 86.39

Current as of: 01/29/2008 02:31:42

A CENS project powered by Nokia
Exposure to Traffic-related Pollutants

Lifelong damage found in 13-year study of 3,600 Southland youngsters living within 500 yards of a highway. The Los Angeles Times, 1/26/07

Figure 2. Prevalence of asthma by distance of residence to a major road within 500 m, among long-term (A) and short-term (B) residents with no family history of asthma. Dotted lines indicate 95% confidence interval.

Implications of Scale and Zone Selection

- Health affected by “complex interactions between genetic and environmental factors”

- Measurement scale affects detection of relationships between exposure and health outcomes
  - Aggregation may obscure significant intra-county variation in exposure.
  - Disease incidence reported at county level ... therefore, environmental exposure data should be aggregated at the same resolution.


Example of the zoning effect on mortality events within a unit.
Merging models and sensing
Personalized Environmental Impact Report (PEIR)

- Personalized daily assessment for individuals and communities to reduce impact and minimize exposure
- Users view their own practices and habits as seen in data and inferred from models
- Employ built-in capabilities of mobile handsets to scale without specialized hardware
- Leverage model-based analyses of location traces generated using GPS, GSM cell tower, WiFi

Server side tools: analyze individual spatio-temporal patterns, activity-annotate location trace, calculate exposure/impact metrics, generate reports/visualizations, support exploratory data analysis

Burke, Estrin, Hansen, et al
Sunday, August 10, 2008
Estimating Pollution without Pollution Sensors

- Users location traces are sampled and timestamped
- CO2 and PM2.5 emissions are computed as a function of speed and weather conditions using Emission Factor (EMFAC) model
- Sensitive sites impact is computed using PM2.5 emission and location information
- PM2.5 exposure is computed using historic traffic conditions
- Fastfood exposure is computed using location information
Personal Environmental Impact Report: 4 examples

Illuminate our individually-made, globally-felt choices through daily assessment of personal environmental impact and exposure, using data sensed by mobile handsets.
Powering Personal Choice for Global Impact

PEIR, the Personal Environmental Impact Report, is a new kind of online tool that allows you to use your mobile phone to explore and share how you impact the environment and how the environment impacts you.

What's unique about PEIR? Taking a step beyond a “footprint calculator” that relies only on your demographics, PEIR uses location data that is regularly and securely uploaded from your mobile phone to create a dynamic and personalized report about your environmental impact and exposure.

How PEIR Works

PEIR gives you greater control over your environmental impact and exposure by allowing you to interactively explore how it creates its results from your activity patterns.

Join PEIR

We're currently in private beta, but sign up to get notified when PEIR is open for new user registration. Also, feel free to check out the demo.

FEATURED

Press Release: UCLA Researchers Create PEIR Using Cell Phones as Sensors

We unveiled our new tool this week to help you understand your relationship with the environment, and we want to know what you think.

PEIR News

PM 2.5 Exposure Model Values

Since the PEIR launch, we have noticed some small bugs related to our modeling computations. But instead of blocking

Eric Howard, Vinayak Naik, and the PEIR Team
June 18, 2008
- User interface designed to promote data exploration and legibility
- User’s data exploration begins with trip log
  - List of trips sortable by model (e.g., most carbon impact or most particulate matter exposure); can also be filtered by trip type
  - Calendar used to advance directly to specific points in time
- Modest Maps library supports freedom to adjust colors, layout, and overall style—promotes good design practice, useful visualization
PEIR Processing

Raw Location Data

<table>
<thead>
<tr>
<th>Longitude</th>
<th>Latitude</th>
<th>Timestamp</th>
</tr>
</thead>
<tbody>
<tr>
<td>-118.499</td>
<td>34.15867</td>
<td>2008-05-23 08:32:46</td>
</tr>
<tr>
<td>-118.4936</td>
<td>34.15858</td>
<td>2008-05-23 08:33:16</td>
</tr>
<tr>
<td>-118.4983</td>
<td>34.15865</td>
<td>2008-05-23 08:33:46</td>
</tr>
<tr>
<td>-118.498</td>
<td>34.15845</td>
<td>2008-05-23 08:34:16</td>
</tr>
</tbody>
</table>

