Collaborative Effects of Distributed Multimodal Sensor Fusion for First Responder Navigation

Jim Kaba, Shunguang Wu, Siun-Chuon Mau, Tao Zhao
Sarnoff Corporation

Briefed By: Jim Kaba
(609) 734-2246 jkaba@sarnoff.com
Overview

• Sensor-independent distributed multimodal sensor fusion framework for improving navigation accuracy
  – Theoretical & analytical models and simulations of how performance scales versus
    • Different algorithms
    • Different sensor error models
    • Varying numbers of users

• Practical navigation algorithm and system design
  – Excellent implementation characteristics
  – Capable of achieving predicted error reduction effects

• Collaborative Error Reduction Effects -- Exploit the collaborative nature of team-oriented operations
  – Teamwork Effect
    • Enables firefighters operating in groups to achieve better navigation accuracy than when operating individually
  – Anchor Effect
    • Flexible use of minimal numbers of Deployable Anchor Nodes as RF navigation reference beacons
  – Reset Effect
    • Immediate opportunistic accuracy gains under common conditions
Motivation: GPS-denied Navigation

• GPS is not always available
  – Weak signal, corrupted signal, no signal
  – Urban Canyons, Indoors, Underground
  – Jammed and/or spoofed

• Significant challenges or complications
  – Cluttered RF & magnetic environment
  – Size, Weight and Power (SWaP) and Cost issues
  – Mobility
  – Pragmatic operational use and deployment constraints for certain applications

Hostile operating environment compounded by mission constraints
Locatus System Design Goals

**Target Application:** Dismounted Warfighter Navigation in a fully GPS-denied Environment

- Provide absolute & relative 3-D position to ground forces for:
  - Individual warfighter navigation
  - Team coordination with neighbors (fireteam, squad, platoon)
  - Position status updates to command / headquarters

- Support Military Operations on Urban Terrain
  - Outdoor urban areas, building interiors, subterranean environments...and open areas

- Maintain strict position accuracy
  - 25m SEP after traveling 20km over 8hrs => 0.125 % “system error”...while GPS-denied

- Man portable; size, weight and power restrictions
  - < 400cm³ & < 1kg per unit, battery powered
  - Associated pragmatic operational constraints

Strong match to Firefighter requirements
Locatus System Overview

...a multimodal position/navigation system for GPS-denied environments*...

Primary Subsystem Components

- Inertial Navigation System
  - 3-axis accelerometer, rate sensors, magnetometers, pressure altimeter
- Inter-node Distance Measurement
- Inter-node Data Communications Network

*Illustrated as a man-portable position/navigation system for GPS-denied urban operations. System approach and algorithms can be applied to heterogeneous combinations of aircraft, vehicles, UAVs, UGVs, munitions, etc.
Concept of Operation

- Each firefighter wears a Mobile Locator Node
  - Inertial Navigation System + RF Ranging & Comms
- Deployable Anchor Node(s) positioned around the periphery of the operational area (optional, mission-permitting)
  - RF Ranging + Comms
  - Provides a framework of RF “beacons” at known locations
- Firefighters move into the GPS-denied operational area
  - INS tracks 3-D location (with some error)
  - RF Ranging Radios track inter-node (Anchors and Firefighters) distances (with some error)
  - Locatus system fuses inertial and RF position estimates, appropriately weighted for operational & error characteristics
- Firefighters move deeper into the GPS-denied operational area
  - Warfighters deploy additional Anchor Nodes as needed to maintain RF measurement connectivity with external framework
- Throughout the incident response
  - 3-D position estimate is maintained with bounded (but growing) error as the incident progresses (with time, distance, constrained operational areas)
  - Situational Awareness (navigation capability and accountability) is provided throughout incident for firefighters and command structure
Sarnoff’s Technical Approach

Continuous, real-time fusion of error-prone position estimates from multiple technologies to achieve accurate absolute & relative location, navigation & mapping capabilities

• Distributed fusion of multiple position / location / navigation modalities
  – Multiple sensors on each warfighter/platform and across multiple warfighters/platforms

