CogniSense: Center on Cognitive Multispectral Sensor

JUMP 2.0 Theme 3: Intelligent Sensing-to-Action

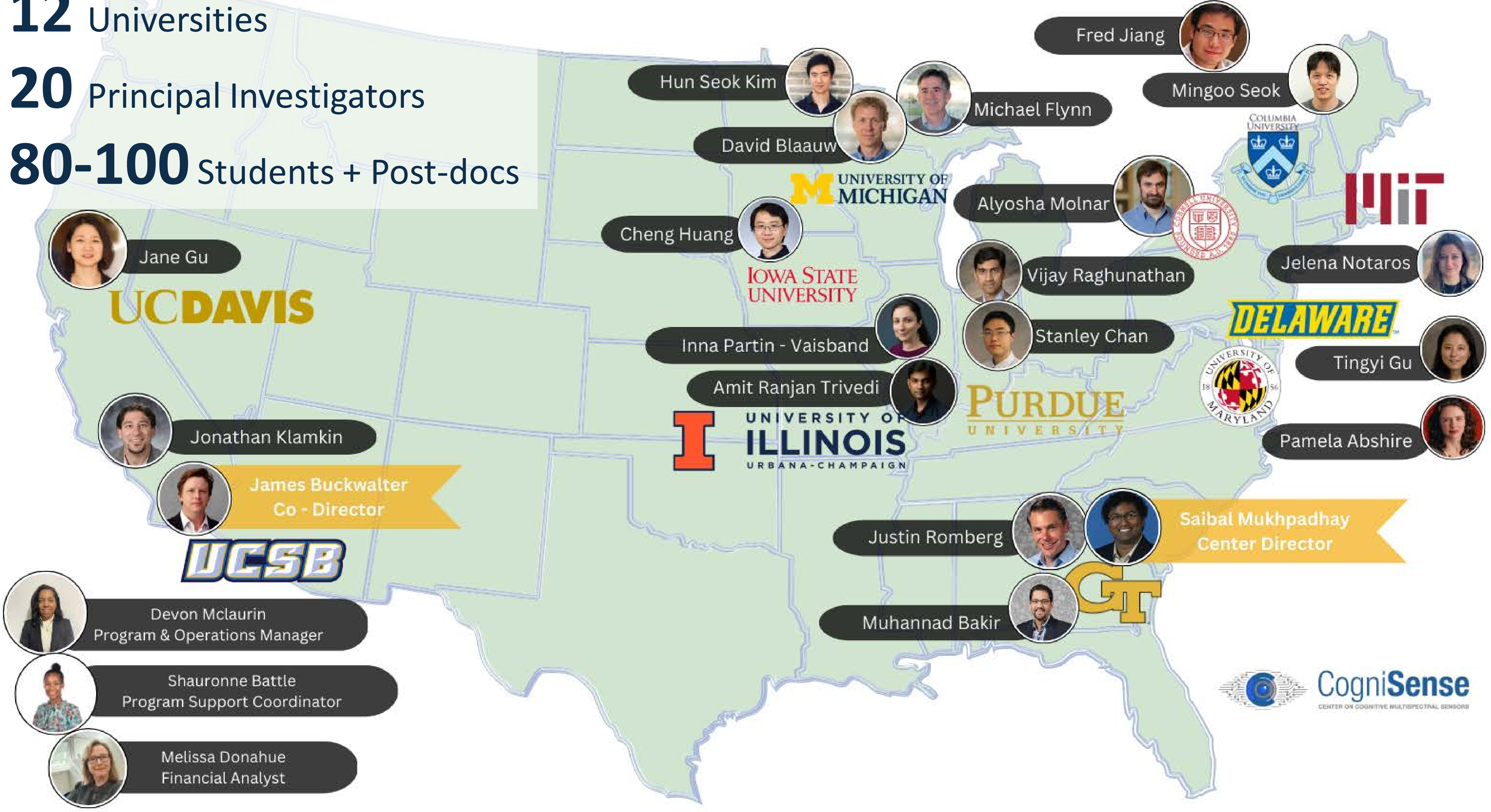
Director: Saibal Mukhopadhyay, Georgia Tech
Co-Director: James Buckwalter, University of California, Santa Barbara

Georgia Institute of Technology, UC Santa Barbara, University of Michigan, University of Illinois Chicago, Columbia University, Purdue University, Cornell University, Massachusetts Institute of Technology, University of Maryland, University of Delaware, University of California, Davis, and Iowa State University,

