3D-CHESS: Decentralized, Distributed, Dynamic, and Context-aware Heterogeneous Sensor Systems – Preliminary Results

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Why 3D-CHESS?

Overarching Goal: To provide **proof of concept** (TRL 3) for a **context-aware** network of **heterogeneous** sensors, in the context of an **inland water ecosystem monitoring** mission

- Inland water bodies can dramatically change states within minutes to hours.
  - These changes are increasingly extreme and difficult to predict due to climate change.
- Need for high spatial, temporal, and/or spectral resolutions, from **heterogeneous** sensors.
- To monitor and respond to a dynamic environment, significantly more **autonomy** is needed in the Earth observing systems.
- Autonomy requires **context awareness** and **decentralized** coordination.

	State of practice	State of research	3D-CHESS
Context information used for planning	Own state	Own state **Earth system state (from own measurements)**	Own state **and capabilities** Earth system state (from own and others' measurements) **Others' states and capabilities**
Sensors and platforms	Homogeneous	Homogeneous or **Heterogeneous**	**Heterogeneous**
Mission	Single Static Objective	Single **Dynamic** Objective	**Multiple** Dynamic Objectives
Planning strategy	Centralized	Centralized or **Decentralized** with predefined functions	**Decentralized**

Example Mission: River Flooding

- River level can change dramatically in a matter of minutes after heavy rainfall – poses a significant challenge in **temporal resolution**
- The majority of Earth's rivers – especially those sensitive to flash floods – are not visible at coarser **spatial resolution**
- Many types of instruments can observe river extent (visible and infrared) and river height (altimeters) – making this perfect for a **heterogeneous** sensor web
- Most of the world's rivers, especially in less developed nations, are **ungauged and unmonitored**
- Total suspended sediment (TSS) changes with river level – how do floods affect **water quality**?

- **Question:** With a decentralized, distributed, dynamic and context-aware heterogeneous sensor system, how many more floods can we observe than the current remote sensing status quo?

