Real-Time Avalanche and Landslide Analysis through Sensor Networks with High Speed Local Positioning

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Goal

- **What we want to do**
  - Analyze the dynamics of an avalanche or a landsliding mass in real time

- **Where**
  - In a controlled environment
  - In the field

- **Why**
  - To gain insight into currently unknown phenomena (scientific)
  - To model and validate novel sensor network paradigms (scientific)
  - To gain experience in distributed warning and monitoring systems for life saving purposes (social)
Analytical Modeling

1-dimensional: Sliding block model

\[ \frac{d^2 \zeta}{dt^2} = g \sin \theta(\zeta) - \frac{F_t}{m}. \]

2D: « shallow-water » (flow-depth averaged) model

\[ \frac{\partial h}{\partial t} + \frac{\partial h \overline{u}}{\partial x} = 0, \]

\[ \ddot{\varrho} \left( \frac{\partial \overline{h u}}{\partial t} + \frac{\partial \overline{h u^2}}{\partial x} \right) = \ddot{\varrho} g h \sin \theta - \frac{\partial \overline{h \dot{p}}}{\partial x} + \frac{\partial h \overline{\sigma_{xx}}}{\partial x} - \tau. \]

3D: none

[Ancey 04], [Ancey 109]
Numerical Modeling

**Slope conditions**

- **Bulk weight**: 25 kN/m³
- **Rock friction angle**: 23°-40°
- **Cohesion**: 1Pa – 1 MPa
- **Young Modulus**: 100 MPa
- **Pore pressure**: Reservoir and groundwater
- **Failure surface friction angle**: 8.74°
- **Cohesion**: 0.15 Pa
- **Reduction factor for FS**: 0.38
Warning Systems

Catastrophic event: 5min
Event evolution: 4months

Origin of landslide

Damaged area

Five-point earth shift

Precipitation

Δt – 10 days
Motivation for Using Sensor Networks

- Upon appropriate design, SN nodes can take strategic positions within avalanche/landslide front, body, and tail and *move with it*

- With high speed, precise positioning, nodes can rely on physical quantities to verify and improve theoretical models

- Through self-organized nature of SN, deployment and measurement is seamless

- Nodes can be deployed for months, thus enabling to monitor precipitation and other parameters

- Long-term deployment enables warning systems
Proposed Approach

- Self-organized SN of reinforced nodes with OD antennas
- Local positioning system (LPS)
  - Reverse-GPS TOA on medium bandwidth RF system (less accuracy)
  - Direct-GPS TOA on single photon optical channel (LoS)
  - ps accurate time discrimination
- Transponder-like position update in nodes using RF com-link
Technical Challenges and Solutions

- **Optical TOA**
  - 30ps precision time discrimination at the node
  - Multireflection
  - Fading, range
  - Approach: Single Photon Avalanche Detectors (SPAD) rangefinding [Charbon JSSC 05]

- **RF TOA**
  - Arrival of frequency pulse in presence of multipath
  - Approach: mix of classical detection and Finite Rate of Innovation (FRI) based rangefinding [Vetterli 05]

- **Time discrimination**
  - 30ps accuracy time differential
  - Approach: Time-to-digital Converter (TDC) rangefinding [Charbon ISSCC 05]
Expected Outcome & Scientific Contribution

- Through off-board optical/RF LPS, a real-time high-precision positioning estimation will be possible in a self-organized SN

<table>
<thead>
<tr>
<th>Specification</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>-</td>
<td>3</td>
<td>10</td>
<td>cm</td>
</tr>
<tr>
<td>Accuracy</td>
<td>-</td>
<td>3</td>
<td>10</td>
<td>cm</td>
</tr>
<tr>
<td>Update Rate</td>
<td>1</td>
<td>10</td>
<td>33</td>
<td>s(^{-1})</td>
</tr>
<tr>
<td>Range</td>
<td>250</td>
<td>500</td>
<td>1000</td>
<td>m</td>
</tr>
<tr>
<td>Number of nodes</td>
<td></td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Speed</td>
<td>1</td>
<td>10</td>
<td>20</td>
<td>m/s</td>
</tr>
<tr>
<td>Acceleration</td>
<td></td>
<td>9.81</td>
<td></td>
<td>m/s(^2)</td>
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</table>

- For the first time, a number of FRI theoretical results will be tested on a self-organized SN, evolutionary FRI will be tested
- For the first time, inner-dynamics in avalanches and landslides will be studied in detail
- Potential impact in landslide/avalanche and warning systems
## Envisioned Cooperations

