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# Rapid abstract perception to enable tactical unmanned system operations

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# Tactical Operations: A Significant Leap for Unmanned Systems (UMS)

- **US DoD's future visions include dramatic expansion of UMS roles**
  - UMS Integrated Roadmap: "autonomous 'wingman' capable of *human-like tactical behaviors*, in-stride support …. *tactical decision making while in enemy contact*; advanced perception of individual humans in urban environments" by 2022
  - Work: robot "first through a breach" by 2025
- **Evolution of unmanned missions**
  - Today: Mostly uncontested, slow, planned, support role
  - Future: <u>Dynamic</u>, <u>tactical</u>, <u>collaborative</u>, <u>adversarial environments</u>
- **What determines superiority in unmanned operations?**
  - Autonomy (control and perception) will play a major (decisive?) role
  - Reactive, dynamic behavior by <u>*heterogeneous teams*</u>
- **Today's state of practice**
  - Operationally: Teleoperation dominates; rely on humans for perception, decisions
  - Commercially: Autonomous perception & control in structured environments using extensive training data and supervision
  - Research: Autonomous geometric mapping, simple swarming, semantic labeling

Contention: UMS control methods that prevail today will not scale to a dynamic, tactical operational future

# Tactical Operations with Unmanned Systems

***Long-term goal*: Operate UMS teams tactically at human (or faster) speeds, with human (or better) effectiveness, against adversaries & defenses**

| *Level of Instruction* | *Capabilities* | *Technologies* |
| --- | --- | --- |
| "Go win the battle / war!" | Strategic mission decisions | AI / Strategic Reasoning / ??? |
| | Alter priorities on-the-fly | AI / Online Mission Plan. / ??? |
| Likely ethical limit | | |
| "Take the hill" | Dynamic tactical engagements | Tactical Reasoning |
| "Find all the _____ in there and ______ them." | Take *action* in unknown env. | Rapid Abstraction |
| "Go through that facility, bring back a map and pictures" | Navigate unknown / denied env. | ✓ SLAM (Simult. Local. & Map.) |
| | Navigate known environments | ✓ GPS, path planning |
| Drive / fly with joystick | | |

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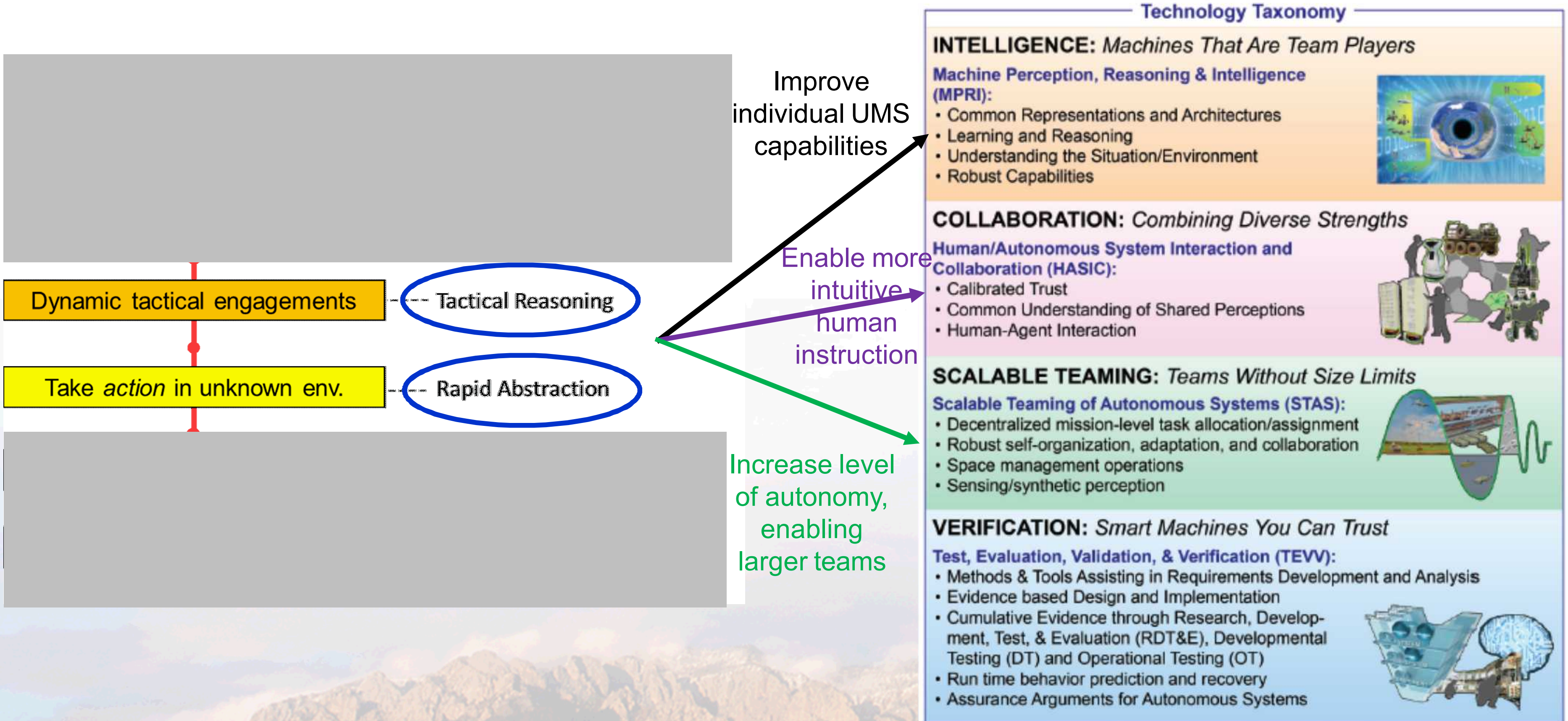
# Relate to DOD Autonomy COI