- Pedernales State Park, TX

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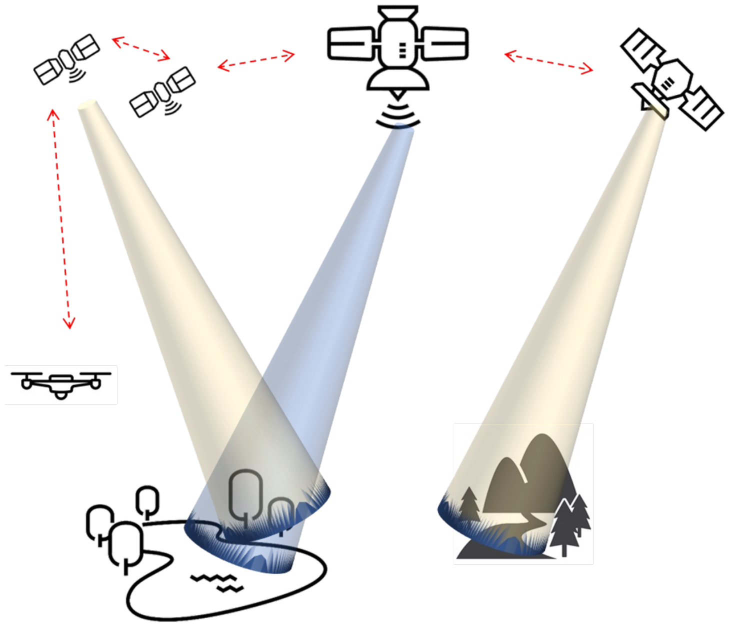
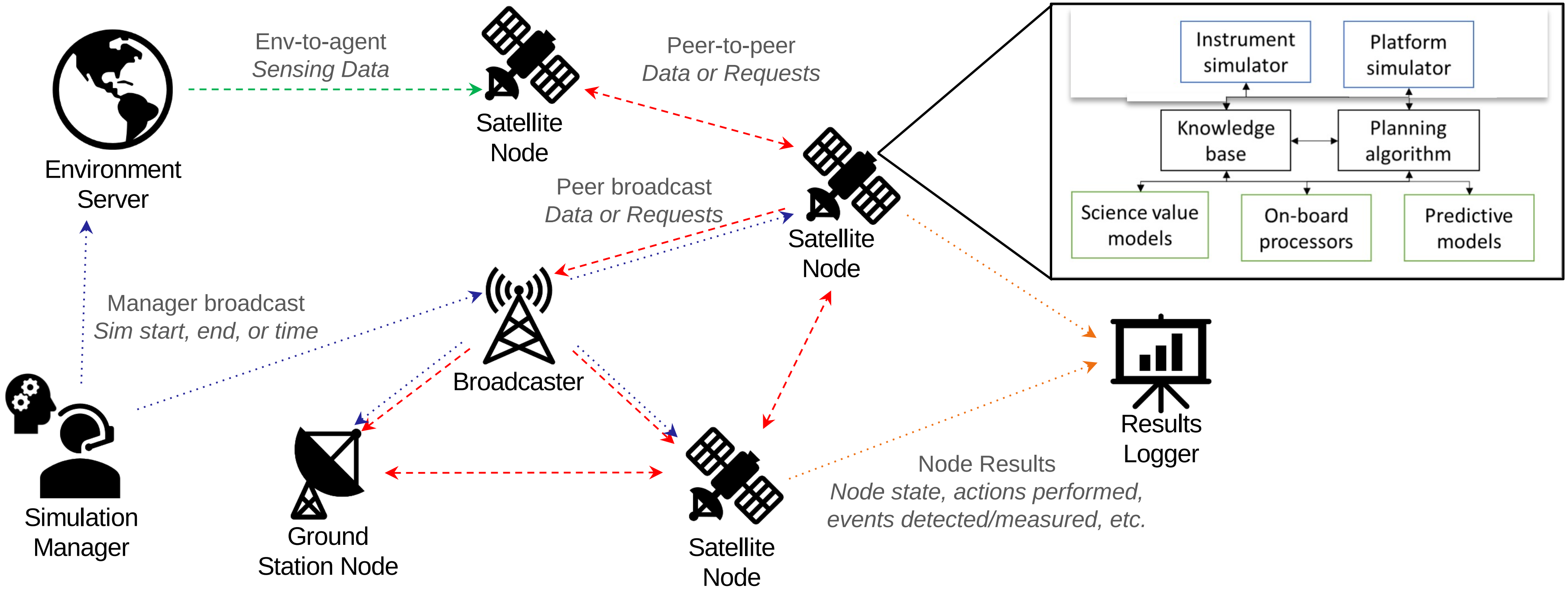
Scenario Details



- Taking 16 days of river discharge data from the USGS gauge network, and comparing to historical levels
- Classifying "floods" as 1 year floods, and "high flow events" as >75th percentile discharge
- Sensor Web:
  - Imagers: Landsat, Sentinel-2A/B
  - Altimeters: Sentinel-6A/B, SWOT, Jason-3, CryoSat-2
  - Ground nodes acting as the measurement request generator

