Towards Natural and Reliable Peer-to-Peer Teams

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Illustration by Andrew Rae

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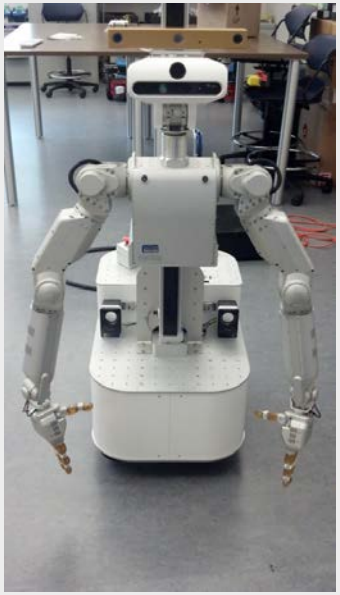
UTK's Distributed Intelligence Laboratory

- Mission: Create autonomous software solutions for distributed intelligent systems, including teams of multiple agents, robots, and people; sensor networks, and embedded systems.
- Personnel:
  - Director: Prof. Lynne E. Parker; *Students:* PhD: Joshua Fagan, Mike Franklin, Bob Lowe, Sudarshan Srinivasan, Chris Reardon, Chi Zhang; B.S.: Andrew Messing, Stephen Richmond



DILab URL: http://dilab.eecs.utk.edu

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My vision for multi-robot teams…

- Human-quality cooperation and interaction of multiple robots that are:
  - Heterogeneous
  - Able to share resources
  - Robust
  - Adaptive and learning
  - Able to communicate implicitly
  - Able to work with human teammates/peers
- Solution approaches that are:
  - General, scalable, integrated

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Outline of Presentation

- Peer-to-peer teaming:
  - Motivation and definition
  - Related work
  - Key research challenges

- Achieving robust behavior in teams of humans and/or robots
  - Risk-aware action selection
  - Cooperation without explicit communication
  - Intelligent learning for robustness

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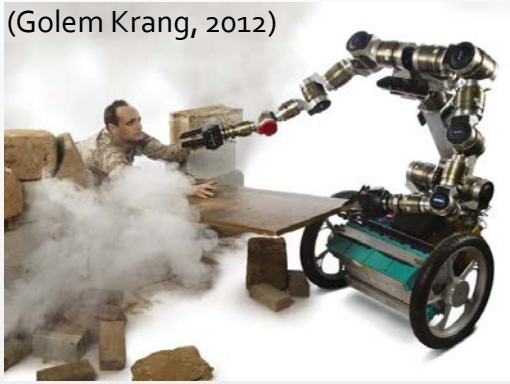
Motivation for Peer-to-Peer Teaming

Search and Rescue

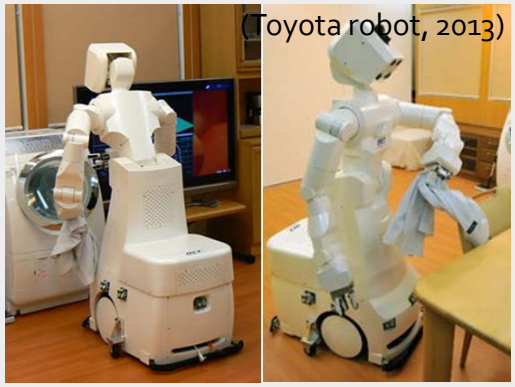


Elderly & Disability Care

Child Education

Security

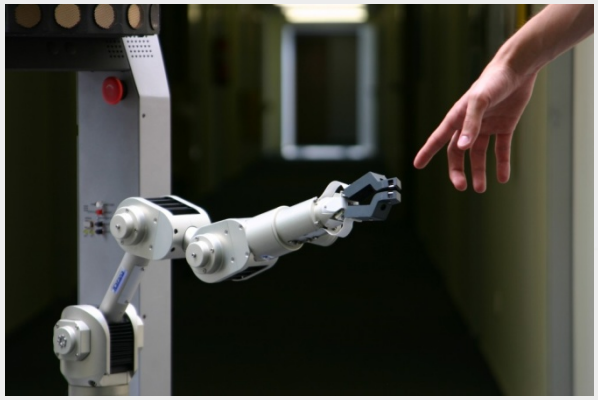
Daily Life Assistance



Entertainment

What are the typical "relationships" between humans and robots?