- **Autonomy Community of Interest has established a taxonomy that is useful for placing autonomy R&D into operational context**

Bornstein et al., 2015



# One Controlling Many (OCM):

**Fundamental algorithms & architecture to enable *dynamic, tactical UMS engagements* via *operator control* – regardless of level of platform autonomy**

# Sandia's "One Controlling Many" Internal R&D Investment

**Goal: Demonstrate a system that makes unmanned systems as responsive to *command intent* as squads of soldiers**

- Defining characteristics of our approach
  - Single operator
  - Multiple heterogeneous multifunctional unmanned systems
  - Dynamic, simultaneous heterogeneous objectives
  - Operator directs mission needs (e.g. show me what is behind that shed), *not* specific UxV actions (e.g. UGV #2 drive NE 10 m and turn to face SE)
  - Reactive / adaptive behavior in response to observations
  - Operations integrated with real-time mod / sim engine to provide 3D common operating picture
  - Layered & modular

# New Mission Focus for Unmanned Combat

- **Close-quarters tactical operations against unpredictable adversaries**
  - **Limited pre-planning: Need to respond rapidly to events on the ground**
  - **Use parts of available techniques (teleoperation, swarms, resource assignment)**

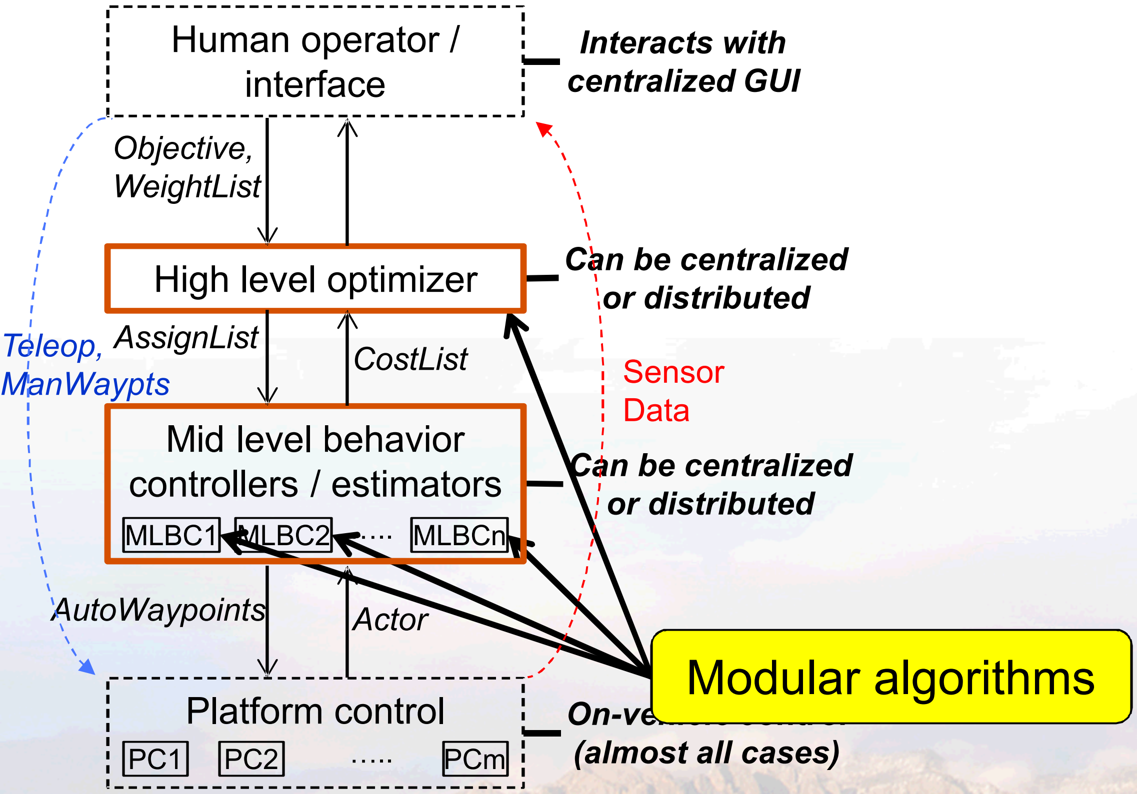
- **Operator: Closely controls outcomes, performs highest level thinking**
  - **High level perception, tactics, prioritization, monitor / correct autonomy**
  - **Directs system by specifying desired outcomes**
  - **Automate the rest (asset-task assignments & execution)**