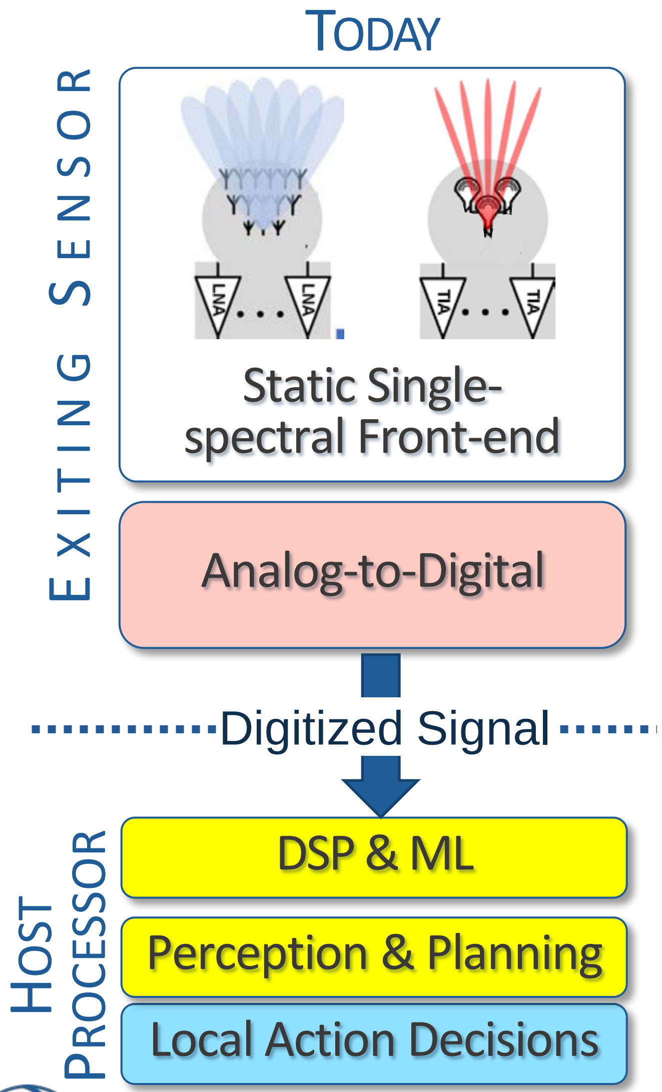
12 Universities

20 Principal Investigators

80-100 Students + Post-docs

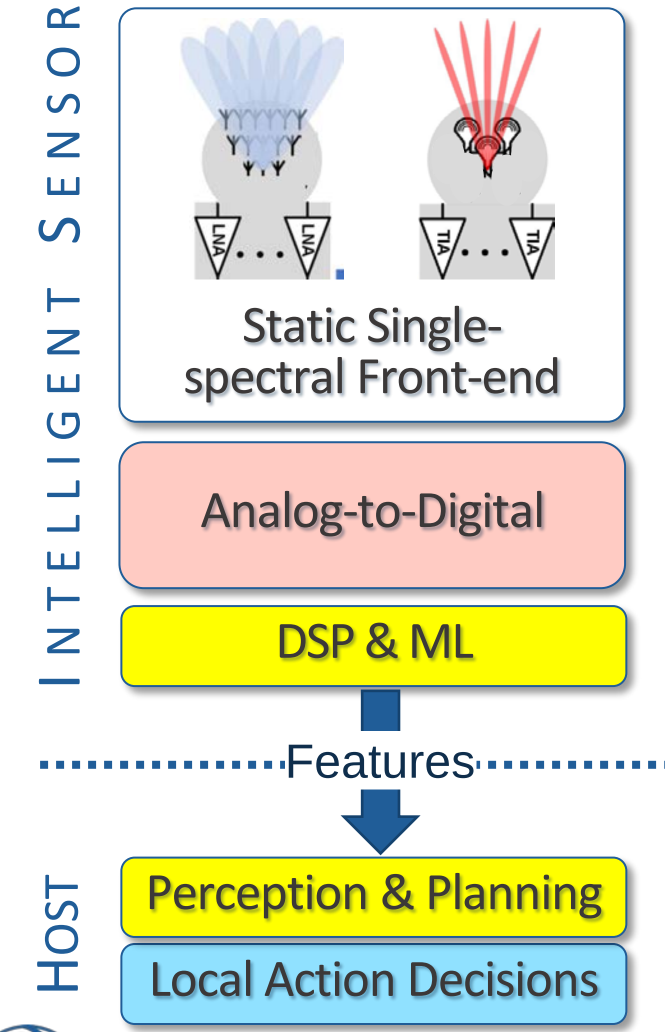


‘Traditional’ Sensors

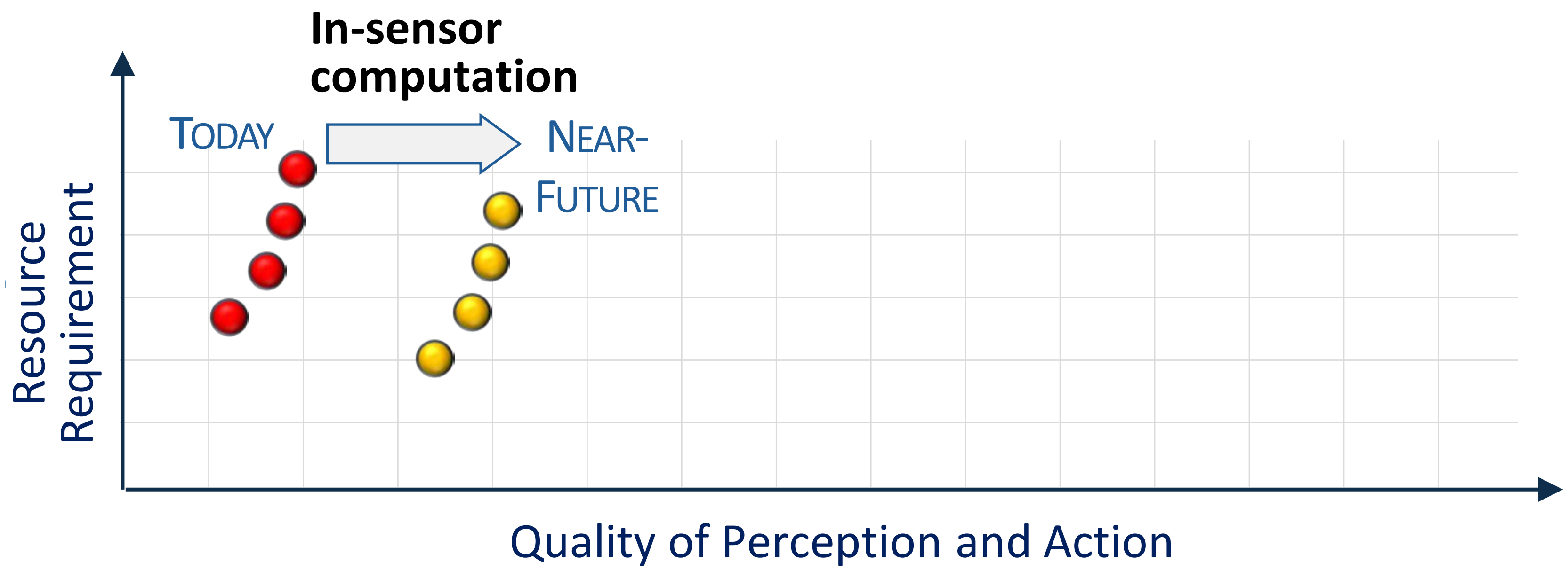


- Large-scale arrays at 140 GHz improve spatial resolution and MIMO feature processing
- Wideband pixel arrays can provide high-quality imaging for perception.
- Increasing number & bandwidth of pixels leads to
- *Analog data deluge* - large volume of digitized data
    - Large power dissipation in many analog-to-digital converters.
    - High data-rate between a sensor and a processor.
  - High sensing power as all pixels are always ‘on’
- Power and data volume ultimately limits the quality of traditional sensors.

‘Intelligent’ Sensors of ‘Near’ Future



- Integration of Digital Signal Processing and Machine Learning models within a sensor can extract (digitized) features from (digitized) signals.
- Reduces “data volume” from sensor relaxing the resource requirements.
- Challenge: Intelligent sensors will also continue to ”sense” and “digitize” all pixels resulting in high sensing and digitization power.
- Power dissipation will ultimately limit sensing quality.



Challenges of Scaling "Quality" under a Power Budget

- Traditional sensors continuously digitize everything sensed into bits and then extract features using a fixed algorithm.
- Sensors deployed in an autonomous system operate in an evolving environment.
- A *fixed set of features* derived from samples of the *entire analog input* leads to sub-optimal performance and enormous, arguably unnecessary, power.
- The "static" design and operation of sensors leads to sub-optimal performance.

Can we break the paradigm of "static" operation of a sensor?

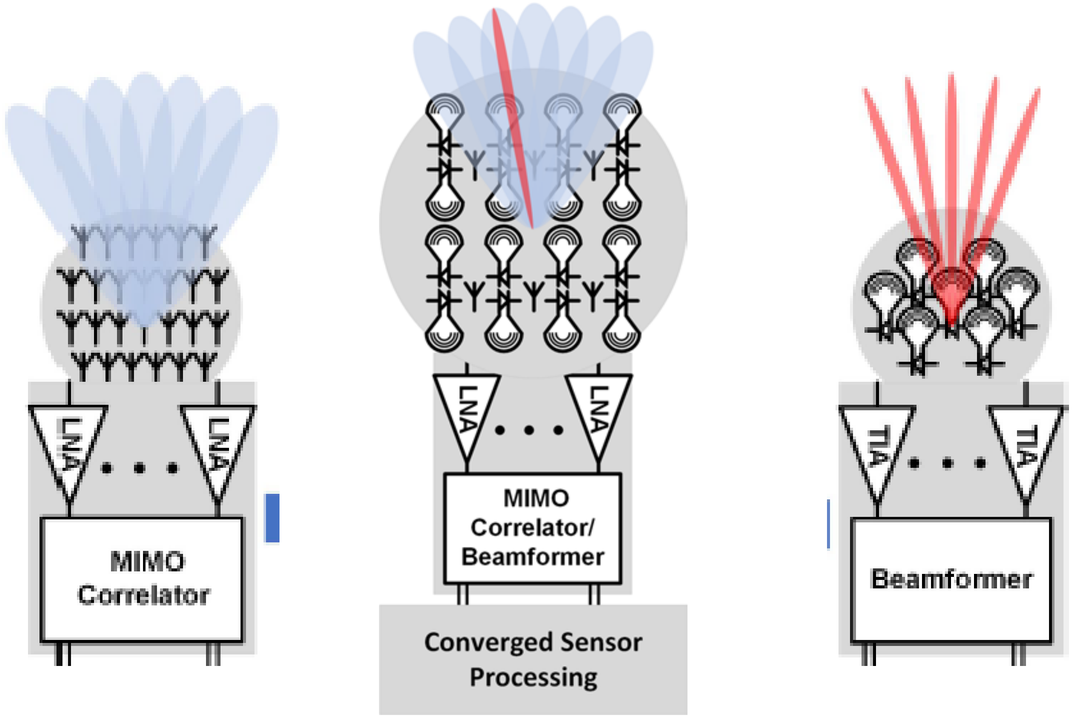
Vision of CogniSense

The CogniSense vision is to break the paradigm of static sensor operation to dynamically adapt what is being sensed and how sensed signals are processed to real-time changes in the environment.

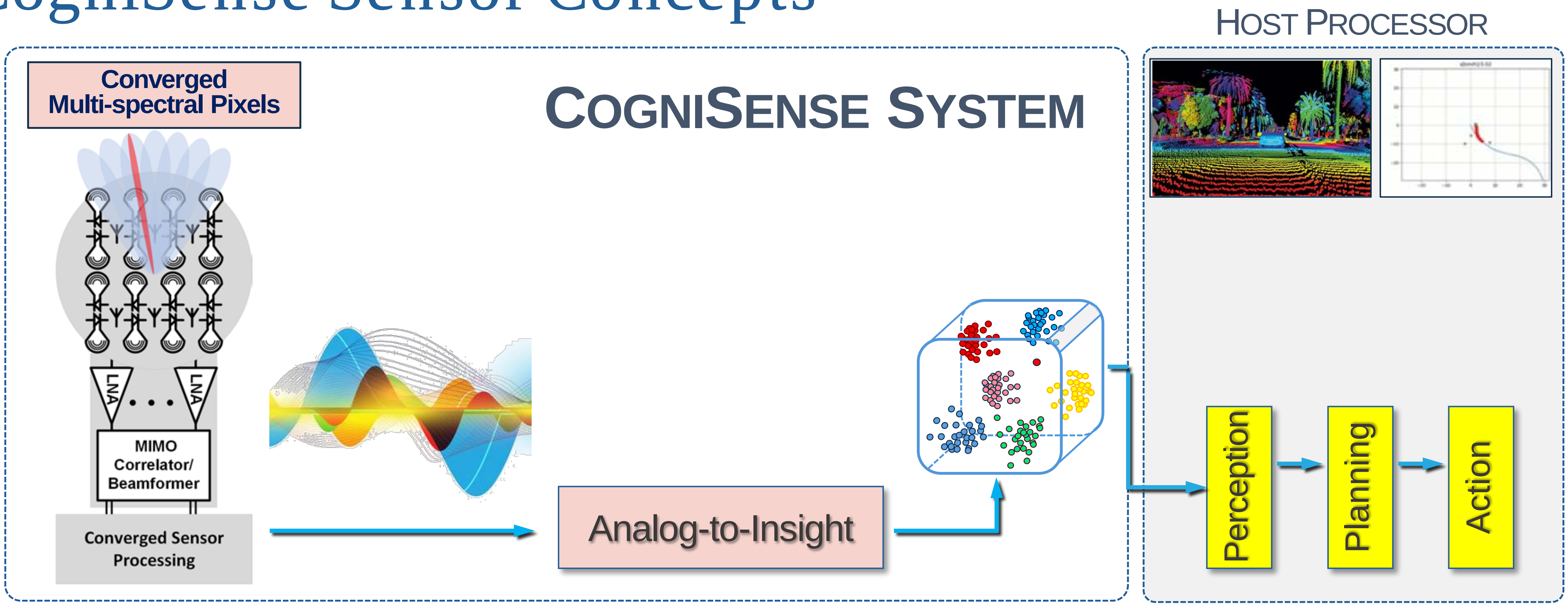
- We are inspired by biological systems where closed-loop feedback from the senses allows the brain to adapt the level of engagement and the depth of cognitive processing based on task demands.
- We rely on this biological concept of attention to create ‘cognitive’ wideband active sensing arrays that learn to focus on what is most important in a scene.