- Human's roles in human-robot teams (partially from [Scholtz, 2002]):



  - Supervisor/Commander: provides goals, oversees activity, and interjects when needed
  - Teleoperator: commands all robot motions remotely
  - Developer/Operator: develops and modifies software or models
  - Mechanic: modifies robot hardware when needed
  - Peer: involved in face-to-face interactions, contributing skills to the team just like the robot
  - Bystander: watcher from the sidelines, as (more-or-less) disinterested party

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Authority Relationships for Different Human Roles

Authority Relationships: Levels of Control		
Authority Relationship	**Function**	**Context required**
Supervisor / Commander	Commands "what"	Tactical situation
Developer / Operator	Commands "how"	Detailed perception
Peer	Cross-cueing	Shared environment, functions
Bystander	Interacts	Shares environment

(Adapted from NSF/DARPA workshop, 2001)

For peer relationship: *cross-cueing* involves picking up human social cues (attentional state, body language) and interpreting human behavior (intent, goals, desires)

Spatial Relationships for Different Human Roles

Spatial Relationships: Intimacy and Viewpoint		
Role	**Human's POV**	**Spatial Relationship**
Supervisor / Commander	god's-eye	remote
Peer	bystander	beside
Teleoperator	robot's-eye	"robo-immersion"
Developer / Operator	homunculus	inside

(Adapted from NSF/DARPA workshop, 2001)

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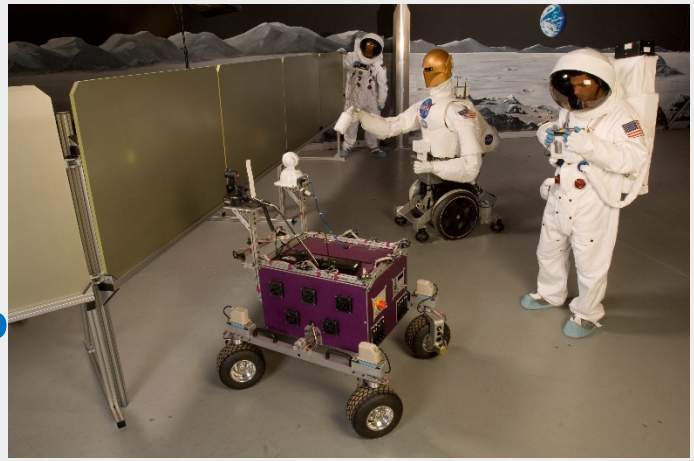
Related Work in H/R Peer-to-Peer Teaming

1. Human treated as reliable remote source of information or control
   - Human does not physically operate in same face-to-face environment
   - Collaboration is treated as a control or communications problem
   - Strong focus on decision-making; little work on challenges of physical interactions
   - *Examples:*
     - **NASA Ames' Peer-to-Peer H/R Interaction Project** [Fong, et al, '01+]
       - Humans perform higher-order cognitive and perception functions while robots perform reactive, precise, and physically demanding functions
       - Focus is on how robot can ask meaningful questions of humans, and make use of human expertise



     - **CMU's Peer-to-Peer H/R Teams for pickup teams** and treasure hunt task [Dias, …, Veloso, …, Stentz, et al, '06+]
       - Humans provide help for recovering from failures
       - Humans interact with robots via a GUI
       - Humans retrieve "treasure" by following robots to location and back

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Related Work in H/R Peer-to-Peer Teaming (2)

1. Human treated as reliable remote source of info/control (con't.)
   - *Examples (con't):*
     - INEEL's Supervisory vs. Peer-Peer Interaction [Marble, Bruemmer, et al, '04]
       - Focus is on ***mixed-initiative* control** (equivalent to ***sliding autonomy*** in other research), where robots accept varying degrees of control from human
       - Robot operates in environment; human oversees remotely via computer-based HRI
     - Large amount of related research in ***sliding* (or *adjustable*) autonomy**, which varies the degree to which the human controls the robot [Dias, et al, '08; Bruemmer, et al, '04; Tambe, et al, '04; Sycara, et al, '04; Kortenkamp, et al, '97; Goodrich, et al, '01; Desai '05; Sellner, …, Simmons, Singh, et al; and many others]
       - Human controls robot in one of several modes: teleoperation, safe mode, shared control, full autonomy
       - Robot operates in environment; human oversees remotely via computer-based HRI

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Related Work in H/R Peer-to-Peer Teaming (3)

2. Human directly operates robots that are physically identical to autonomous robots operating in the same workspace
   - Autonomous robot does not have to interpret or understand physical motions of human body
   - From an autonomous robot's perspective, it isn't really necessary to know that a human is driving one other robots
   - *Example:*
     - CMU's Peer-to-Peer Segway Soccer Team [Veloso et al, 2005+]
       - Humans ride on, and control, Segway robots operating in same space as autonomously-controlled Segway robots