• Exploit the complementary nature of sensor’s operational characteristics and errors
  – Absolute vs. relative, localized vs. distributed, range unlimited vs. tethered, long-term drift vs. short-term random error

• Use dynamic and continuous cross-modal feedback to bound system errors
  – Detect & minimize errors, constrain measurements

• Achieve graceful (vs. catastrophic) degradation of system performance over time & distance as dictated by the mission

- Use dynamic Bayesian (belief) network to build a graphical model of inferred node location
  – Intractable joint probabilistic distribution of all node locations & uncertainties is factored into a combination of simpler local distributions
Multimodal Fusion Algorithm Overview

Issues:
- Performance
- Computation
- Overhead
- Scalability
- Reliability
- Communications
- Fault-tolerance
- Overhead
- Scalability
- Reliability
- Communications
- Fault-tolerance

Family of Inference Methods

- Iterative
- Extended
- Non-parametric
- Markovian
- Gaussian
- Approximate
- Neighbor

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Arrows connote added assumptions/constraints
iEKF Fusion Algorithm Data Flow

- Formulated as a rapidly converging, iterative, message-passing algorithm

Nodes individually estimate their position & certainty using localized sensors (INS, altimeter)

Nodes exchange their estimates with neighbors

Nodes refine their estimate using neighbor’s estimates and inter-node range constraints

Nodes repeat the exchange/refine cycle multiple times

• Comparable performance to centralized/optimization algorithms
Multimodal Fusion: Implementation Benefits

- Provides accurate Absolute and Relative Positioning
  - Using real-world sensors under real-world conditions

- Sensor flexibility
  - Robust to varying inertial sensor noise/performance models
  - Easily extensible to include additional individual and distributed sensors
  - Handles asynchronous sensor inputs
  - Tolerates inaccuracies of inter-node range constraints
    - Achieves low overall position error even with low-accuracy ranging
    - Accurate positioning even as RF range measurement accuracy fluctuates due to obstructions and multipath interference in urban environment
  - Tolerates variations in inter-node ranging interval
    - Minimal effect on the absolute system accuracy, minor (short term) effect on relative accuracy

- Superior implementation characteristics:
  - Algorithm is naturally fully distributed
  - Scalable, robust to dynamic changes in # of users
  - Iterative algorithm rapidly converges in steady state operation
  - Computation and communication are inherently localized to nearest-neighbors
  - Communication load is well within the “Kbps” constraints of tactical military radios
The Teamwork Effect

• The Locatus “Teamwork Effect” enables warfighters operating in groups to achieve significantly better navigation accuracy than when operating individually.

• Opportunistic Peer-to-Peer Ranging Constrains INS Drift
  – Range estimate between two warfighters serves as a “Wireless Tether” between them and bounds their otherwise independent drifts.
  – Using multiple inter-asset range estimates constrain INS drift further.

• Teamwork Effect holds as team size varies
  – Single pair to large groups

\[ \varepsilon(n, s) \propto \varepsilon(1, s) / \sqrt{n} \]

• i.e. Position accuracy improves by a factor \( \sqrt{n} \) for an n-node group.

• General performance prediction guideline for distributed multimodal fusion.
Absolute Position Accuracy

**Tight grouping of performance results for four fusion algorithms**

**Centralized vs. Distributed; Optimization vs. EKF**

**Substantial (2-3 X) performance increase even with a small size network**

**Systematic error reduction with increasing network size**

INS Stds: \( \sigma_{dx} = 0.2 \text{m}, \sigma_{dy} = 0.2 \text{m}, \sigma_{dz} = 0.001 \text{m}, \text{MSSI std } \sigma_d = 1 \text{m} \)

**Error vs. Time for varying team sizes**
The Teamwork Effect: Simulation Validation

- Validation of the “Teamwork Effect” error scaling law
- $1/\sqrt{n}$ reduction in system error with a team of “n” collaborating nodes
- Robust to variations in multimodal fusion algorithm
- Robust to variations of inertial sensor noise model (not shown)
Relative Position Accuracy