CogniSense Sensor Overview

Converged Multi-spectral Pixels



CogniSense Sensor Concepts



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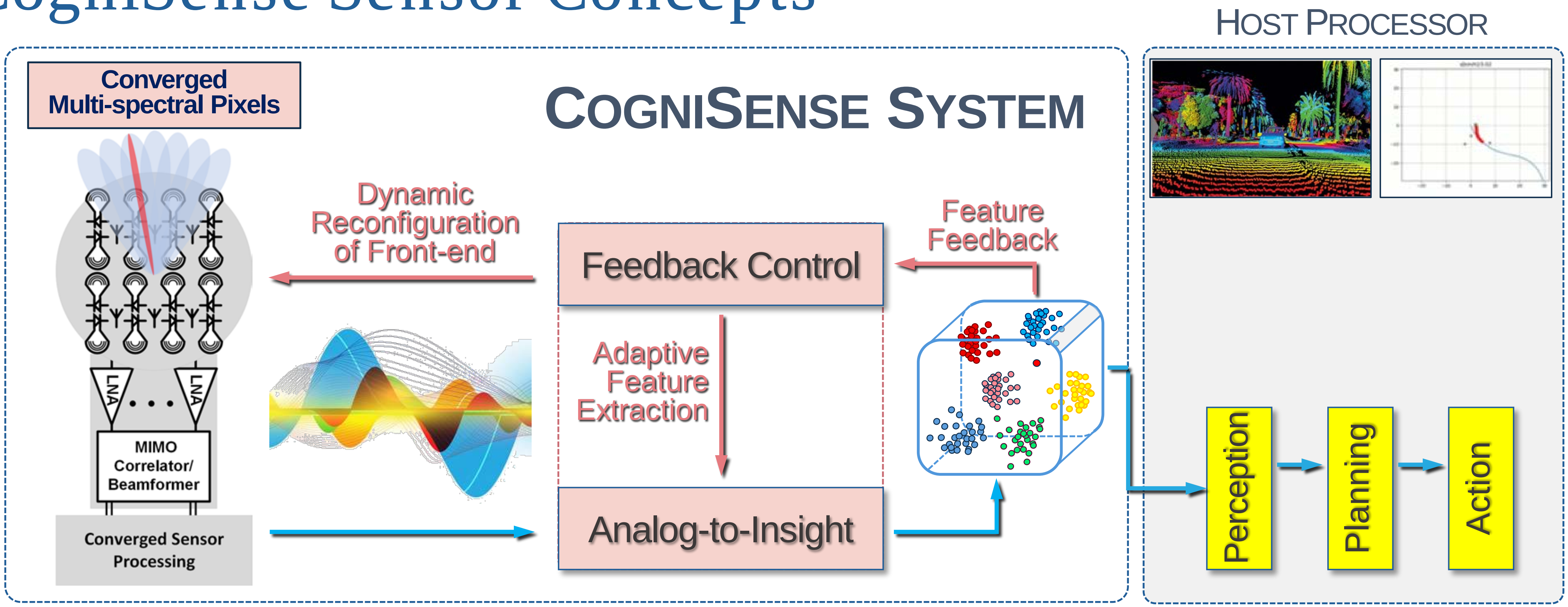

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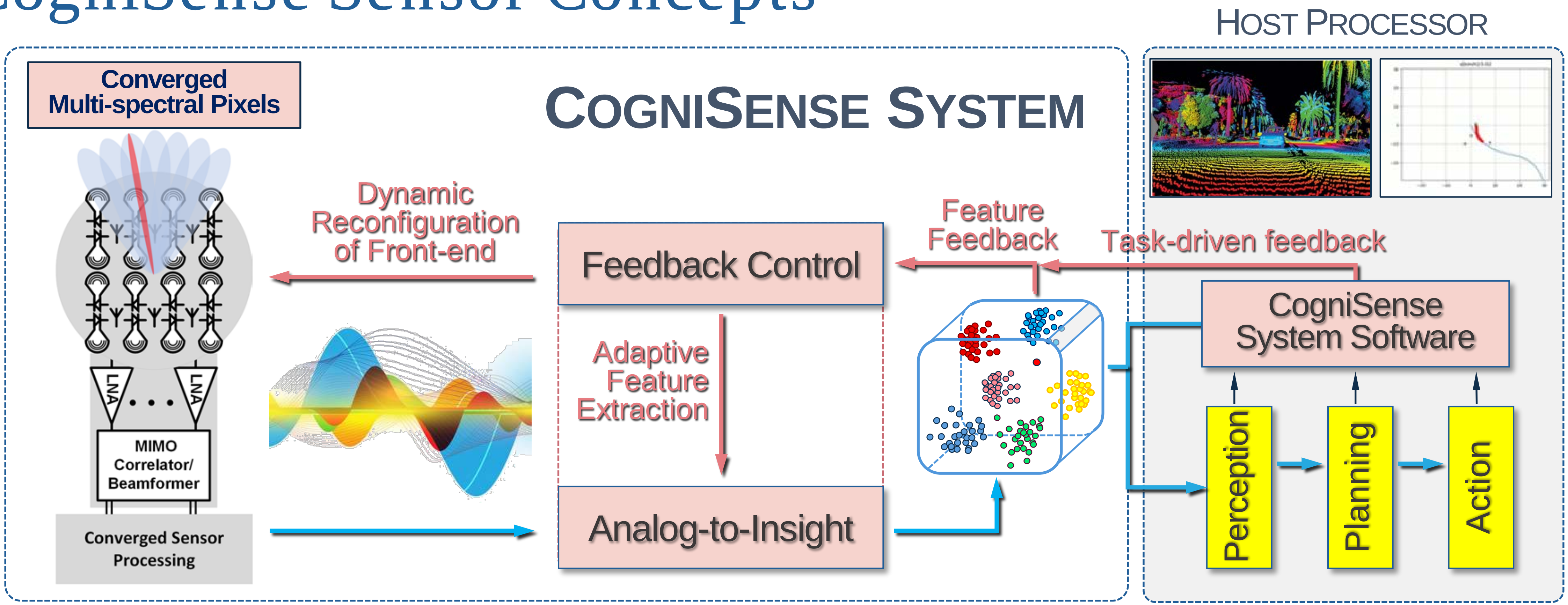