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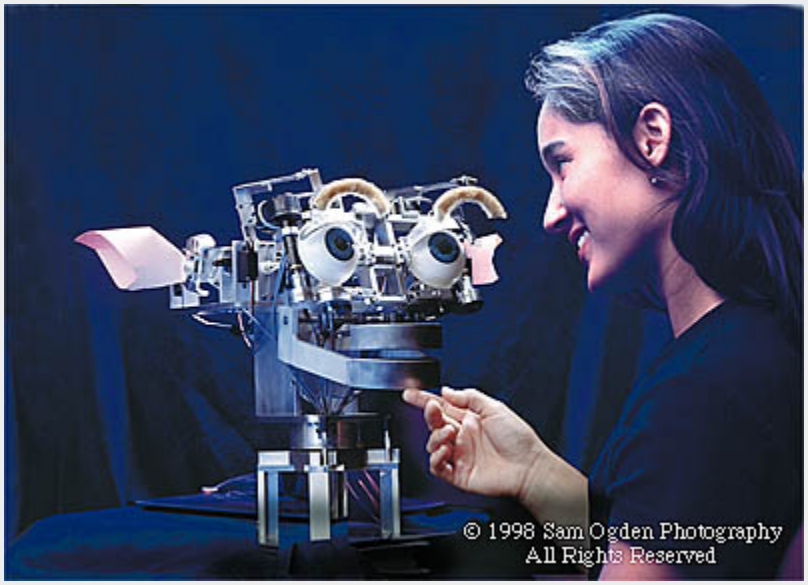
Related Work in H/R Peer-to-Peer Teaming (4)

3. Human and robot work face-to-face; emphasis is on social skills
   - Makes extensive use of rich physical cues – nodding, head poses, hand gestures, facial expressions, eye gaze, shrugging, etc.
   - Requires highly expressive robot capabilities
   - *Example:*
     - Breazeal's social robots (Kismet, Leonardo) [Breazeal, et al, 1990s+]
       - Robot is non-mobile, workspace is directly between human and robot
       - Human can teach child-like skills to robot, and then work together to perform tasks (such as pushing buttons or categorizing blocks)



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What is Peer-to-Peer Human-Robot Teaming?

- Variety of definitions on literature:
  - Face-to-face interactions, in which humans and robots both contribute skills to the team according to their ability [Scholtz, '03]
  - Side-by-side interactions, in which humans and robots interact in a competent, natural manner [Fong, '04]
  - Non-hierarchical relationship between humans and robots, in which humans and robots can assign tasks to each other through direct requests/commands or through automated task allocation systems [Dias, .., Veloso, Stentz, '08]
  - No fixed hierarchy for decision making; all team members are equal participants, with distributed decision making [… Veloso, '05]

and more…

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What is Peer-to-Peer Human-Robot Teaming? (2)

- Variety of definitions on literature (con't.):
  - Robots are considered part of a dynamic human-machine team, rather than a passive tool [Marble, Bruemmer, …, '04]
  - Teamwork, involving partnership in which humans and robots work "jointly with" others, rather than "acting upon" others, requiring social adeptness on the robot's part [Hoffman and Breazeal, '04]

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Our working definition of peer-to-peer human-robot teaming

Our Working Definition:

Peer-to-Peer Human-Robot Teams:

- Humans and robots operate in the same physical space, side-by-side
- Team works on "Shared Cooperative Activity" [Bratman, '92]:
  - Mutual responsiveness: each agent attempts to be responsive to intentions and actions of the other, knowing that the other agents are also attempting to be similarly responsive
  - Commitment to the joint activity: each agent has an appropriate commitment to the joint activity
  - Commitment to mutual support: each agent is committed to supporting the efforts of the other to play their role in the joint activity (i.e., provide help when needed for the other agent to achieve its role)
- Assumes humans and robots share common ground [Hoffman and Breazeal, '04; Clark '96]

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What is our goal in peer-to-peer H/R teaming?

Peer-to-peer interaction:

- Should be more natural to humans
- Could enable human-robot coordination in (wireless) communications-limited environments
- Emphasizes *implicit* interactions
- Ultimately, could allow humans and robots to work together in a manner similar to human-only teams today

***Example*:**

Search and rescue teams

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What is our goal in peer-to-peer H/R teaming?

Peer-to-peer interaction:

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Another Example:

Fireteam of soldiers clearing a building; through training, they understand well how to interact and work as a team, with minimal need for explicit communication.

Our objective is to add robots to this type of team, while maintaining the same "natural" interaction capabilities within the team.

What are fundamental issues in peer-to-peer teaming?

- Interpreting and understanding the **goals**, **intentions**, and **actions** of teammates (from both human and robot perspectives)
  - From the robot's perspective, this involves sensor-based analysis of human activity
- How to **represent** human (and robot) **capabilities**
- How robots **decide which tasks to pursue**, and how to provide support for human as needed
- How to **adapt** to changing capabilities or team members
- How to ensure **reliability** and **robustness** of the interaction

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More generally – How to ensure reliability and robustness?