- **Teams of 4-5 diverse, multi-functional agents**
  - **Use existing platform-level autonomy & interoperate platforms from multiple suppliers**
  - **Team size limited primarily by operator attention**


Dynamic, tactical missions in which human and control system *both* apply intelligence

# Sandia Architecture for Heterogeneous UMS Control (SAHUC)

- **Command & control is layered, modular, & distributed**
- **Custom message set facilitates tactical command & control**




Link to previously approved UUR video

Framework allows multiple vehicle types, multiple operating systems, and control codes from multiple developers to work together in fast, tactical ops

# OCM / SAHUC: Capabilities Demonstrated

- Single operator controlling heterogeneous UMS team
  - Real-time mission definition
  - Variable levels of autonomy used within single mission

- Real time task management
  - Real time task creation
  - Automatic assignments based on heterogeneous capabilities
  - Automatic re-assignments / handoffs

- Mix of centralized and decentralized modular control elements
  - Different software implementations unified by the architecture
    - Windows / Linux
    - ROS / Umbra / Matlab

Relatively basic vehicle-level autonomy limits complexity of assigned behaviors

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Navigate known environments ✓ ---- GPS, path planning

Drive / fly with joystick

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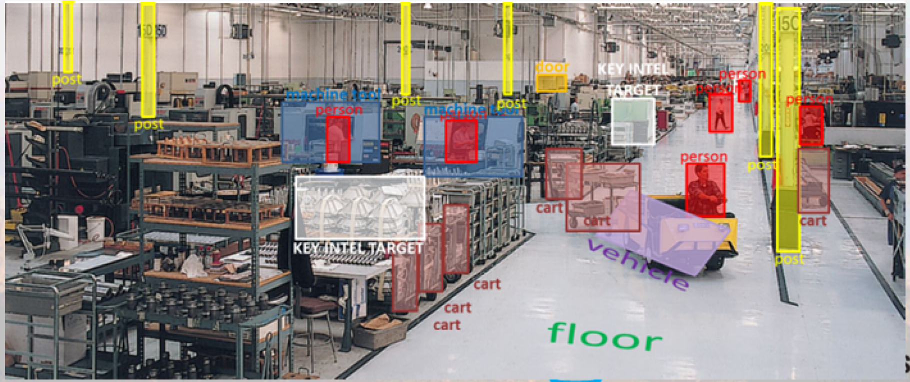
# Rapid Abstraction:

**Ability to automatically generate abstract labels for relevant objects, enabling *object-centered actions* within autonomous missions**