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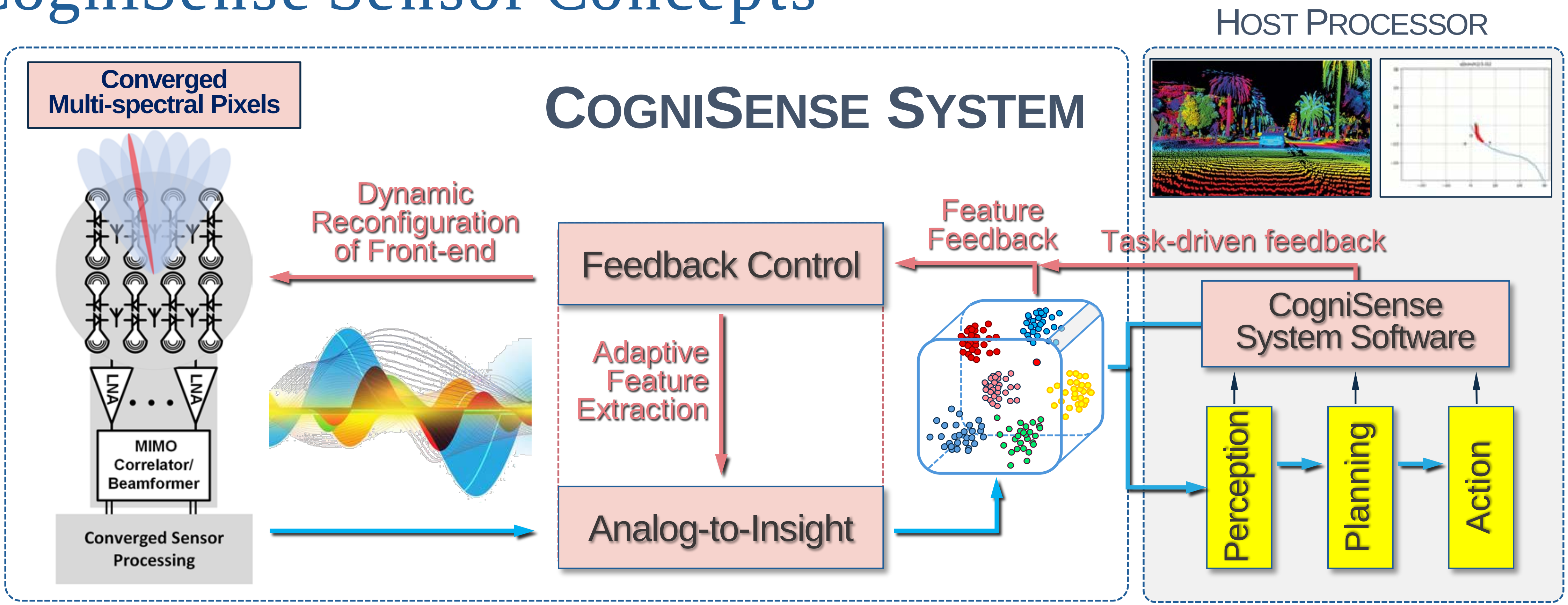
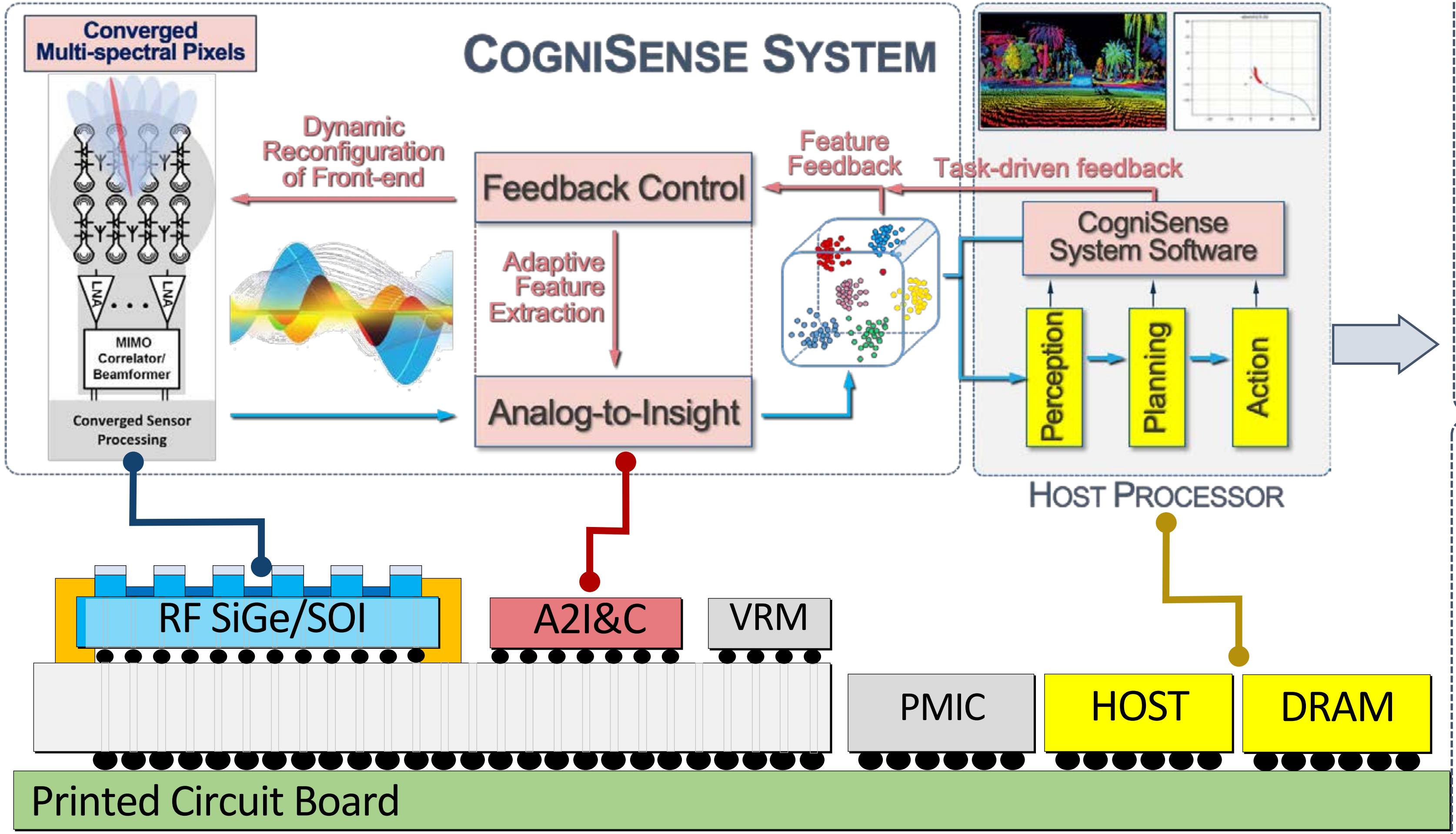
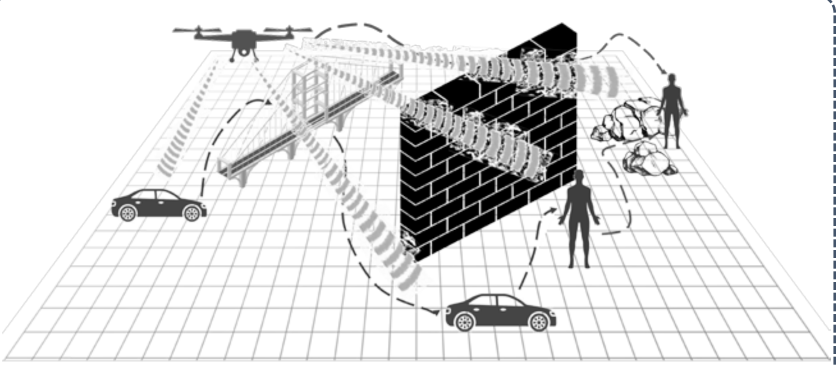


Cognitive multi-spectral sensors directly generate trustworthy insights from wideband multi-modal analog signals using closed-loop feedback control of the sensor hardware and feature extraction algorithms that enable energy-efficient sensing-to-action.