INU-only (ZUPT sqrt(d) inertial drift):
- Relative position error exceeds 30m SEP after 20 km & 4 hrs GPS-denied

Multimodal Fusion:
- Relative position error bounded to a constant level < 1m SEP after 20 km & 4 hrs GPS-denied
- Even with high-error INS exceeding 400m a relative error ~2-3m SEP achieved (not shown)
The Anchor Effect

• Deployable Anchor Node
  – Reference beacon deployed at fixed location
  – Zero INS drift error: position estimate (and error) remains constant
  – Anchor point for mobile nodes whose position estimates degrade with time/distance

• Deployed opportunistically (pre- or during mission) as stationary wireless tethers and communication relay nodes
  – Self-calibration of deployed nodes based on best location estimate available at the time of deployment

• The use of even a single Deployable Anchor Node can increase system accuracy by a factor of 2 to 3

• The use of two Deployable Anchor Nodes can bound absolute system error to <1m SEP

• Contrast with classical Time Difference of Arrival (multilateration) and Time of Arrival (trilateration) approaches that require at least 4 constraining measurements
The Anchor Effect: Simulation Validation

Absolute Position Accuracy Shown

- **1 Anchor** → 2-3X performance improvement
- **2 Anchors** → Constant, low level error 1-2m SEP
The Reset Effect

• Locatus’ continual refinement of position estimates can result in estimates that improve, rather than degrade, over time
  – The inaccurate position estimates of Mobile Locator Nodes are “reset” to a lower level in the middle of a mission even after those errors have grown
  – Provides immediate, rather than gradual, improvement of the estimate accuracy

• “Reset Effect” conditions:
  – a) A Mobile Locator Node whose position error has grown establishes contact with a stationary Deployable Anchor Node. The mobile node’s position estimate, and its confidence in accuracy of that estimate, will improve
  – b) A Mobile Locator Node whose position error has grown establishes contact with another Mobile Locator Node with a better location certainty
  – c) An individual or a small group of Mobile Locator Nodes merges with another group of Mobile Locator Nodes, forming a larger group allowing for collectively better error performance (e.g. due to the “Teamwork Effect”)

• The “Reset Effect” is demonstrable for Deployable Anchor Nodes and large groups of Mobile Locator Nodes

• The “Reset Effect” enables teams of warfighters that split into subgroups and merge some time later to regain the same level of positioning performance as if they had not split
The Reset Effect: Simulation Validation

- Simulation results support the Locatus “Reset Effect” by which system errors can actually decrease over time.

Example: Encounter with Anchor Node(s)

Opportunistic encounter with 1 or 2 anchor nodes resets error to a lower level.

Unaided Operation

RF-aided Operation

Contact with Anchor

Error “Reset” 1 and 2 Anchors
The Reset Effect: Simulation Validation

- Simulation results support the Locatus “Reset Effect” by which system errors can actually decrease over time

### Example: Team Split/Merge

<table>
<thead>
<tr>
<th>Teams</th>
<th>Error</th>
<th>&quot;Reset&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>8-node</td>
<td>&quot;Reset&quot;</td>
<td>8-node teams operate independently</td>
</tr>
<tr>
<td>2 teams merge</td>
<td>&quot;Reset&quot;</td>
<td>Two 4-node teams merge</td>
</tr>
</tbody>
</table>

### Absolute Error

### Relative Error

*Affects not just error rate (curve slope), but absolute level as well!"
Summary

• **System Design & Multimodal Sensor Fusion Framework**
  – Sensor independent
  – Excellent implementation characteristics

• Exploits the collaborative nature of team-oriented operations
  – Expected performance trends & behaviors

• **Teamwork Effect** – Firefighter position accuracy can improve through collaboration with other mobile nodes
  – ...without additional infrastructure requirements

• **Anchor Effect** – When reference beacons can be used, they can be used
  – In minimal numbers
  – With flexibility, deployed at any time

• **Reset Effect** – Position accuracy need not be constantly degrading
  – Improvements over time can be expected
End of Brief...

Jim Kaba
(609) 734-2246
jkaba@sarnoff.com