Processing

Visualization
Processing of Data

- Emission annotation: Compute CO2 and PM2.5 emission using EMFAC mode
- PM2.5 exposure annotation: lookup traffic density and compute PM2.5 exposure
- Fastfood and Sensitive sites annotation:
  - Lookup number of fastfood and sensitive sites using maps
  - Compute fast-food exposure and sensitive sites impact
- Trip chunking: Divide traces into trips when there is a gap in the data or change in the activity
- Aggregation over trips: Aggregating impact and exposure values for each trip
- Aggregation over time: Aggregating impact and exposure values over day, week, month, and year
- GIS data used: pier_freeway, lastreets, and scag_area for map matching and activity classification; weather, weather_stations, ca_zippoly, and ca_zip_to_station for weather annotation and emission annotation
- am_roads, md_roads, pm_rodads, and nt_roads: Used by pm2.5 exposure annotation; fastfood and sites_buffer for fastfood and sensitive sites annotation
Weather Calculations

Location Trace Processing

Location Trace

Zipcodes + 5 Nearest Weather Stations

Weather Station Data

<table>
<thead>
<tr>
<th>Station ID</th>
<th>Timestamp</th>
<th>Temp (K)</th>
<th>R.H.</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAI</td>
<td>2006-05-23 08:00:00</td>
<td>272.372</td>
<td>79%</td>
</tr>
<tr>
<td>PANW</td>
<td>2006-05-23 08:00:00</td>
<td>252.039</td>
<td>19%</td>
</tr>
<tr>
<td>PPRC1</td>
<td>2006-05-23 08:00:00</td>
<td>279.817</td>
<td>37%</td>
</tr>
<tr>
<td>CN01</td>
<td>2006-05-23 08:00:00</td>
<td>268.786</td>
<td>81%</td>
</tr>
</tbody>
</table>

Trip Aggregation

Trip | Avg Temp | Temp S.D. | Avg R.H. | R.H. S.D.
-----|----------|-----------|----------|----------
2752 | 284.68   | 1.9556    | 92.08%   | 2.7526   |
3059 | 293.97   | 2.7501    | 67.26%   | 9.7105   |
3345 | 296.29   | 3.3123    | 95.48%   | 11.88
PM 2.5 Exposure Calculations

Location Trace Processing
Location Trace + Weather + Activity Classification

Trip Aggregation

Road Buffers

Trip Summary

EMFAC

E. Howard, V. Naik

Sunday, August 10, 2008
PM 2.5 Impact Calculations

Location Trace Processing
Location Trace + Weather + Activity Classification

School and Hospital Locations

Name
Westwood Elem.
Overland Elem.
Century City Hosp.

Type
School
School
Hospital

EMFAC

User Table
IMEI               Vech. Type       Vech. Year
10101010101010101  LDA              2002
20202020202020202  LDA              2003
10000000000026351  LDT1             2005

Trip Aggregation

Lat.  Lon.  Speed (MPH)  Temp (K)  R.H.  Act. Class
34.045257  -118.447998  75  282.039  80%  Driving
34.045795  -118.448588  49  282.039  80%  Driving
34.02837   -118.42833   34  284.817  78%  Driving

Lat.  Lon.  PM 2.5 (g/sec)  Sites (Count)
34.045257  -118.447998  0.000044  0
34.045795  -118.448588  0.000032  1
34.02837   -118.42833   0.000046  0

Trip Summary

Trip  PM 2.5 Emissions (kg/sec)  Sites (Count)  Impact (hours)
2432  0.00123  0  0
2423  0.03456  2  0
2410  0.00456  1  0

PEIR U.I.