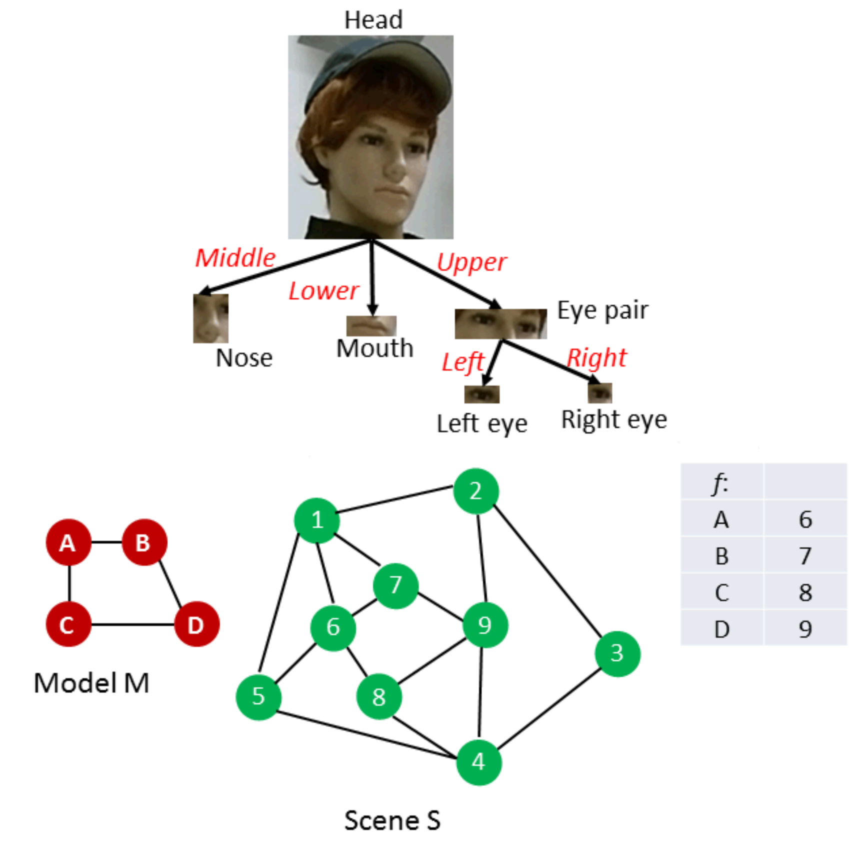
# Rapid Abstraction Approach

- **To increase level of autonomy requires the ability to <u>rapidly identify objects</u>**
- **For defense & security applications, there are 2 important obstacles:**
  - **The general problem is hard / unsolved**
  - **Limited realistic training data**
    - **Particularly relative to popular "deep learning" methods**
- **Three pronged approach:**
  - **1 - "Physics based" multi-sensor fusion**
    - **Train algorithms to identify features / properties – *independent* of specific targets**
  - **2 - Intelligently control sensing vehicle motion to optimize sensor perspective**
  - **3 - Use multi-physics sensors to complement most common sensors (LIDAR, visible cameras)**
    - **E.g. to identify material properties**
- **Ultimately:**
  - **Integrate object ID with mapping**



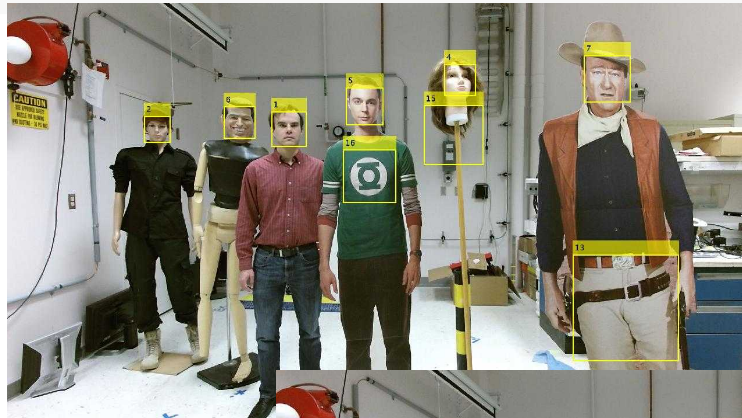
# Physics-Based Multi-Sensor Fusion

- **Build object definitions from relational combinations of features / properties**
  - **Define with graphs**
  - **May be learned or constructed a priori**
- **Detect features / properties independently via various methods**
- **Scene mapping:**
  - **Detect features / properties in scene**
  - **Search for object matches (full or probabilistic) within scene graph**
  - **Simplify with geometric segmentation (SLAM)**