CogniSense Sensor Overview

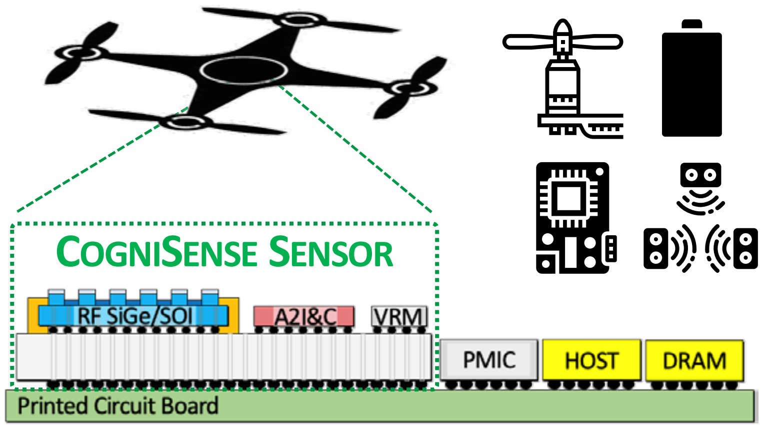


CogniSense Applications



CogniSense Sensing-to-Action

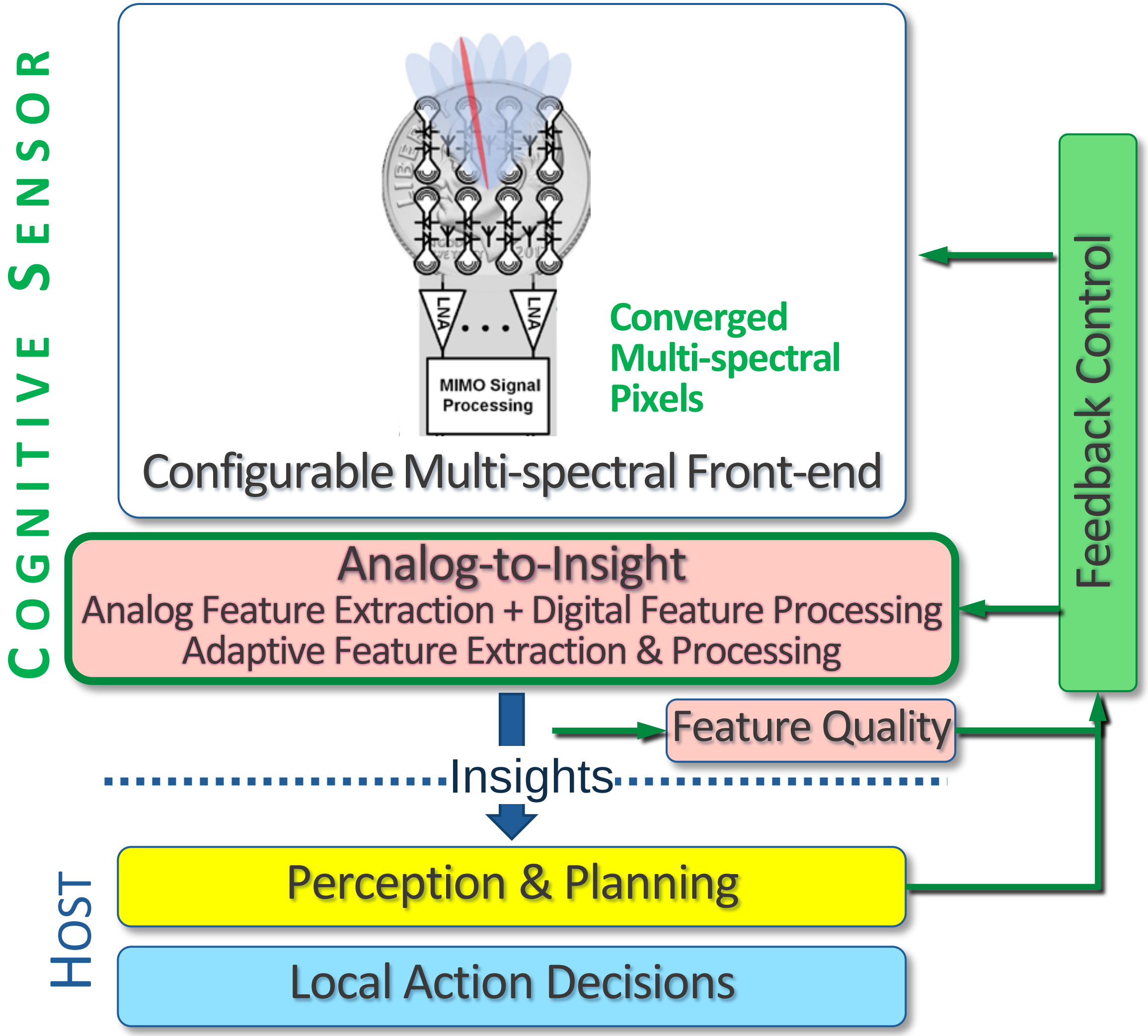
Demonstration of object detection and following in complex and adversarial environment



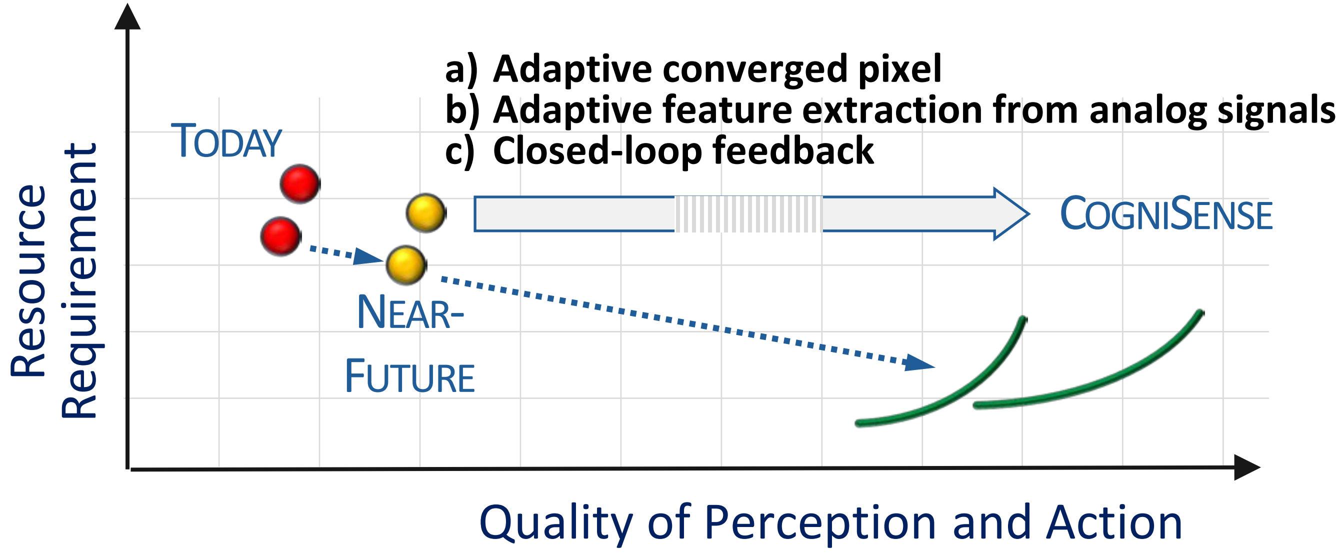
CogniSense Sensor in a System

Custom drone with CogniSense Sensor

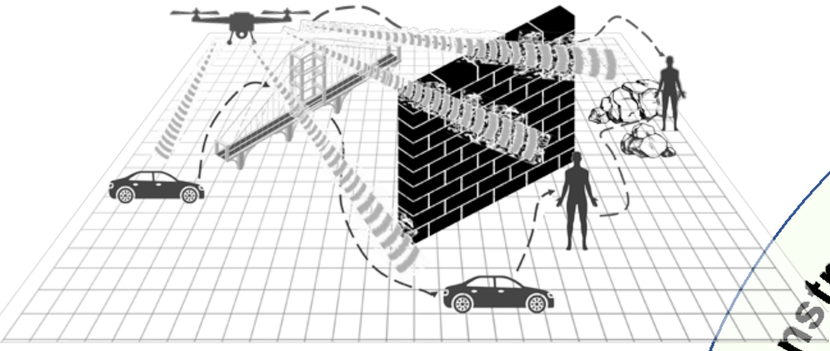
CogniSense: A New Direction in Sensor Research

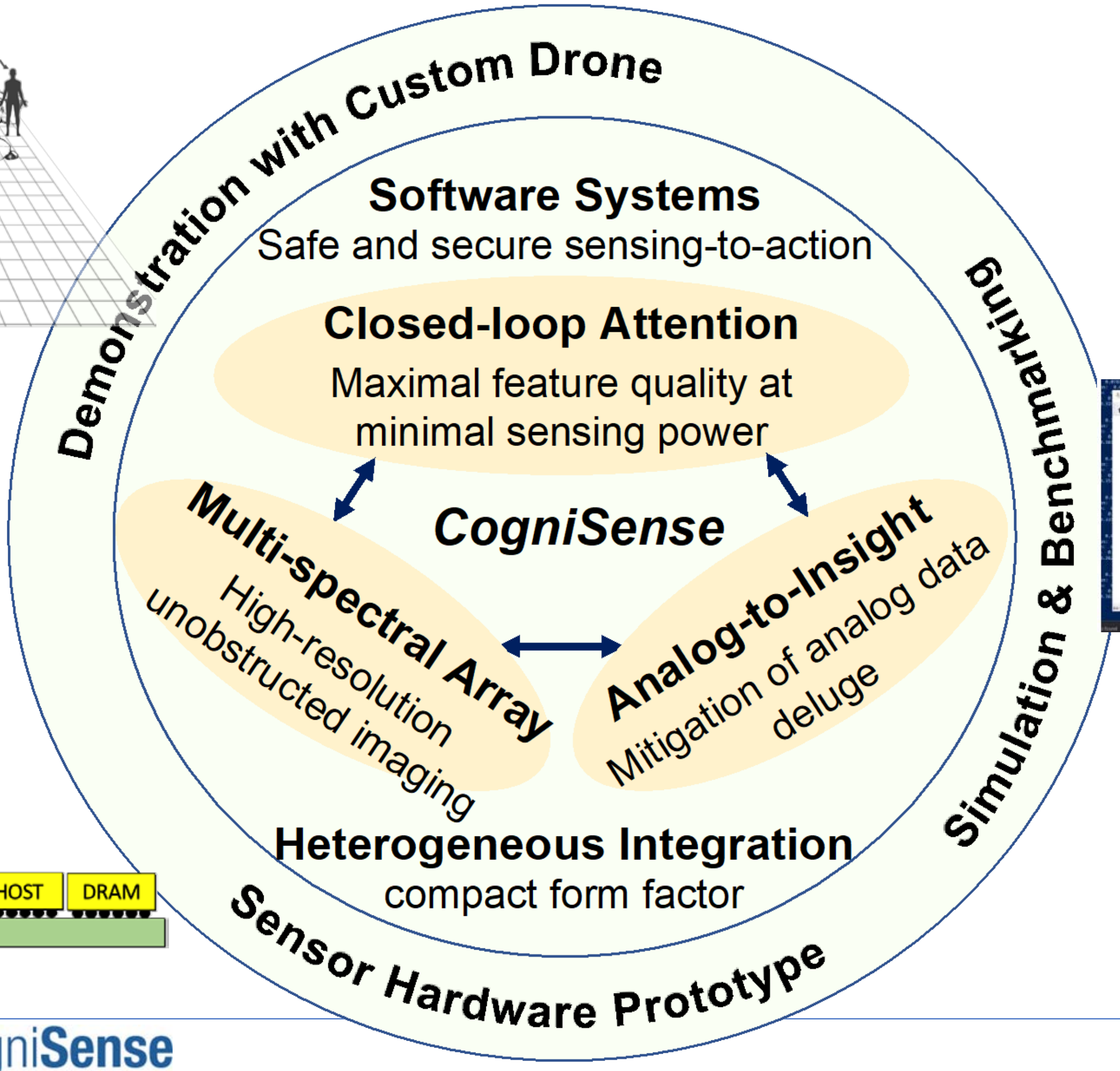


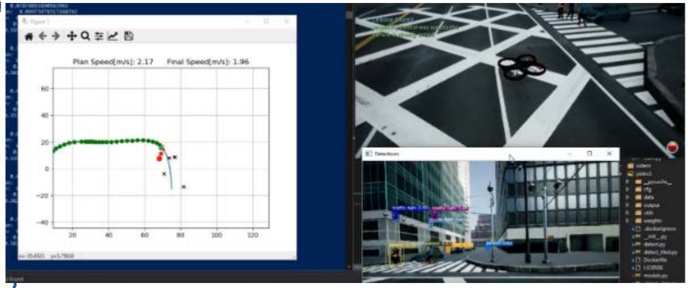
CogniSense sensors are not “static" points in the quality-resource space; rather they can dynamically traverse a curve in the quality versus resource curve using closed-loop attention coupled with adaptive sensing and feature extraction.