<table>
<thead>
<tr>
<th>University/Lab</th>
<th>Projects</th>
<th>Contact Person</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC/LCAV</td>
<td>FRI theory and instruments</td>
<td>Dr. L. Sbaiz</td>
</tr>
<tr>
<td>ENAC/INTER/TOPO</td>
<td>Indoor navigation, localization for isolated workers, and general navigation algorithms</td>
<td>Prof. B. Merminod</td>
</tr>
<tr>
<td>Università degli Studi di Milano Bicocca</td>
<td>Landslide Dynamics Modeling</td>
<td>Prof. G. Crosta</td>
</tr>
<tr>
<td>Norwegian Geotechnical Institute</td>
<td>Slope stability, Slide Dynamics</td>
<td>Dr. P. Gauer</td>
</tr>
<tr>
<td>Technische Universiteit Delft</td>
<td>Natural Disaster Hazard and Risk Analysis</td>
<td>Prof. J. K. Vrijling</td>
</tr>
<tr>
<td>WSL</td>
<td>Rockfalling Dynamics Modeling</td>
<td>B.W. McArdell</td>
</tr>
<tr>
<td>University of Ljubljana</td>
<td>Flood Analysis and Warning</td>
<td>Prof. M. Brilly</td>
</tr>
</tbody>
</table>
BACKUP
## State-of-the-art in Positioning Systems

<table>
<thead>
<tr>
<th>Technology/ Technique</th>
<th>System</th>
<th>Range [m]</th>
<th>Resolution [m]</th>
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<tbody>
<tr>
<td>TOA</td>
<td>GPS (worldwide)</td>
<td>&gt;1000</td>
<td>0.1~10</td>
</tr>
<tr>
<td>IEEE 802.11 / TOA</td>
<td>TI</td>
<td>&lt;30</td>
<td>0.5~1</td>
</tr>
<tr>
<td>IEEE 802.11 / RSS</td>
<td>“RADAR” (Microsoft)</td>
<td>&lt;100</td>
<td>~5</td>
</tr>
<tr>
<td>915MHz / RSS</td>
<td>TinyOS LPS (UCB)</td>
<td>&lt;15</td>
<td>~3(?)</td>
</tr>
<tr>
<td>IEEE 802.11 / RSS</td>
<td>Robotic-Based Location Sensing (Rice)</td>
<td>&lt;10</td>
<td>~1.5</td>
</tr>
<tr>
<td>BT / CWPS</td>
<td>BlueSoft (Commercial)</td>
<td>&lt;30</td>
<td>1</td>
</tr>
<tr>
<td>5.8GHz / RFID tags</td>
<td>PinPoint/ WhereNet</td>
<td>120</td>
<td>1~3</td>
</tr>
<tr>
<td>RSS</td>
<td>SpotON (U. Washington)</td>
<td>&lt;4</td>
<td>~1</td>
</tr>
</tbody>
</table>
Reinforced Node

- Symmetrically damped package to sustain acceleration and speed
- All solid-state components, possibly a single chip
- Optical detectors mounted on shell
- Spherical antenna deposited on shell
LPS by Way of Reverse GPS

- Position is computed using the difference in TOA
  - If emitters and receivers are synchronized at least 3 beacon stations are needed to compute position uniquely
  - Else, at least 4 beacons are needed
LPS by Way of Reverse-GPS (Cont.)

- Detect TOA of a train of M cycles originated by the node

Problems
- Exact pulse detection
- TX, RX, and Channel distortion, Multipath and fading
Pulse Detection

- **M = 1, classic method**
  - Threshold $\rightarrow t$
  - Error: $\sigma(d) = c/B$
  - E.g.: $B=192MHz \rightarrow \sigma(d) = 1.6m$

- **M > 1,**
  - Sample $N$ times $x_R = [x_{R1}, \ldots, x_{RN}]^T$
  - $N$ samples are fitted to delayed transmitted signal $A\sin(\omega t + \varphi)$
  - $A$ and $\varphi$ are computed solving $\hat{p} = (M^T M)^{-1} M^T x_R$

$$M = \begin{bmatrix}
sin \omega t_1 & \cos \omega t_1 \\
\vdots & \vdots \\
sin \omega t_N & \cos \omega t_N
\end{bmatrix}$$

Error: $\sigma(d) \approx c \sqrt{\frac{1}{N\pi f} \frac{\sigma_n^2}{A^2}}$

E.g.: $\text{SNR}=80\text{dB}, N=192,$
$B=192\text{MHz} \rightarrow \sigma(d) = 8cm$
But…

- Distortion, multipath, fading prevent accurate detection of first pulse

- Possible solutions:
  - Use pseudorandom sequences
  - Finite Rate of Innovation concepts
Pseudorandom Coding

Scheme:

Choose $a(nT)$ s.t. $R_{aa}(nT) \approx \delta(nT)$

TX interpolator

Consecutive TOF signals can be resolved in $1/B$ seconds

E.g.: 10cm multipath resolution will require $B=3$GHz
Finite Rate of Innovation (FRI) and Evolution

- The method enables high resolution with fewer samples, provided one knows how many peaks P to expect.
- If one underestimates P, then TOA may be inaccurate.
- Else, spurious TOAs are added.
- For infinite SNR, P can be estimated exactly by checking when matrix no longer well-conditioned.
- For finite SNR boundary is fuzzy.
- Possible solution:
  - Use a mix of classical and FRI detection.
  - Reduce uncertainty of well-conditioned detection.