E. Howard, V. Naik

Sunday, August 10, 2008
Fast Food Exposure Calculations

Location Trace Processing

Location Trace

Lat. 34.048257, Lon. -118.447998
Lat. 34.045795, Lon. -118.445858
Lat. 34.02637, Lon. -118.429833

Fast Food Buffers

Name
Restaurant 1
Restaurant 2
Restaurant 3

Trip Aggregation

Trip Duration (hours) Time spent near fastfood (hours)

<table>
<thead>
<tr>
<th>Trip</th>
<th>Duration</th>
<th>Near Fastfood</th>
</tr>
</thead>
<tbody>
<tr>
<td>2432</td>
<td>0.45</td>
<td>0.03</td>
</tr>
<tr>
<td>2423</td>
<td>0.25</td>
<td>0.10</td>
</tr>
<tr>
<td>2410</td>
<td>0.15</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Trip Summary

<table>
<thead>
<tr>
<th>Name</th>
<th>Lat.</th>
<th>Lon.</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Restaurant 1</td>
<td>34.048257</td>
<td>-118.447998</td>
<td>2</td>
</tr>
<tr>
<td>Restaurant 2</td>
<td>34.045795</td>
<td>-118.445858</td>
<td>0</td>
</tr>
<tr>
<td>Restaurant 3</td>
<td>34.026370</td>
<td>-118.429833</td>
<td>0</td>
</tr>
</tbody>
</table>

PEIR U.I.

E. Howard, V. Naik

UCLA USC UCR CALTECH UCM

Sunday, August 10, 2008
Carbon Dioxide Impact Calculations

Location Trace Processing
Location Trace + Weather + Activity Classification

EMFAC

User Table
IMEI  Vech. Type  Vech. Year
101010101010101  LDA  2002
202020202020202  LDA  2003
100000000026351  LDT1  2005

Trip Aggregation

Lat.        Lon.        CO2 (g/sec)
34.048257  -118.447998  8.7116699
34.045795  -118.445858  16.179814
34.02637   -118.429833  14.578712

PEIR U.I.

Trip Summary

Trip  Trip Duration (hours)  CO2 Emissions (kg)
2432  2.61               14.01
2423  0.35               2.17
2410  0.1                0.58
Hardware Requirements

- **Current**
  - Symbian S60 third edition/Windows Mobile phones with data plan or WiFi
  - GPS capability (either built in to the phone or via an external GPS device)
  - GPS
  - Web access

- **Future**
  - Ability to input location traces in the maps on computers
Sampling and Uploading of Data

- Campaignr software samples data every 30 seconds
- Starting and stopping Campaignr: 3 button pressings
- Data is confidential
- Data is transferred in JavaScript Object Notation (JSON): more efficient wire format compared to XML

JSON String:
{"index__":"187","timestamp":"2008-06-23T13:12:57.123375-07:00","location":
{"country_code":"310","network_id":"260","location_area_code":56,"cell_id":60442,"signal_strength":84,"signal_bars":7}
A week in PEIR
Problems of total time/space accountability

Prevents “little white lies” for convenience, social cohesion

Potential chilling effect on legal but stigmatized activities

Safety concerns

Social discrimination:
Employment, Economic, Health care

Los Angeles Times

http://www.latimes.com/news/columnists/la-fi-lazarus6apr06,1,6618279.column
From the Los Angeles Times

ZIP Code still a factor in auto insurance

David Lazarus
Consumer Confidential

April 6, 2008

Center News
April 29, 2008

New Study Finds California Neighborhoods "Designed for Disease"
Designing for privacy from the ground up:

Share derived statistics instead of raw traces

Detailed data only accessible to individual

Illustrated in this *Facebook* sharing application
### Breakdown

For trip #1505 : Saturday, August 09 2008 : 5:46 AM to 6:31 AM

The table explains the transformations that are applied to your data to give you your final statistics for impact and exposure. The process is broken into a series of steps, with each step determining and passing along new information about your data. When all the pieces are in place, PEIR will generate the final statistics and display them on your profile page.