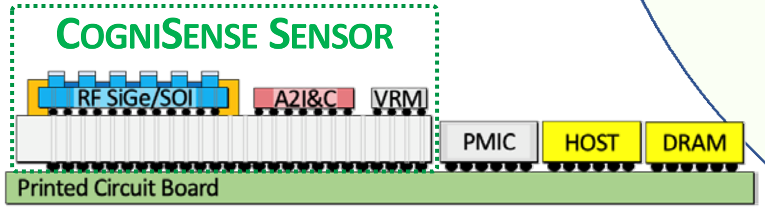


Research Vectors







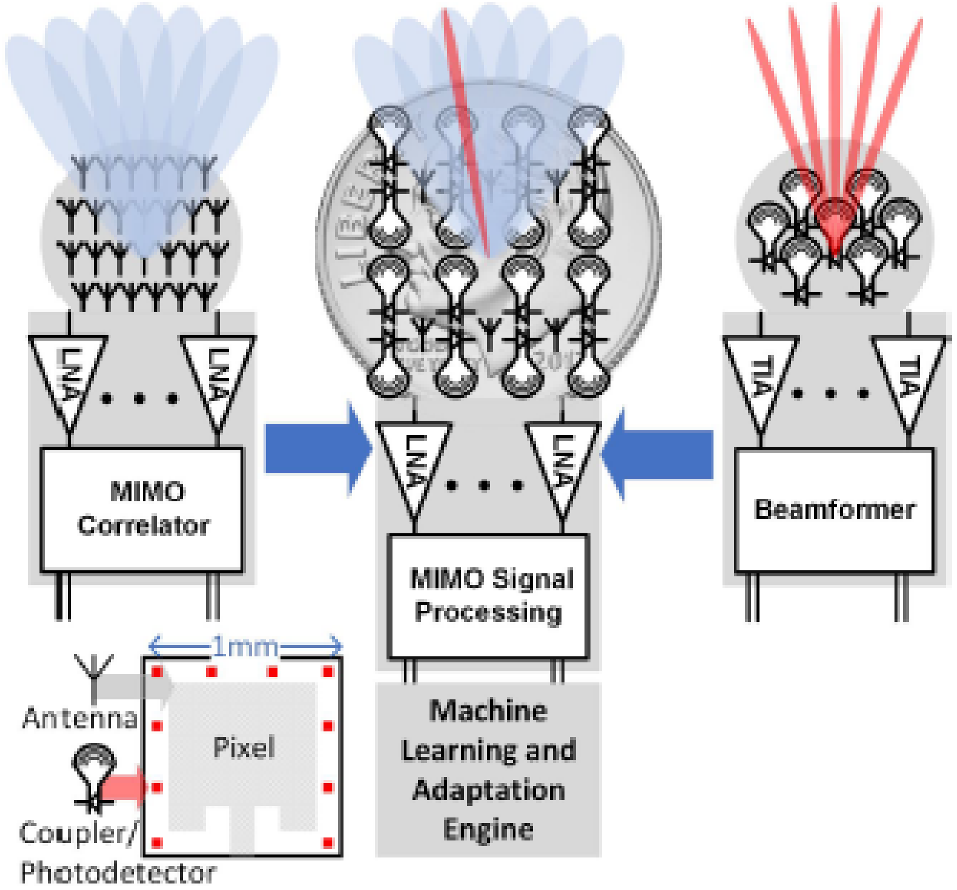


Research Plan

Thrust 1: Multi-spectral Array

Lead: J. Buckwalter (UCSB)
Co-lead: J. Notaros (MIT)

Advancing the capability of mm-wave MIMO radar, passive imaging, and lidar to achieve sensor convergence with adaptation for energy-efficient feature detection.



- Produce a rich set of sensing data by simultaneously combining
  - MM-wave radar
  - Lidar
  - Passive sensing
- Leverage low-power MIMO signal processing for sensing
- Adopt digital waveform techniques
- Adapt front-end circuitry power consumption through machine learning engine

Thrust 2: Analog-to-Insight

Lead: J. Romberg (GT)
Co-lead: H. Kim (U Michigan)

Mission: *Mixed-signal and digital feature extraction at the sensor to mitigate the data deluge*

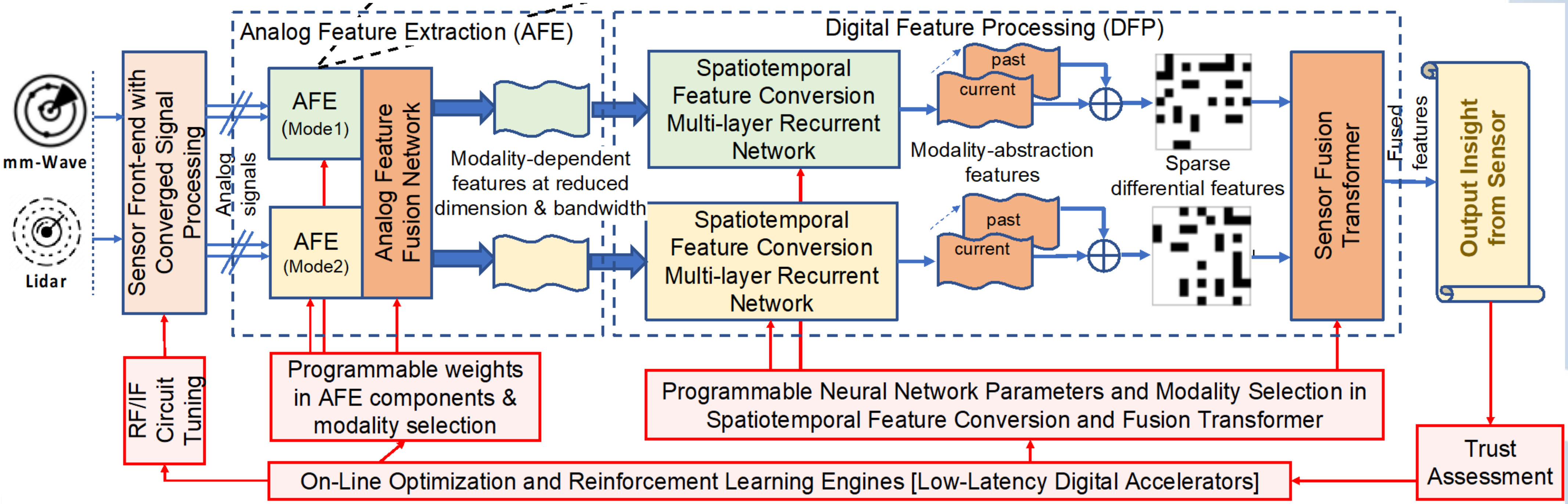
Pipeline combining computation and dimensionality reduction to dramatically reduce the data flow off the sensor

Adaptable feature extraction, integrated with Thrust 3

Multi-layer: analog feature extraction (AFE) followed by digital feature processing (DFP)