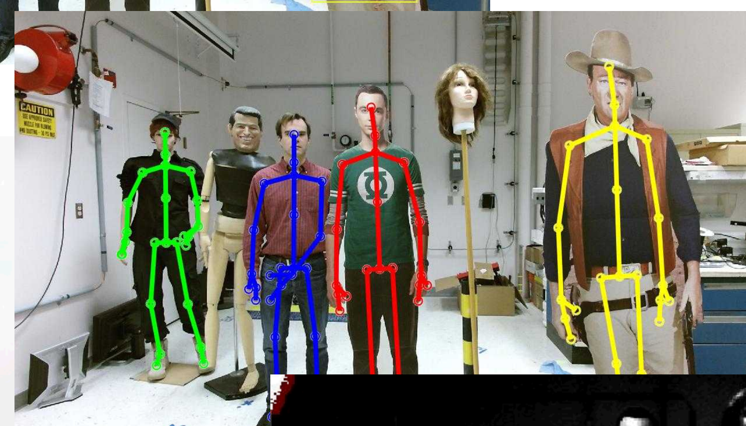


# Proof-of-Concept Demonstration

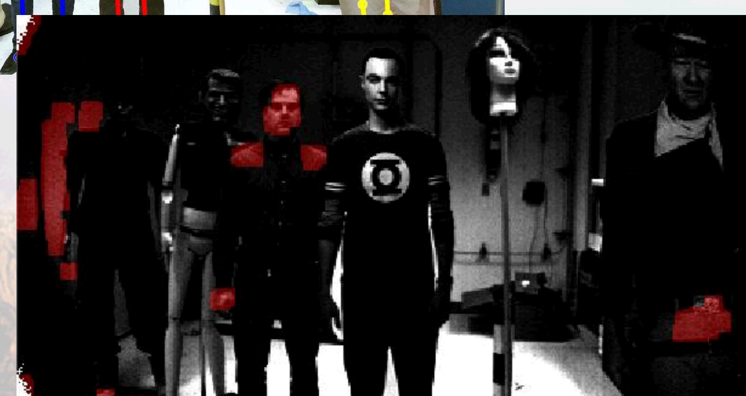
- **Detect people in decoy-filled environment**
- **Demonstrate several core principles**
  - **Hierarchical fusion methods**
  - **Perspective changes**
  - **Integration of multi-physics sensors**