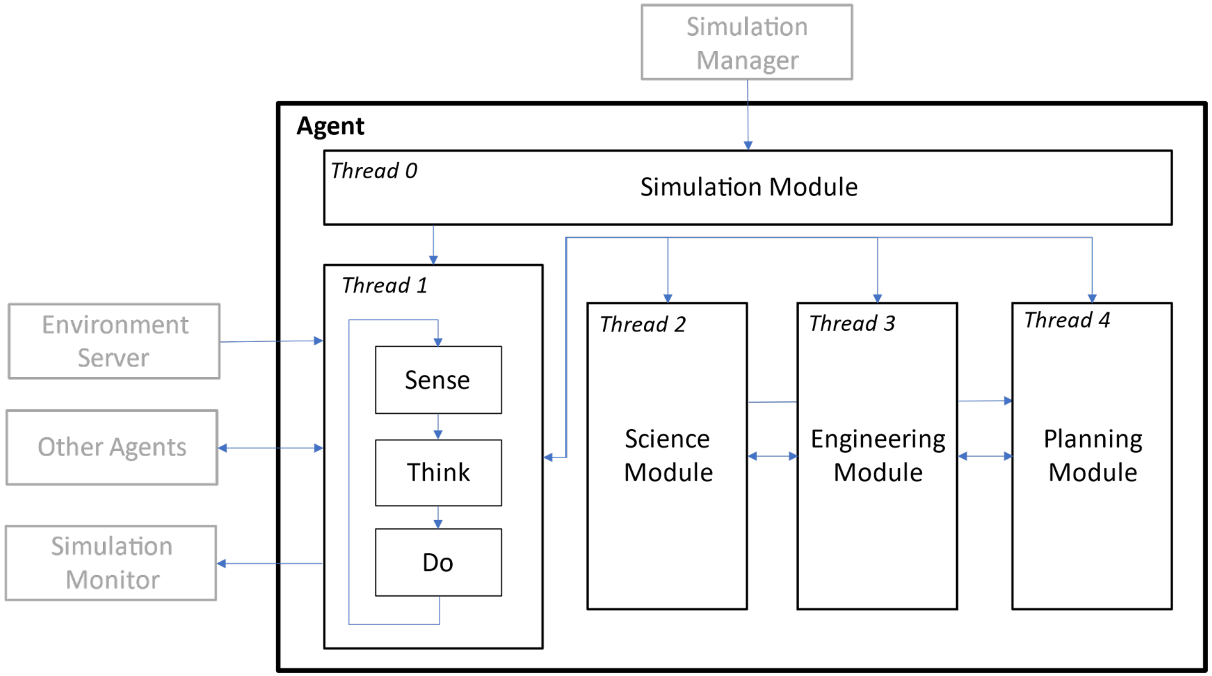
- **Metric:** How many co-observations (i.e. imagery+altimetry) can we make?
- **Variable:** Nadir pointing (status quo) vs. 3D-CHESS (dynamic, decentralized, distributed, context-aware)

3D-CHESS Architecture Overview



- 3D-CHESS Nodes modeled as Agents
- Environment modeled as a server to be accessed by nodes
  - Simulates Earth system AND agent state (e.g., position, velocity, comms accesses, coverage metrics)
  - Nodes “sense” the environment by requesting data from the environment server
- **Message-driven** architecture. Agents exchange messages via TCP
  - Point-to-point (REQ/REP ports) for agent comms and agent-to-server sensing
  - Publish-subscribe (PUB/SUB ports) for note-to-node broadcasts and manager-to-nodes/environment simulation control messages
  - Push-pull (PUSH/PULL ports) for nodes and environment results logging
- Time management can be Real-time, Accelerated real-time, or Event-driven.