- Variety of techniques:
  - Awareness of risk in action selection
  - Increased reliance on implicit communication
  - Intelligent learning:
    - Adaptive causal models
    - Data-driven learning of "normal" behavior, for use in detecting anomalous behavior
      - Applied in:
        - » Multi-robot teams
        - » Sensor networks
        - » Human-robot teams

Let's review some examples from our research…

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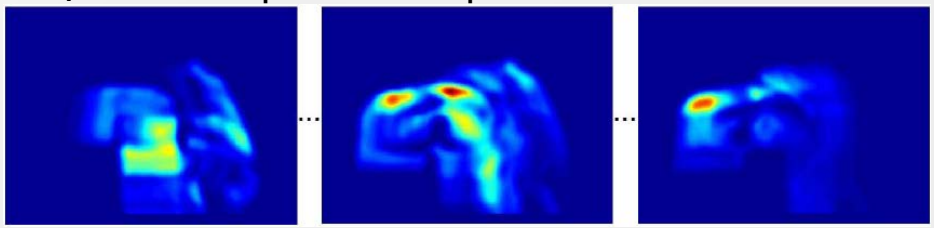
Our work in Peer-to-Peer Teaming

Our work is focused in several areas:

- Features for human activity recognition
- Human activity recognition
- Multi-human perception
- Robot action selection in response to human activity recognition

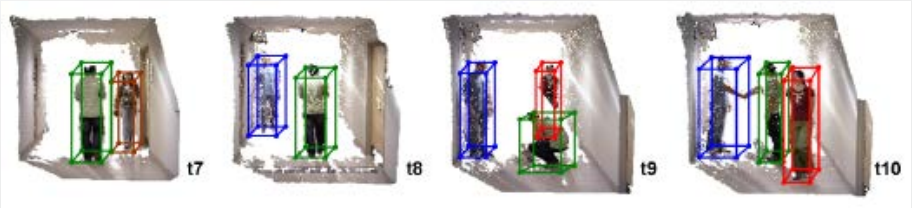
Features:

4D Local Spatial Temporal features

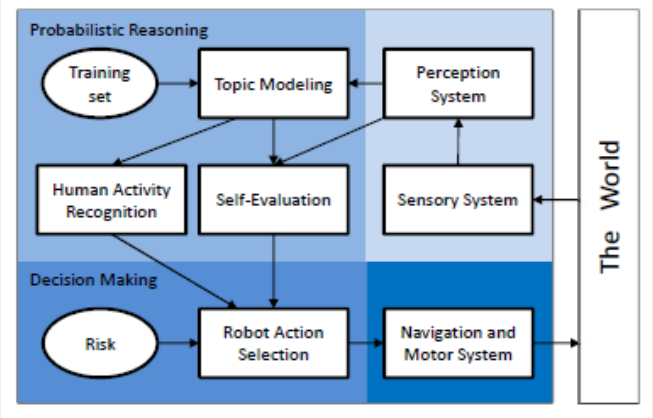


Human Activity Recognition

Multi-Human Perception:



Risk-Aware Action Selection:



For more information:

Hoare & Parker, *IROS 2010*
H Zhang & Parker, *ICRA 2011*
H. Zhang, Parker, & Edwards, *ICMLA 2012*
H. Zhang, Reardon, & Parker, *IEEE Trans. on Cybernetics*, 2013
H. Zhang, Zhou, & Parker, *ICRA 2014*
H. Zhang, Zhou, Reardon, & Parker, *CVPR 2014*

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UTK Project – Human Activity Recognition

Video of some of our results with new feature definition:

For more information:

H. Zhang and L. E. Parker, "4-Dimensional Local Spatio-Temporal Features for Human Activity Recognition", *IROS* 2011.

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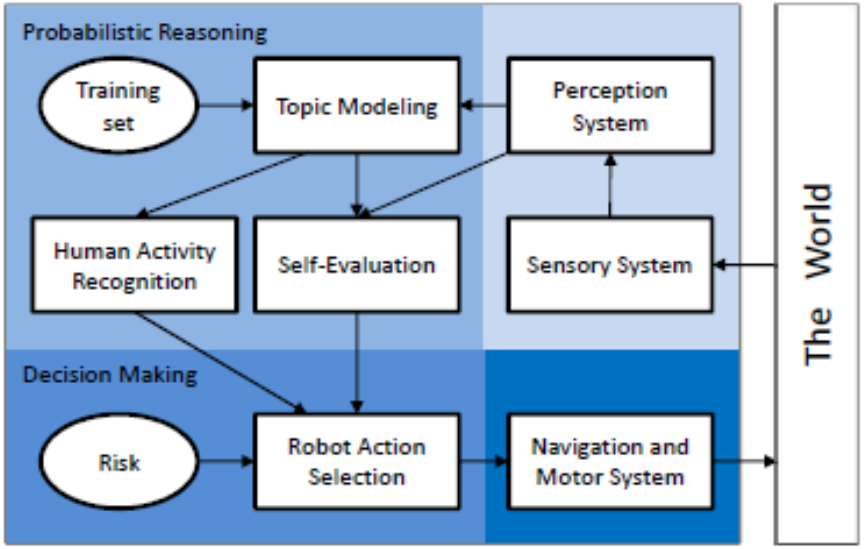
UTK Project: Risk-Aware Action Selection