RGB face detection



RGB+D (MS Kinect) skeleton tracking

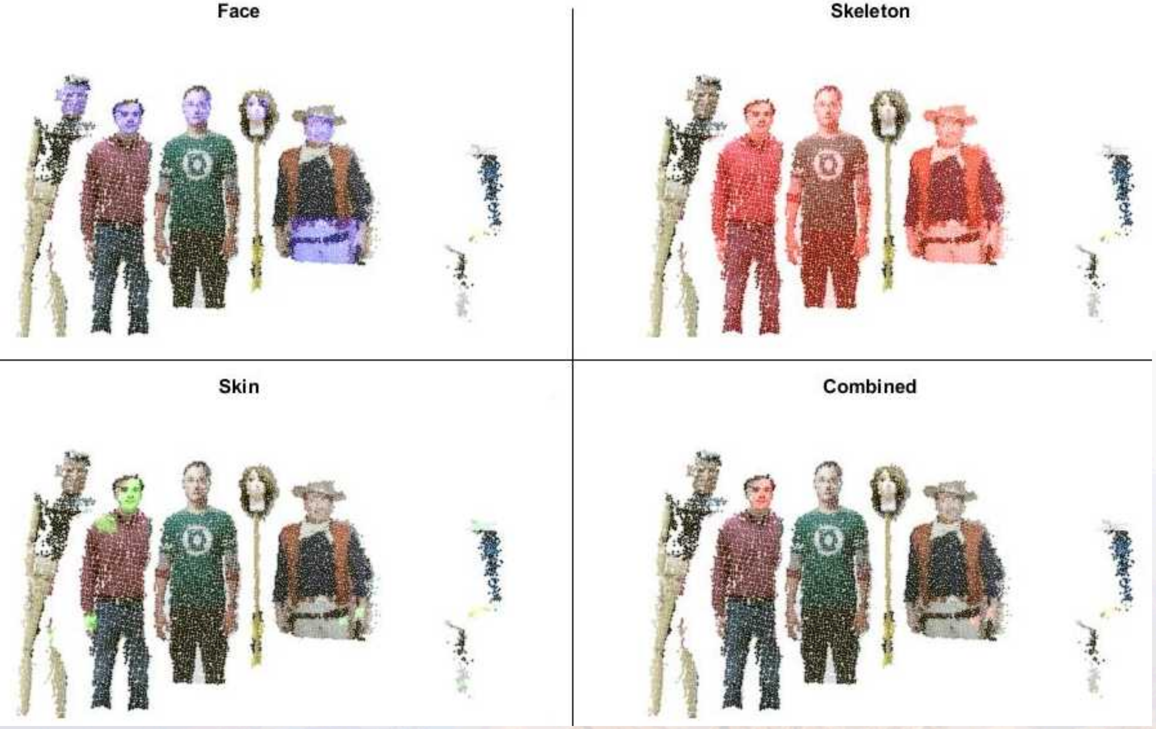


Hyperspectral skin detection

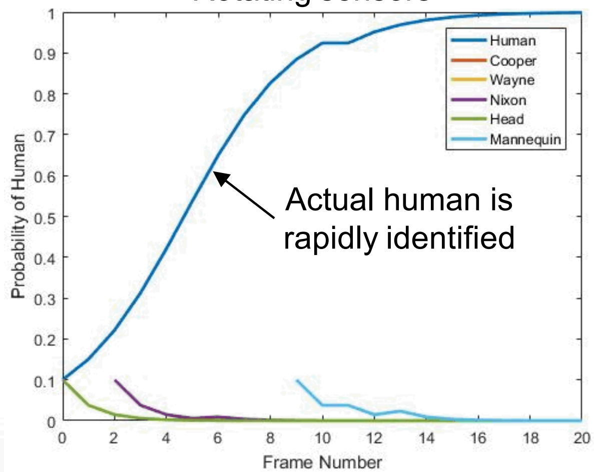
# Proof-of-Concept Results (1)

*Bayesian tracking / classification update*

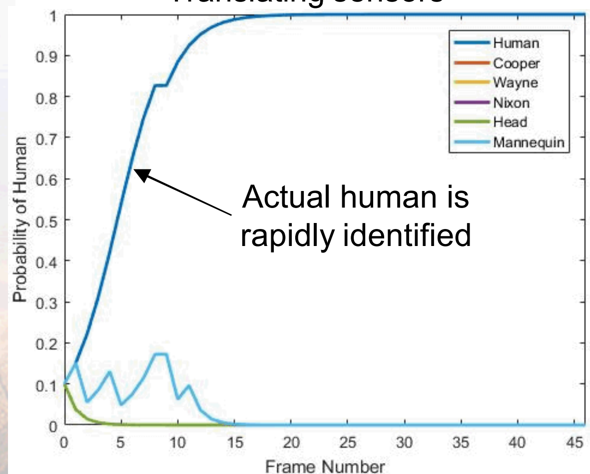
*Frame-by-frame composite detection*




Rotating sensors

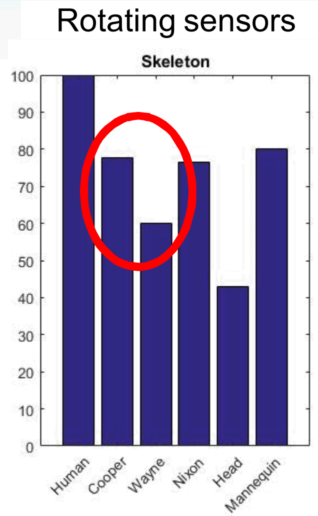


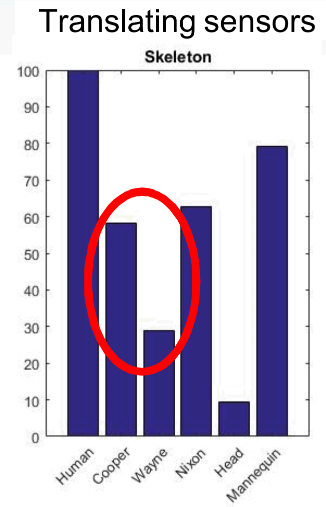

Translating sensors

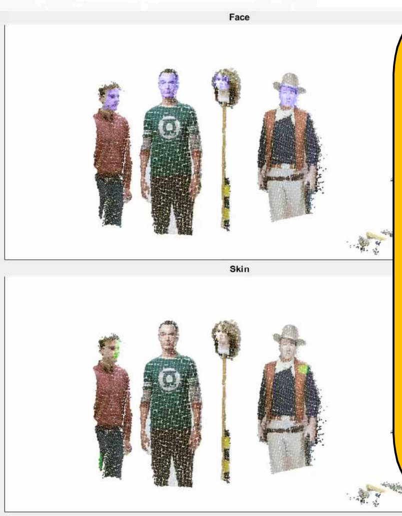


# Proof-of-Concept Results (2)

- **Perspective change (even subtle) matters**




Initial Results Highlight Value of Approach:

1) Learned features, defined objects *a priori*
2) Perspective changes help
3) Multi-physics sensors reduce false positives

# Summary and Next Steps

- **Rapid abstraction (RA) and tactical reasoning (TR) are big technical leaps required to be able to use UMS in fast-paced tactical applications**
- **OCM approach relies on human for RA and TR; tries to relieve them of all other duties and translate their goals seamlessly**
- **RA is the gateway to higher-level, more intuitive instruction**
- **Need to integrate object labeling with 3D mapping and make it *fast***

Questions?