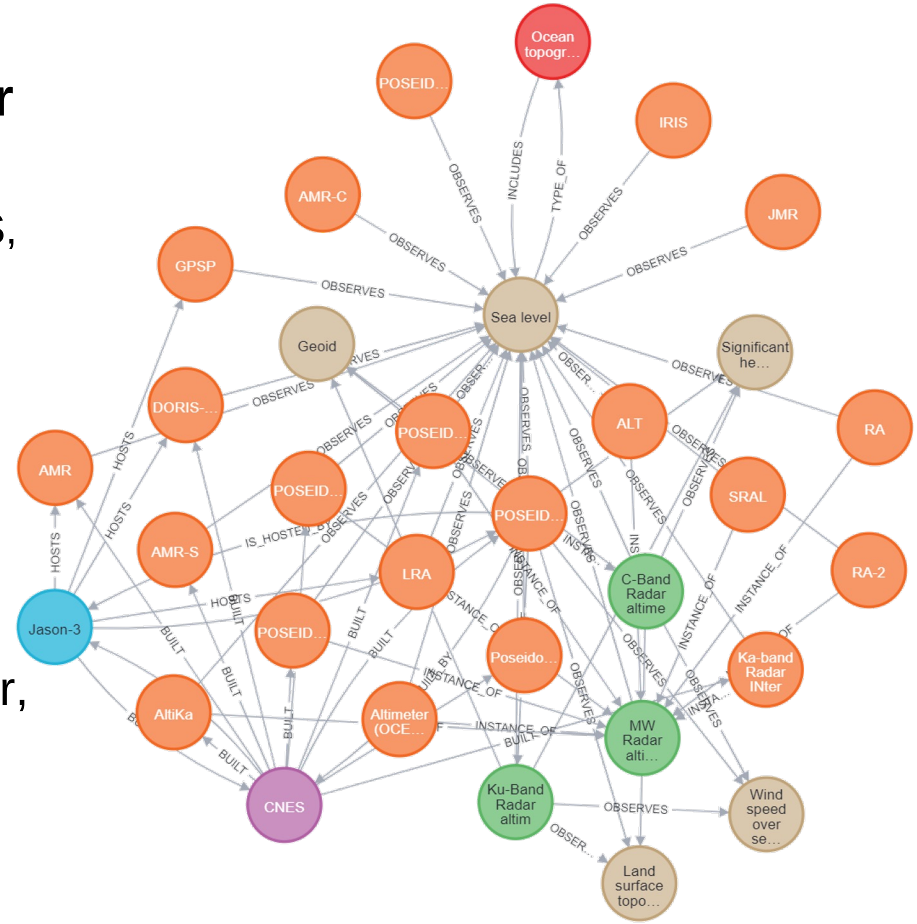
Agent Node Architecture



- Message-Driven Internal Modules
  - Intra-agent modules modeled as concurrent asynchronous processes
  - Communicate by sending messages into asynchronous message queues

Planning Module – Knowledge Graph

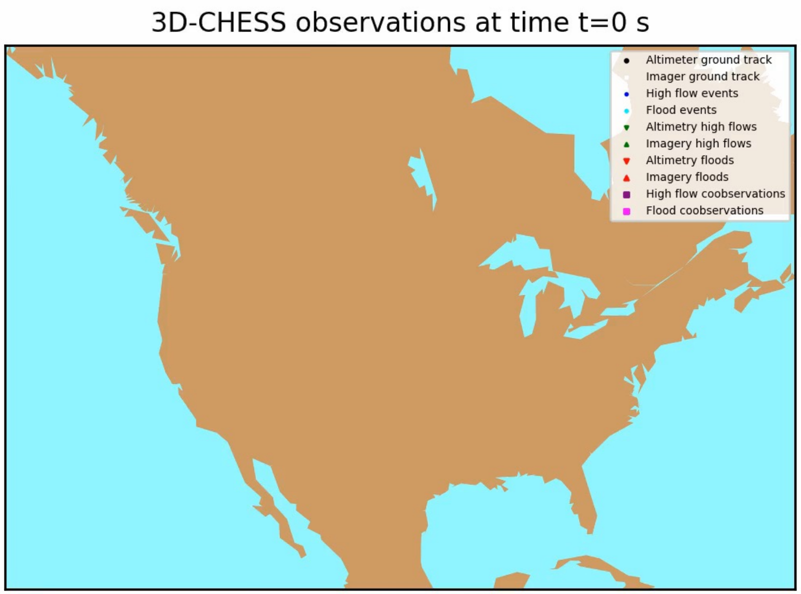
- KG types of entities and relations loosely based on **Semantic Sensor Network** ontology
  - BUILT, BUILT_BY, HOSTS, INCLUDES, INSTANCE_OF, IS_HOSTED_BY, OBSERVES, TYPE_OF
- Data mined from **CEOS database**
- Implemented in **Neo4j**
  - 3,162 nodes; 15,591 relations
- Example triplets:
  - **Observes**(POSEIDON-3B Altimeter, Sea level)
  - **Instance_of**(POSEIDON-3B Altimeter, Ku-band radar altimeter)