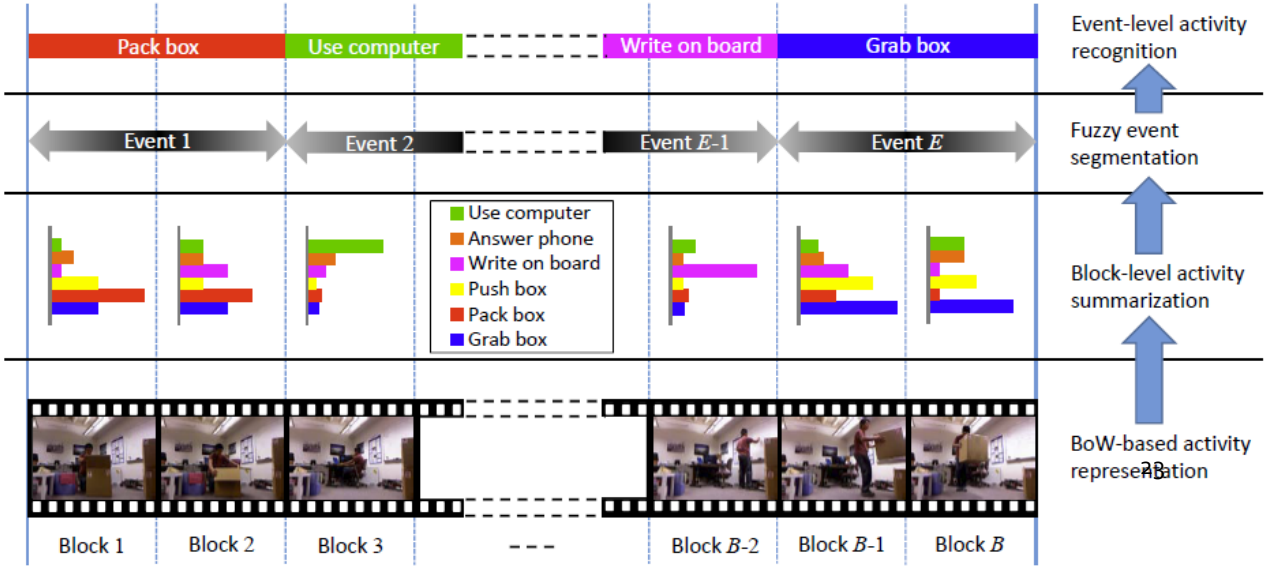


Impact:

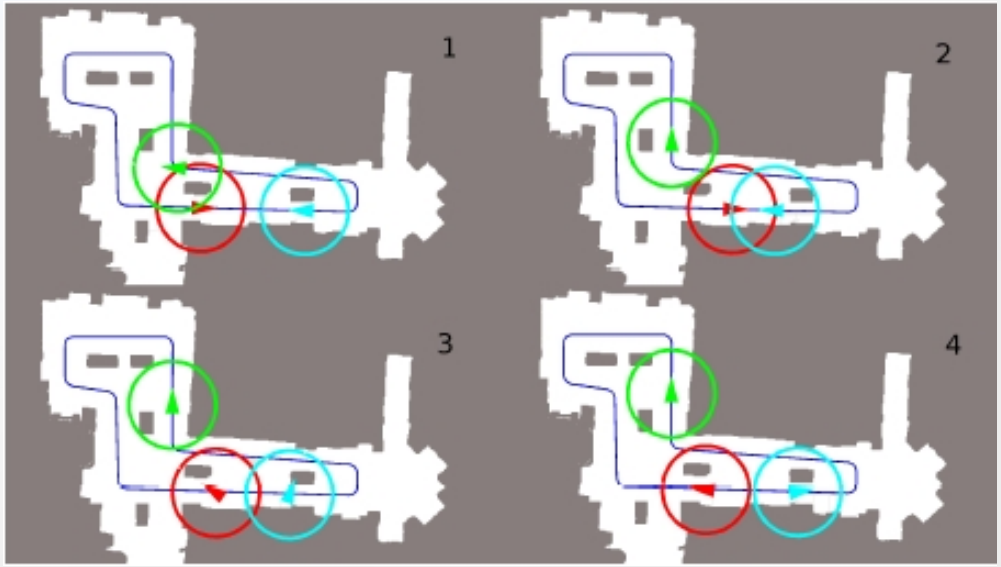
- Allows robots to behave in more resilient manner, in light of sensor uncertainties
- Enables robots to behave more naturally to humans, in that they intelligently consider variety of possible states, rather than only maximum likelihood