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# Backups

# Teleoperation

- **Today's prevailing control methods: Teleoperation / Waypoint Control**

robotshop.com

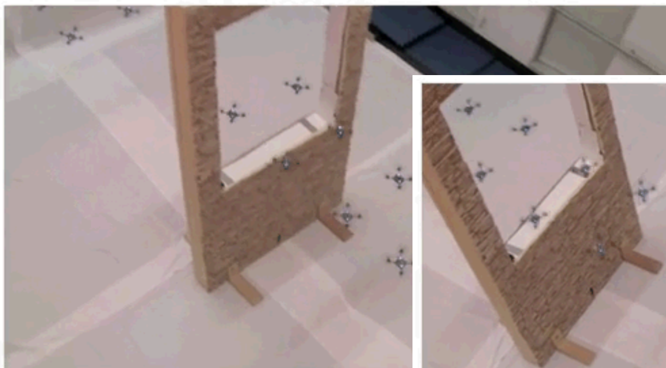
nytimes.com

- **Common missions**
  - ISR ("Go to location and loiter")
  - Drone strikes ("Go to location, fire smart weapon when so ordered")
  - EOD ("Make a series of small and simple movements – very slowly")
- **Characteristics**
  - Actions fully attributable to operator
  - Performance is tightly coupled to comm link characteristics
    - Response time = (motor response to visual stimulus ~150 ms) + (uplink delays) + (increased recognition time due to poor sensor bandwidth) + (downlink delays) > 150 ms
  - Real-time cooperation between agents requires high quality awareness of environment, red force, blue force = additional bandwidth & immersive interfaces

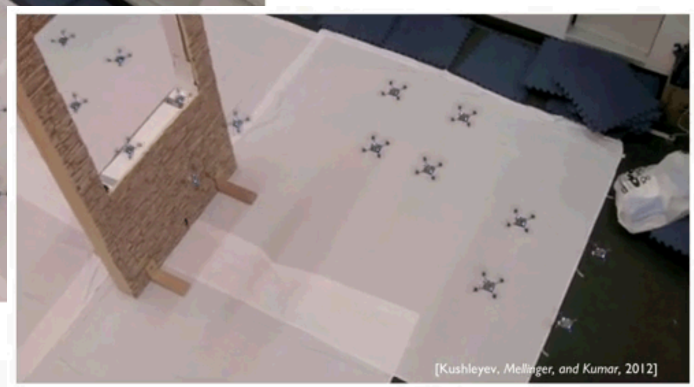
**Are there smarter ways to make a UMS team function as a single unit?**

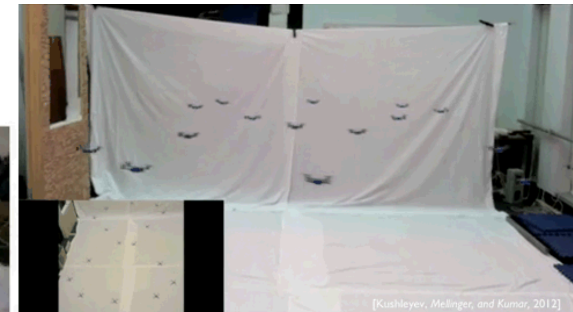
# Cooperative Control

- **"Swarm" control**



V. Kumar TED talk




V. Kumar TED talk

- **Common missions**
  - **Converge on a source (RF, chemical plume, etc.)**
  - **Spread around a perimeter**
  - **Fly in formation**
- **Characteristics**
  - **Decentralized control algorithms – scale well to large N**
  - **Assets are single-functional & homogeneous (or treated as such)**
  - **One objective at a time, typically with one target**
  - **Mission outputs depends primarily on moving to correct state (e.g. position)**

Swarming is a part of UMS team operations, but not sufficient. Can we do better?