<table>
<thead>
<tr>
<th>Step</th>
<th>Procedure</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>trace analysis</strong></td>
<td>Phone Data (\rightarrow) Location Trace in DB</td>
<td><strong>Start:</strong> 5160 Chesebro Rd, Agoura Hills CA</td>
</tr>
<tr>
<td></td>
<td>After collecting location data throughout the day, your phone connects to</td>
<td><strong>End:</strong> 9044 Sepulveda Westway, Los Angeles CA</td>
</tr>
<tr>
<td></td>
<td>the PEIR server and uploads your data. Your data (simply represented as</td>
<td><strong>Duration:</strong> 45m</td>
</tr>
<tr>
<td></td>
<td>points and the times at which you were at those points) is entered into a</td>
<td><strong>NOTE:</strong> The resolved address above is subject to inaccuracy from both</td>
</tr>
<tr>
<td></td>
<td>database where it will be processed by the modules that make up the PEIR</td>
<td>GPS drift and the coarseness of the reverse geocoding process. For</td>
</tr>
<tr>
<td></td>
<td>system. At this point, your points are broken up into &quot;trips&quot;, sequences</td>
<td>instance, you may find that the address specified is down the block</td>
</tr>
<tr>
<td></td>
<td>in which you are traveling from one place to another, or simply staying</td>
<td>from your actual position, or even on another street. In any case, the</td>
</tr>
<tr>
<td></td>
<td>still. Your online PEIR Profile displays these trips, as well as statistics</td>
<td>address is provided for your convenience and is not used in any of the</td>
</tr>
<tr>
<td></td>
<td>computed on a per-trip basis by the following modules.</td>
<td>calculations.</td>
</tr>
</tbody>
</table>

| freeway annotation | Freeway Maps \(\rightarrow\) Freeway- Annotated Trace                     | **Freeway Usage:** 0% (incorrect for now)                              |
|                    | To determine your exposure to pollutants as well as your impact, PEIR    |                                                                       |
|                    | must determine how much of your trip was spent on a freeway. In order   |                                                                       |
|                    | to do this, each point of your trace is compared against a map of       |                                                                       |
|                    | freeways and is classified as being either on or off a freeway.         |                                                                       |

F. Alquaddoomi, J. Burke, M. Hansen, R. West, N. Yau

Sunday, August 10, 2008
A first cut at describing PEIR alpha-trial usage patterns:
Compare number of days (6/9-8/9) that 17 users uploaded data (x-axis) vs. number of days they viewed their data (y-axis)

Two users with very high data views but moderate upload counts were a special cases: “test user” whose data was examined by many system developers, and a “demo user” whose data are available for anyone to view on the PEIR website
Rate at which each involvement group accessed their data over time; each curve is cumulative number of accesses for PEIR alpha users, with demo user (top gray curve) and test user (bottom gray curve) indicated.

While even the medium and low involvement users have relatively flat curves, most do not flatten out completely, indicating that they have not stopped visiting the site entirely.

Hansen, Wang, Yau

Sunday, August 10, 2008
Depth of involvement with the UI

**Left:** average number of times each uploaded trip is viewed by participants, stratified by low, medium and high involvement users

**Middle:** median age (in days) of trips viewed in the UI; two of our heavy involvement users appear to be making comparisons with somewhat old data, perhaps viewing UI as systems developers not true PEIR users

**Right:** median trip size (in uploaded GPS points) for each user; some of the low-engagement users uploaded some fairly long trips, but for just a handful of days ("depth" of engagement measured in terms of the days over which users were active, not volume of data transmitted)
UCLA Researchers Create Personal Environmental Impact Reports Using Cell Phones as Sensors

LOS ANGELES, Jun 16, 2008 (BUSINESS WIRE) -- UCLA researchers unveiled a new tool this week to help people understand their relationship with the environment. The Personal Environmental Impact Report (PEIR) (http://peir.cens.ucla.edu/) lets users see online how their daily choices affect the environment and how the environment affects them, by providing personalized, daily estimates of measures like particulate matter exposure on roadways and carbon emissions due to driving. PEIR was developed by the Center for Embedded Networked Sensing (CENS) at the UCLA Henry Samueli School of Engineering and Applied Science in collaboration with the Nokia Research Center, Palo Alto.

