Actuated Sensing Systems for High Fidelity Environmental Monitoring

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DCOSS
Monitoring Environmental Phenomena

• Global climate change
  – Changing habitats
  – Impact on water supply
  – Impact of pollutants on soil and air quality

• Drought: monitoring water resources
  – Agricultural use
  – Manufacturing
  – Drinking water

• Terrestrial and Aquatic related phenomena
  – Solar light radiation
  – Carbon dioxide flux
  – Nitrate
  – Chlorophyll
  – Specific conductivity
Environmental Phenomena Classification

Spatial Dynamics

Temporal Dynamics

terrain, plant distribution

terrestrial, plant distribution

solar light distribution, CO₂ flux, algal blooms
Dynamic Environmental Phenomena

- Characteristics
  - Highly dynamic in space and time

- Distribution of solar light radiation under a forest canopy
  - Motivation: study plant distribution
  - Bracken ferns: invasive species, indicates health of a forest ecosystem
  - High spatial sensing density is required to achieve the desired fidelity
    - On a centimeter scale over 1000 m² area

Objectives

Problem
• How do we efficiently monitor dynamic spatiotemporal phenomena over large spatial domains to achieve high fidelity reconstruction?

Compare four existing environmental sensing techniques
  – Static Sensing
  – Deterministic Actuated Sensing
  – Adaptive Sensing
  – Multiscale Sensing

Comparison in simulation using field data
  – Performance analysis: number of observations, execution time
  – Analyze performance when vary robot speed and number of robots
Existing Methods: Static Sensing (SS)

- **Implementation** – Network of static sensors is deployed throughout the environment of interest

- Static sensor networks used in a broad range of environmental monitoring applications
  - Obtaining accurate hydrological models for avalanche prediction\(^1\)
  - Studying carbon dioxide flux of moss in a forest\(^2\)
  - Studying spatial and temporal variation of soil respiration\(^3\)

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Existing Methods: Deterministic Actuated Sensing (DAS)

- **Implementation** – A mobile robot actuates along a uniform path over the entire environment of interest

- Used by application domain scientists in data acquisition campaigns\(^1\)\(^-\)\(^3\)

Existing Methods: Adaptive Sensing (AS)

- **Implementation**
  - Mobile robot first performs a coarse scan to extract regions of high phenomena variability
  - Based on a threshold limit or a model, regions of high phenomena variability (high variance) are selected and sensed with higher and higher density, increasing overall sensing fidelity

Existing Methods: Multiscale Sensing (MS)

- Environmental Phenomena
- First Tier: Global View
Existing Methods: Multiscale Sensing (MS)

First Tier: Global View

Environmental Phenomena

Task Extraction
Existing Methods: Multiscale Sensing (MS)

- First Tier: Global View
- Task Extraction
- Task Prioritization
- Task Allocation
Task Prioritization and Allocation

- Prioritize tasks based on largest area

- From the set of prioritized tasks, a set of assignments is computed

\[ \forall a \in A a = \arg \max_{n=(1,\ldots,|R|)} (U(r_n, k)) \]

where \( k \) is the next unassigned task according to criterion C and \( U(r_n, k) \) is the \( n^{th} \) resource (robot) utility value (distance of robot to the task) for accomplishing \( k \)

- Assign highest priority task to nearest robot
- Commitment policy
Existing Methods: Multiscale Sensing (MS)

Environmental Phenomena

First Tier: Global View

Task Extraction

Task Prioritization

Task Allocation
Experiments Comparing Algorithms

Parameters:
- Area 6 m x 4 m
- Sensor measurement time = 30 μs
- Robot speed = 15 cm/s
- Number of robots = 1

For the image:
- Comparison metric = percent root mean square error (RMSE)
  - 100% RMSE of image calculated when no observations are made
  - Five error thresholds: 5%, 10%, 20%, 30%, and 40% of the previously calculated RMSE value
Comparing Number of Observations and Execution Time

- **MS** performs the best
- **AS** requires fewer observations than **DAS**
- Execution time of **DAS** is less than **AS**

Results: $DAS = SS$

Execution time of $SS = 30 \mu s$
Comparing Execution Time when varying Robot Speed

- **MS** performs the best
- Relative performance of **AS** and **DAS** changes depending on required reconstruction fidelity
Multi-Robot Performance for MS

- Execution time decreases until minimum execution time is reached – time required to service the largest task
- As RMSE increases, advantage gained from multiple robots decreases
- Further improvement is possible if large tasks are subdivided into smaller tasks
Conclusions

• Compared several classes of algorithms using the application of solar light radiation
• Implemented representative versions of Adaptive Sensing and Multiscale Sensing without optimizations
• Results can be generalized to other phenomena characterized by spatial and temporal dynamics over large spatial domains
• Multiscale Sensing consistently outperforms the other classes of sensing algorithms
Thank you!

Questions

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