# Key Elements

- Architecture for information sharing and control
- Layered assignment and control algorithms
- Interface to human operator

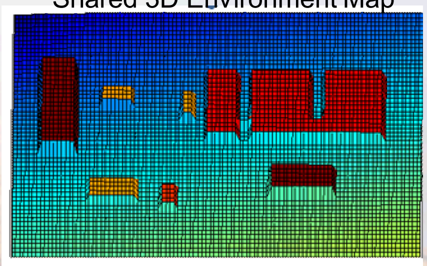
# Sandia Architecture for Heterogeneous UMS Control (SAHUC)

- Intelligent control elements are flexibly distributed across platforms
  - UMS from multiple manufacturers, algorithms from multiple developers
    - Some UMS are capable of greater autonomy than others
    - Need to be interoperable, re-use mid & high level autonomy algorithms
  - Human operator contributes significant intelligence
- Need a way for all agents to share & access critical info at all times
  - Robot Operating System (ROS) does a decent job at a low level
  - Did not find a high-level data architecture that met our needs, so we created our own
- Architecture determines how, where, and when data is passed
  - Implementation can have variable levels of centralization
  - Most agents might need to update most data structures
  - Economize

*Actors (minus header)*

| Actor ID | Actor Location | Active Status | GPS Status | Control Mode | Friend | Type |
|---|---|---|---|---|---|---|
| 15 | 12,14,0, 180,0,0 | 1 (active) | 3 (SBAS Fix) | 2 (teleop) | 1 (friend) | 3 (UAV) |
| 21 | 15,21,0, 92,0,0 | 1 (active) | 2 (fix) | 4 (objective) | 1 (friend) | 2 (UGV) |
| ... | | | | | | |

Shared 3D Environment Map



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# Control Algorithm Summary

- **High level optimizer**
  - **Makes cost-minimizing assignments of agents to assets**

$$\min J = \sum_{i}^{N_A}\sum_{j}^{N_O} z_{ij} * \hat{C}(A_i, O_j)$$

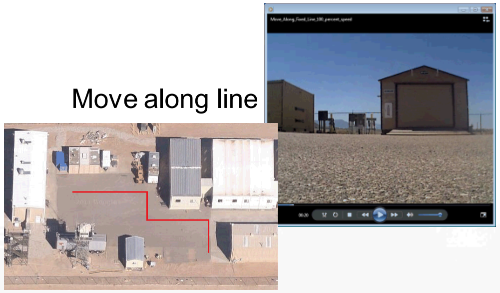
Assignment variables (binary or real valued, 0→1)

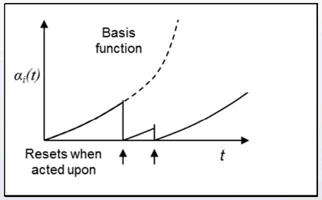
Estimated costs of assigned pairs

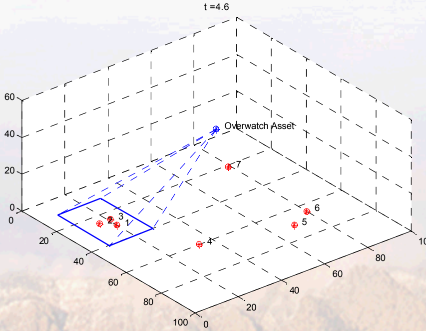

- **Mid level behavior controllers**
  - **Compute estimated costs**
  - **Execute assigned behaviors**
    - **Different behaviors may use different control techniques**
    - **Implemented a simple set of behaviors**
  - ***Attention functions* efficiently create emergent behaviors**
  - **Methods for heterogeneous collaboration**
    - **Adaptations of linear swarm control**
    - **Hybrid distributed model predictive control**

Follow / watch moving target

Move along line

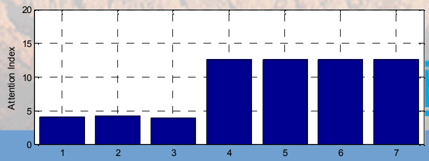





$$\text{minimize } J = -\sum_{i=1}^{N_t} \xi_i \left( \iint_{\text{Camera View}} \left( e^{-\frac{\|\mathbf{x}-\mathbf{x}_t\|}{2\sigma^2}} \right) dxdy \right)$$

where
$\xi_i > 0$ is the attention index
$\mathbf{x}_t$ is the target location
$N_t$ is the number of targets



# Interface to Human Operator

- **Operator must comprehend & influence multiple events in real time**
  - **Operations integrated with 3D real-time model**
  - **Model gives context to real sensor feeds**
  - **Mission metrics, gaps computed in real-time**

- **Operator commands via desired mission outcomes, not instructions**
  - **Operator populates the *Objective* structure through a GUI**
    - ***Objective* is translated into top-level cost functions**
  - ***WeightList* allows optional manipulation of priorities**


3D model view

Real sensor feeds

- **Operator can always reach down to lower layers of control, through a single interface**
  - **Force assignment of asset to objective**
  - **Force waypoints**
  - **Teleoperate directly**

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