New Idea:

By understanding distribution of possible human actions, robots can select response by evaluating the risk of being wrong



UTK Project: Multi-Robot Perimeter Patrol without Explicit Communication



Impact:

- Allows robots to patrol border in fully decentralized fashion, with no communication
- Can enable dynamic reaction in patrolling due to robot failures, or to allow a "friend" robot to pass through

New Ideas:

- Defines behavioral control based on the concept of *action*, obtained by combining elementary behaviors in the Null-Space-Behavioral Framework
- Uses a finite state automata as a supervisor in charge of selecting appropriate action

For more information:

- Marino, Parker, Antonelli, Caccavale, *ICRA* 2009.
- Marino, Parker, Antonelli, Caccavale, and Chiaverini, *ROBIO* 2009.
- Marino, Parker, Antonelli, and Caccavale, *Mediterranean Conf. on Control and Automation*, 2009.
- Marino, Parker, Antonelli, and Caccavale, *Journal of Intelligent and Robotic Systems*, 2013.

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UTK Project: Multi-Robot Perimeter Patrol without Explicit Communication

Video of Results

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Illustration of Challenges in Generating Robust Cooperative Behavior

Team Objective: Convoy (or follow-the-leader), where "smart" leader shows the way to the less-capable follower robots

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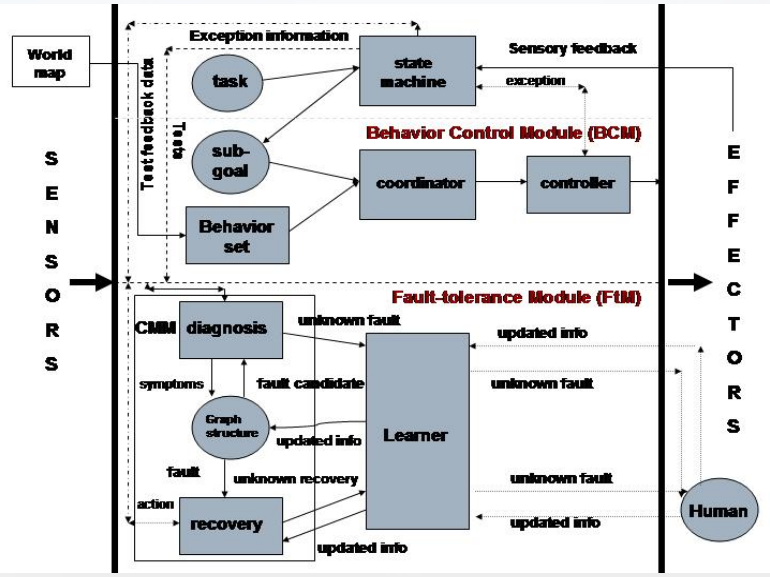
UTK Project: *LeaF* – Learning adaptive causal models for fault detection and recovery in teams



New Ideas:

- Case-based learning for classifying similarity between new fault and previous experience
- Adaptation of LID algorithm (Lazy Induction of Descriptions) for reliable similarity matching
- Metrics for evaluating multi-robot team performance

Impact:

- Increases robustness of teams through easier diagnosis and recovery from errors
- Aids in scalability to larger robot teams, through sharing of fault experience
- New metrics give ability to compare alternative multi-robot team solutions

For more information:

- Parker and Kannan, "Adaptive causal models for fault diagnosis and recovery in multi-robot teams", *Proc. of IEEE Int'l. Conf. On Intelligent Robots and Systems*, 2006.
- Kannan and Parker, "Fault-tolerance based metrics for evaluating system performance in multi-robot teams", *Proc. of PerMIS*, 2006.