Multi-modal: features are fused at the digital output

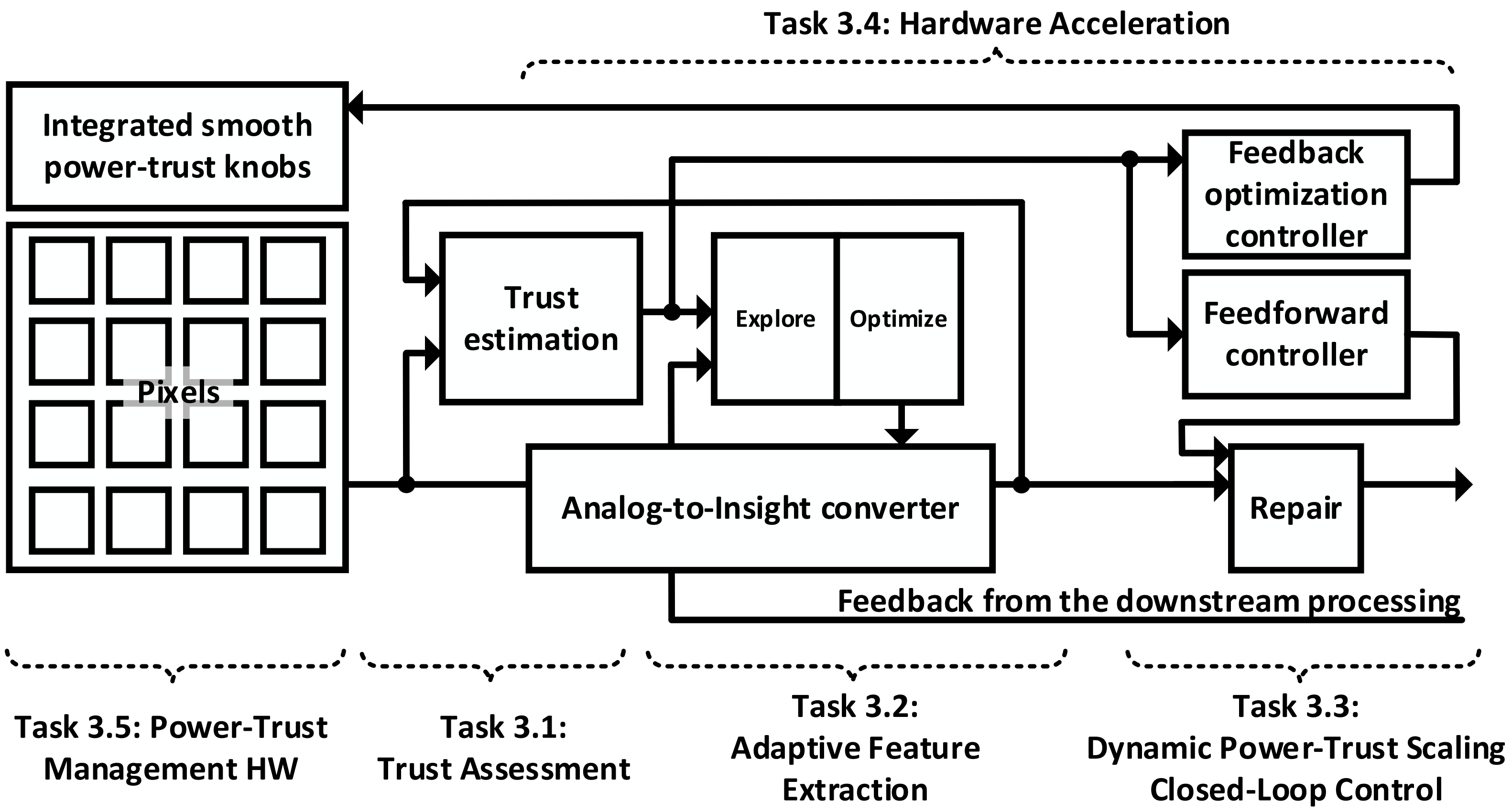
Fundamentals: what are the theoretical limits of a given feature extraction architecture?



Thrust 3: Closed-loop Attention

Lead: M. Seok (CU)
Co-lead: A. Molnar (Cornell)

Add ***adaptivity*** to the sensor front end and feature extraction to extract more informative insight yet consume less energy, robustly across the input and environmental condition changes, some of which are not even known during the design and training time.



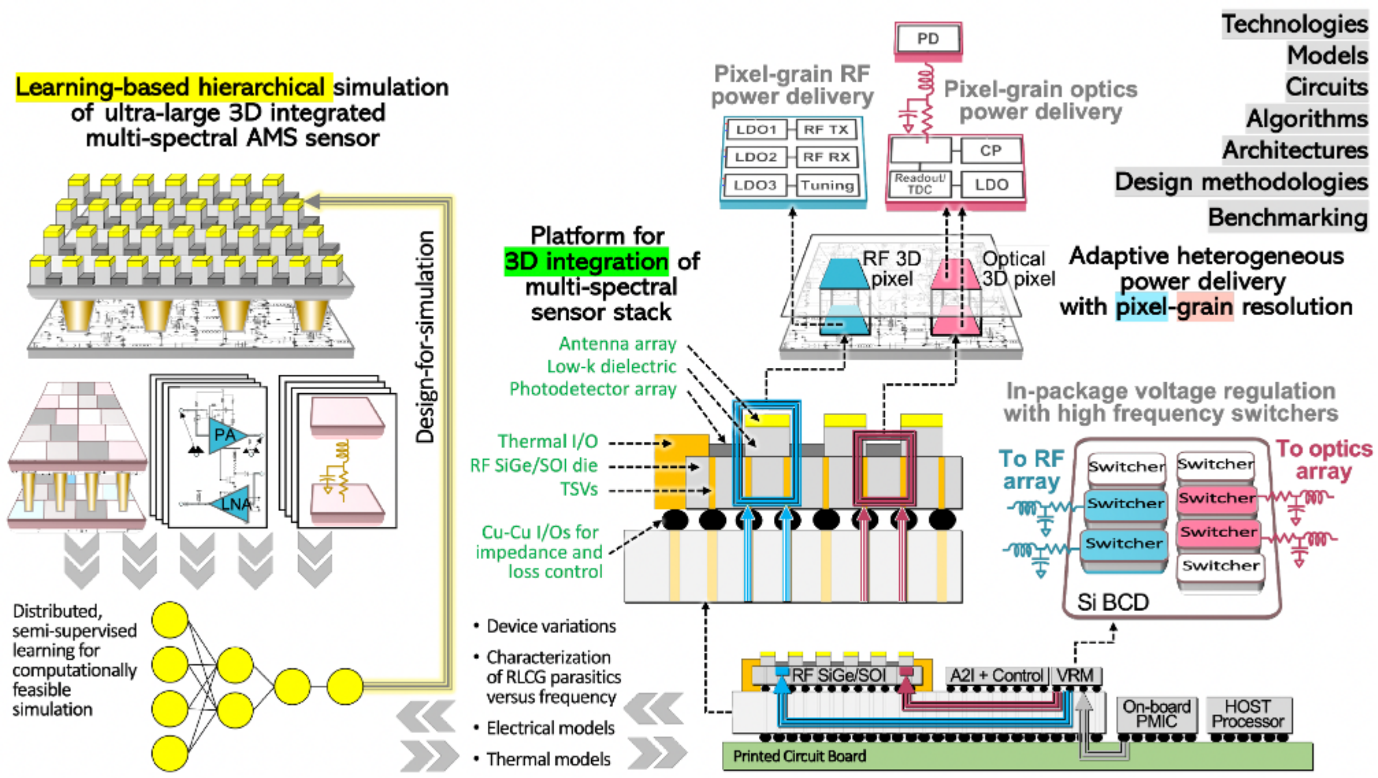
- Create new algorithms and analog-mixed-signal hardware for trust assessment
- Create adaptive feature extraction algorithms for dimensionality reduction
- Create the feedback and feedforward control systems for the dynamic power-trust scaling
- Create programmable energy-efficient hardware for the algorithms to be developed
- Create power-trust scaling knobs in the sensor front-end hardware

Thrust 4: Heterogeneous System Integration

Lead: I. Partin-Vasiband (UIC)

Enabling the A2I&C engine via compact and dense multi-spectral sensor with power, signal, and thermal integrity

- Advance monolithic 3D and heterogeneous integration (3D/HI)
- System-wide thermal management and electro-thermal modeling
- Develop hierarchical distributed power delivery from interposer to multiple voltage domains with pixel-level dynamic voltage regulation
- Develop simulation platform for the A2I&C engine with analog inputs from the 3D stack
- Thrust 4 also serves as a focal point for collaboration with JUMP 2.0 Technology Center 6 for 3D/HI integration and advanced cooling technologies



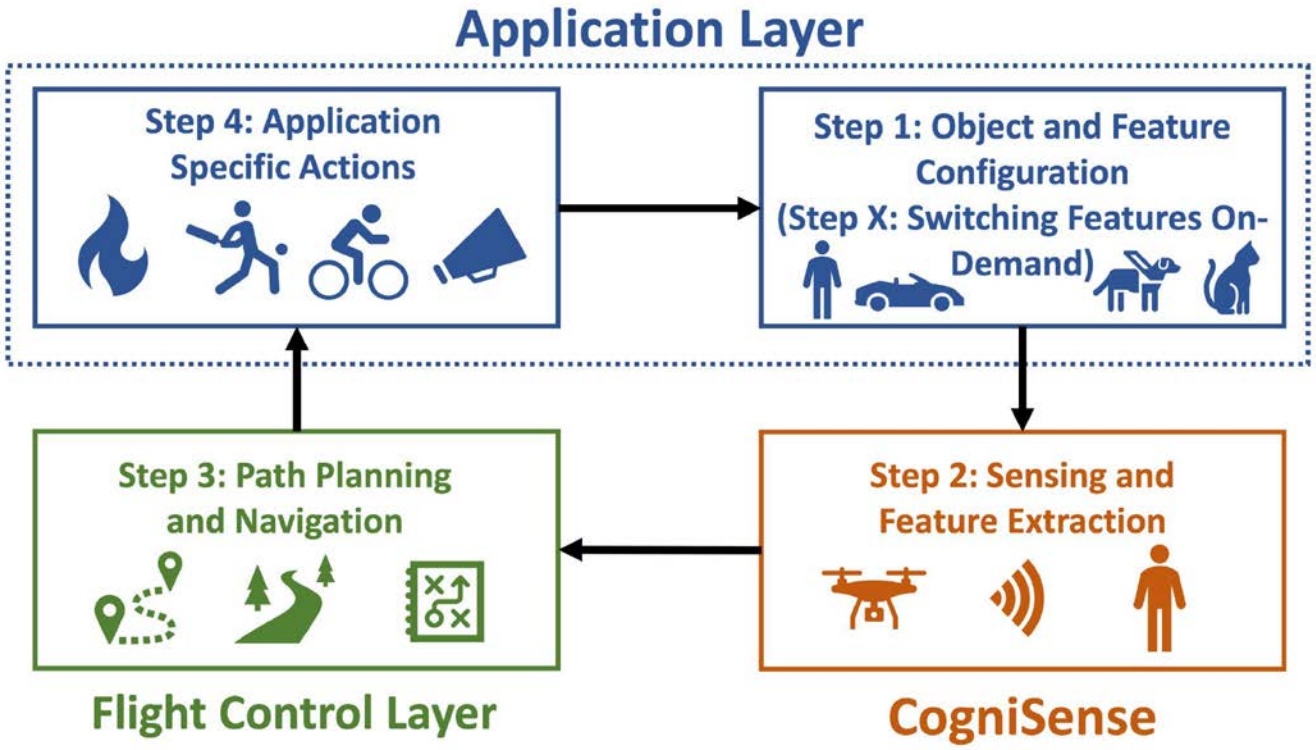
Complete sensor: front-end monolithic 3D ICs, A2I & control engine, and voltage regulation module – all heterogeneously integrated on interposer