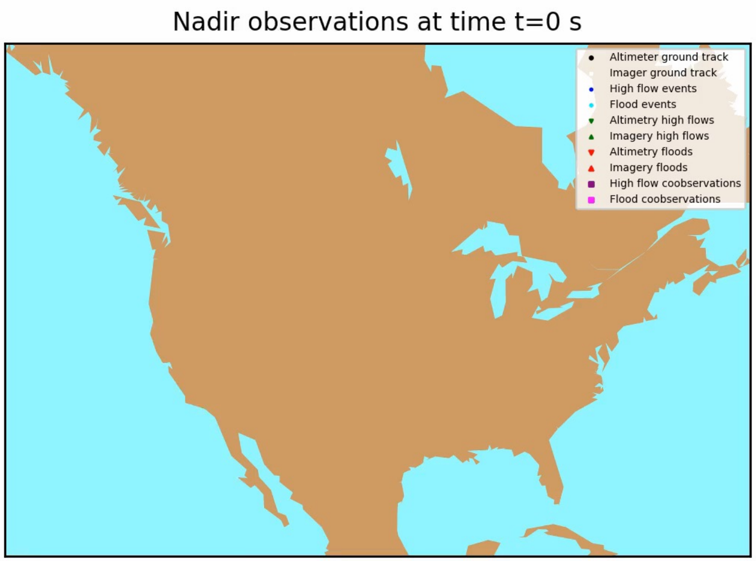


Results

Metric	3D-CHESS	Status quo
Unique floods imaged (total)	6 (12)	16 (32)
Unique floods altimetered (total)	3 (3)	3 (3)
Unique high flows imaged (total)	375 (750)	224 (448)
Unique high flows altimetered (total)	164 (164)	77 (77)
Unique floods co-observed	1	1
Unique high flows co-observed	139	72
Unique floods (total)	162 (2291)	
Unique high flows (total)	355 (7900)	

Results cont.





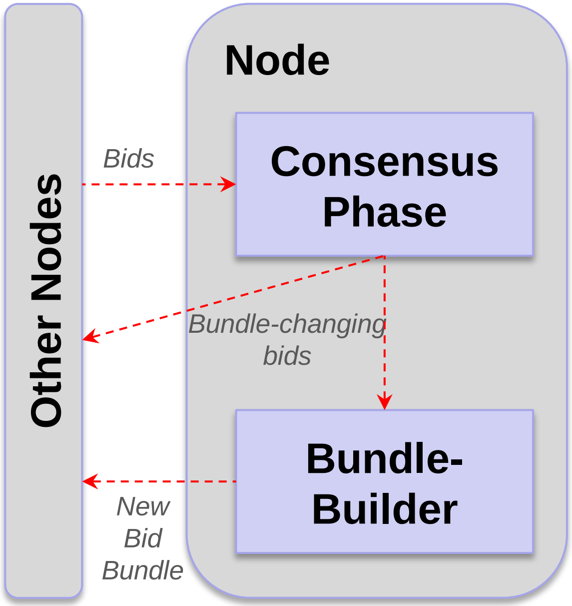
Future Work

- Incorporate decentralized planning using the Modified Asynchronous Coupled-Constraint Consensus-Based Bundle Algorithm (MACCBBA) algorithm

- Coordinate observations based on decentralized Kalman filter of events

- Incorporate probabilistic knowledge and knowledge graph reasoning rather than rule-based system

- Expand scenario definition to include SARs, UAVs, in-situ gauges



Asynchronous MCCBBA