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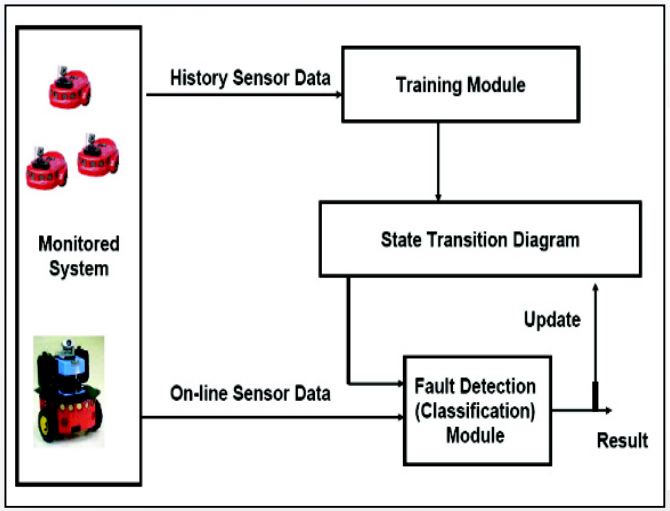
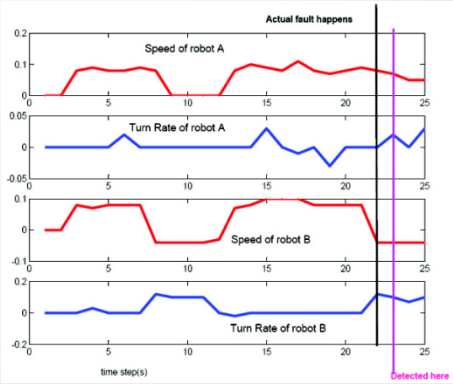
UTK Project: *SAFDetect* – Cooperative behavior monitoring for fault detection





Impact:

- General approach to cooperative fault detection that does not require extensive modeling of control
- Increases robustness of team through easier detection of tightly-coupled task problems

New Ideas:

- Monitor sensor data in multi-robot coalitions to learn model of expected behavior
- "Black box" sensor model makes use of feature selection, fuzzy c-means clustering, HMMs to learn "normal"
- Use online monitoring to detect errors in cooperation – either hard faults, logic faults, or coalition faults

For more information:

- X. Li and Parker, "Distributed Sensor Analysis for Fault Detection in Tightly-Coupled Multi-Robot Team Tasks", *ICRA* 2009
- X. Li and Parker, "Sensor Analysis for Fault Detection in Tightly-Coupled Multi-Robot Team Tasks", *ICRA* 2007.

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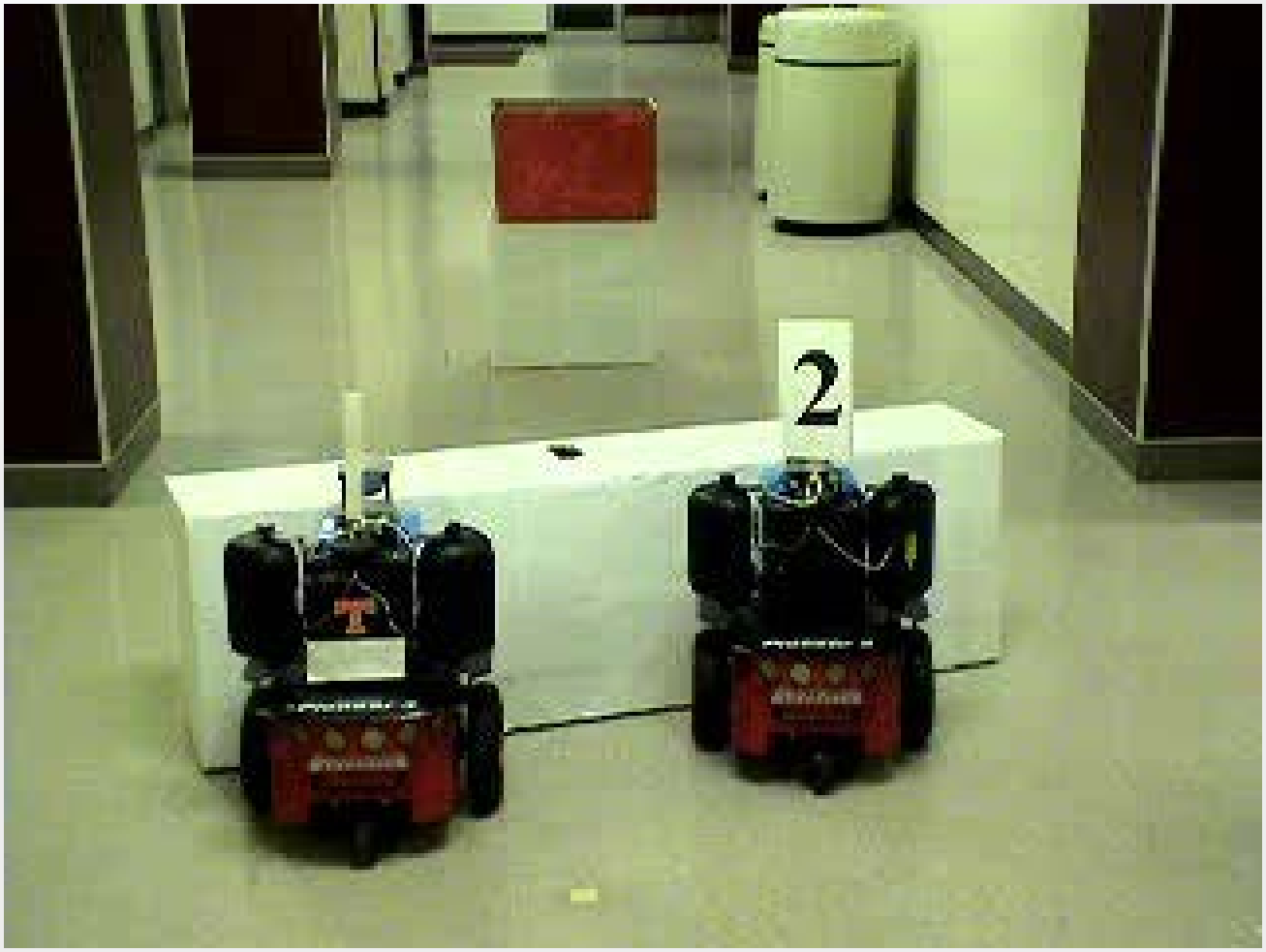
UTK Project: *SAFDetect* – Cooperative behavior monitoring for fault detection