Thrust 5: System Software and Integration

Lead: V. Raghunathan (Purdue)

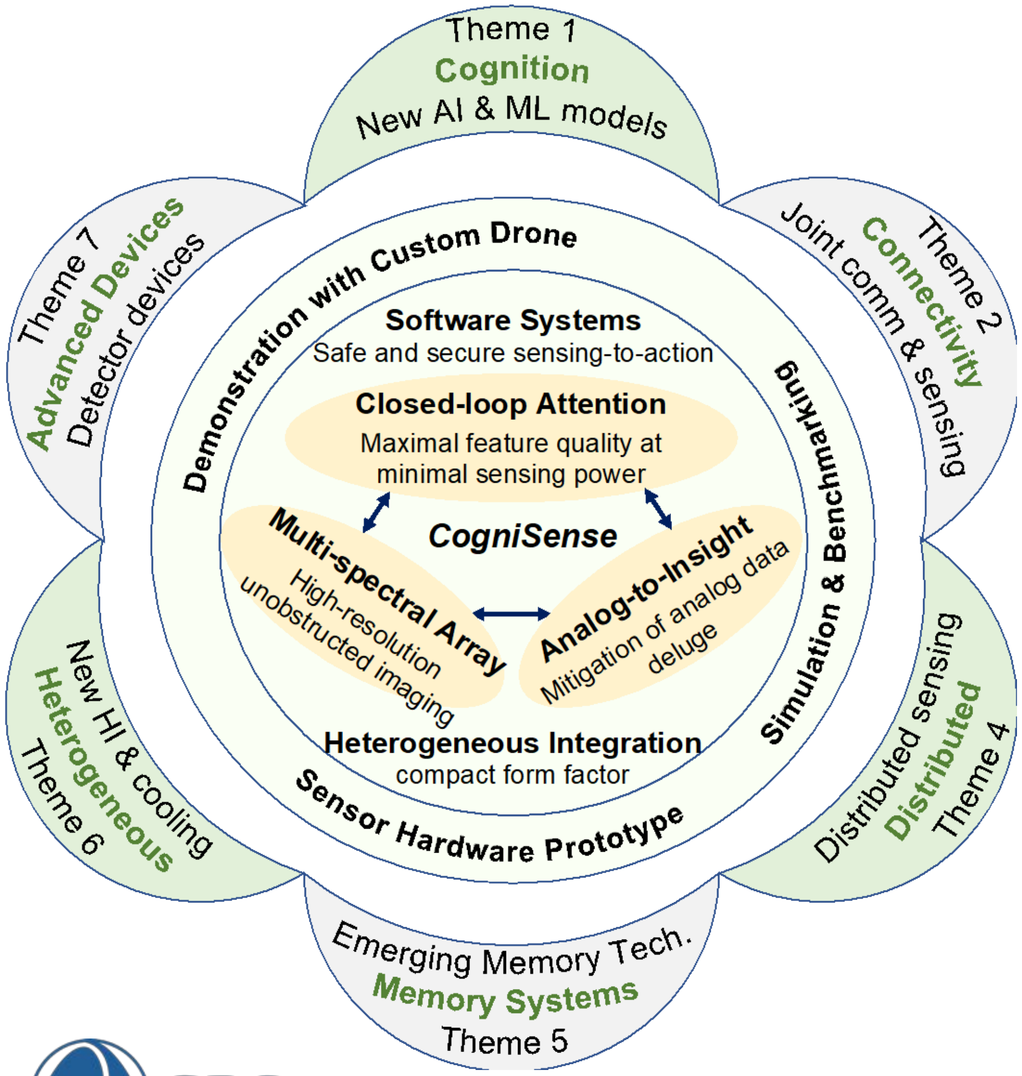
Develop run-time framework for safe and secure sensing-to-action even with unreliable CogniSense sensors

- Develop programming and run-time framework at the host to dynamically manage CogniSense sensors against sensor non-idealities and adversarial attacks
- Develop a framework for tracking sensor's reputation by integrating domain-knowledge and past performance
- Closed-loop perception protocols where host uses reputation and trust scores to continuously configure the in-sensor controller
- **Thrust 5 also integrates various developments across the CogniSense center for proof-of-concept demonstrations**



Dynamic reconfiguration of CogniSense sensors at the application layer by adapting against environment features, autonomy objectives, sensor health and trust, and available energy resources

Cross-Center Collaboration



Theme	Name of the Center	Potential Topic of Interactions
1	Cognition **COCOSYS (GaTech)**	New AI/ML models for feature extraction
2	Communications and Connectivity **CUbiC (Columbia)**	Joint communication and sensing
4	Systems & Architectures for Distributed Compute **ACE (UIUC)**	Distributed sensing with CogniSense and integration with cloud
5	Intelligent Memory and Storage **PRISM (UCSD)**	Impact of new memory technology in design of feature extraction algorithms.
6	Advanced Monolithic and Heterogeneous Integration **CHIMES (Penn State)**	New heterogeneous integration technologies; advanced cooling solutions
7	High-performance Energy-Efficient Devices for Digital and Analog Applications **SUPREME (Cornell)**	New detector devices; new analog devices for feature extraction

Summary

- **Objective.**
  - Develop cognitive multi-spectral sensors that directly generate trustworthy insights from wideband multi-modal analog signals using closed-loop feedback control of the sensor hardware and feature extraction algorithms that enable energy-efficient sensing-to-action.
- **Approach**
  - Technology & circuits for mm-wave MIMO radar, passive imaging, and lidar to achieve sensor convergence with adaptation for energy-efficient feature detection
  - Analog-to-insight algorithms & hardware to extract low-dimension features from high-dimension analog signal.
  - Maximize feature quality and save sensor power in a dynamic scene with real-time closed-loop-attention control.
  - Heterogeneous integration methods to achieve compact form factor with power, signal, and thermal integrity.
  - System software and integration methods for safe and secure sensing-to-action with cognitive sensors.
- **Outcome.**
  - Multi-modal sensing arrays that eliminate corner-case obstructions in machine perception in autonomy.
  - Sensors that make efficient use of the resources (data bandwidth and power) by only sampling the most useful part of a scene and generating only the most useful features.
  - New research direction to design a new class of sensors that, instead of being a point solution, learns to dynamically traverse a curve in the quality versus resource space in evolving environment.

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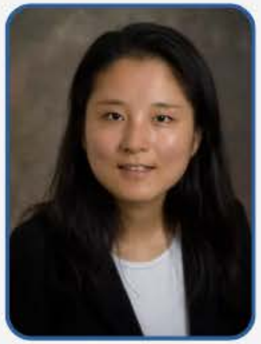

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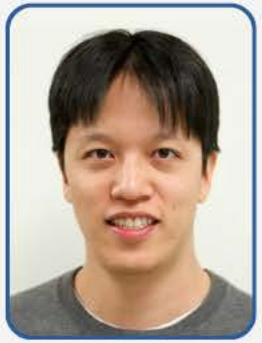

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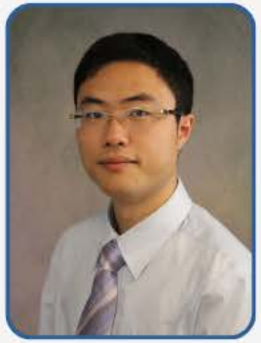

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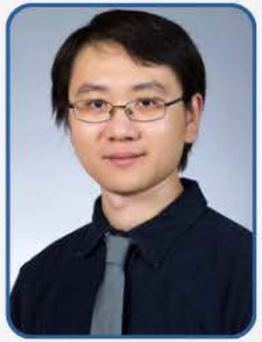

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