PEIR estimates impact and exposure using the actual travel patterns of its users, as uploaded from their GPS-equipped mobile phones. Accepted scientific models, like the California Air Resources Board's Emissions FACTors (EMFAC) vehicle emissions and Southern California Association of Governments traffic models, are used to calculate estimates specific to the user's travel. On the PEIR site, users can compare values for different trips and see how lifestyle changes affect their impact and exposure. They can also compare their averages with other PEIR participants in their Facebook social network.

By employing only the increasingly common location sensing capabilities of modern phones, CENS wants PEIR and projects like it to work on the devices that people already own and use. The project is part of the CENS urban and participatory sensing research program, which aims to make everyday mobile phones act as sensors and collect data for their owners. Applications for participatory sensing range from community "casemaking" to systems like PEIR, which promote personal engagement and reflection.
YouTube Video on PEIR
Can we also leverage mobile devices to support more effective care for *aging in place*?

**Automatic data collection from consumer grade devices**
(mobility, automatic images, acoustic signatures)

+ 

**Legible presentation via Web based applications**

= 

**Consumer-oriented (incrementally adoptable, affordable, and usable), individualized, solutions**
Thought experiment (i.e. we haven’t tried any of this yet):
Activity and mobility profiles for those *aging in place*?

- Observe patterns and trends in *indicative* activities of aging participants:
  - timing and frequency of trips to store, social activities, exercise routines
  - daily patterns of time spent in kitchen, dining area, TV room, bath/bedroom...

- Outdoor: time series of GPS and cell tower data points, combined with map matching

- Indoors: accelerometers and bluetooth stumbling
Social interaction: an interesting indicator at all stages of life

- Co-location interaction patterns give insights for families
- Near term: use bluetooth proximity
- Mid term: Estimate frequency, duration, trends in human communication using audio samples
  - Program phone to automatically capture short audio snippets (avoid content)
  - Process locally/on-server to detect patterns of interactive communication (distinguish from TV, Radio; phone, in person)
- Observe aggregate data to identify sudden or significant changes in social contact and interaction

http://www.kt.tu-cottbus.de/speech-analysis/
Urban Sensing: Research Challenges

Scaling and credibility.

- Coordinated, opportunistic sampling.
- Network attestation and verification of location, time, and other context.

Encouraging sharing.

- Data protection and selective, resolution-controlled dissemination.
- Participatory privacy
- Anonymous and pseudonymous participation.
- Reputation, incentive, and authoring frameworks.

Finding, visualizing, and analyzing data.

- Data stream naming, privacy-respecting discovery, and signal search.
- Server-side signal processing for data processing, browsing, and auditing.
- Spatial interfaces to data and authoring.

Infrastructure for capture, review, processing.

- Adaptive collection protocols.
- Automatic feeding of data to models.

Privacy isn’t a separate concern...

*it’s embedded in the sensing and research activities...*

*it has variable meaning in specific circumstances and settings...*

*it will skew participation and data collection*
Conclusion:
Rationale and precedent for leveraging mobile devices

If you can’t go to the field with the sensor you want... go with the sensor you have! (Anon)

The power of the Internet, the reach of the phone (Voxiva)
CENS Vision...

create programmable distributed observatories to address compelling science and engineering issues...and reveal the previously unobservable.

From the natural to the built environment...

From ecosystems to human systems...
Acknowledgments

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