Video of Results:



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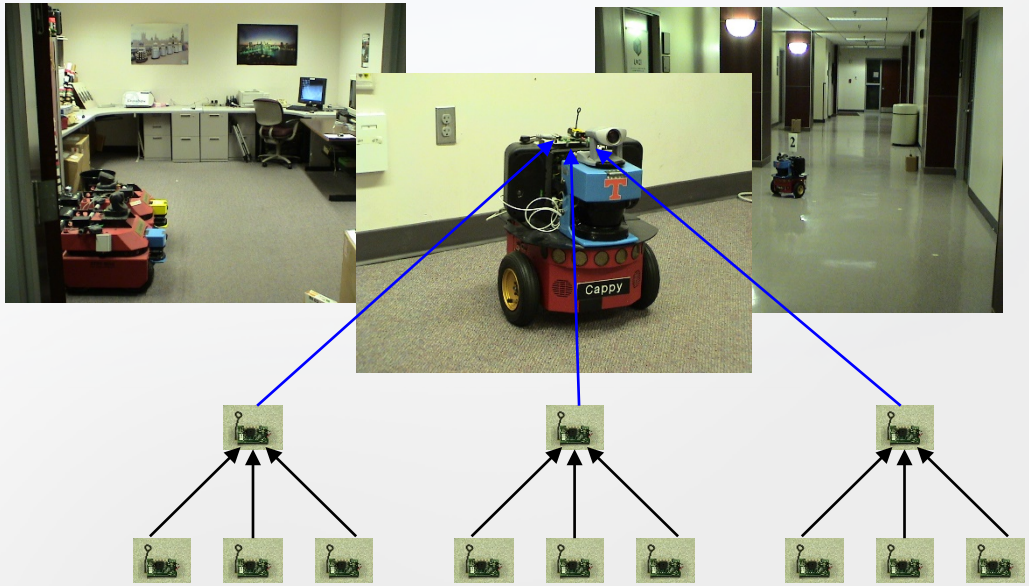
UTK Project: Anomaly Detection in Mobile Sensor Networks



Impact:

- Provides general approach to anomaly detection
- Approach applicable to many applications (e.g., intruder detection, environmental monitoring, etc.)

New Ideas:

- Make use of FuzzyART (Adaptive Resonance Theory) for learning "normal" and detecting anomalies
- Create new category when sensor input is significantly different from what has been seen before
- Mobile nodes (robots) respond to anomalies in sensor network

For more information:

- Li & Parker, "Nearest Neighbor Imputation Using Spatial-Temporal Correlations in Wireless Sensor Networks", *Information Fusion*, 2014.
- Li & Parker, "Sequential anomaly detection using wireless sensor networks in unknown environments, in Springer book, *Human Behavior Understanding in Networked Sensing*, 2014.
- Parker & Li, "Detecting and monitoring time-related abnormal events using a wireless sensor network and mobile robot", *IROS* 2008.
- Li & Parker, "A spatial-temporal imputation technique for classification with missing data in a wireless sensor network", *IROS* 2008.

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Our research next steps…

- Our own research is aimed next at physical human-robot teaming experiments with our new Meka robot…

(just a fun video to show some of the Meka's capabilities)

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Summary and Conclusions

- Ultimate goal is to achieve teams of humans and robots, working together as peers

- To achieve, requires technical advances in many areas:
  - Recognition of human activities
  - Stronger reliance on implicit communication
  - Risk-aware action selection
  - Learning for fault anticipation, detection, and recovery
  - Etc.

- Many advances have been achieved, but much work remains!

Illustration by Andrew Rae

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Thank you! Questions?

Distributed Intelligence Laboratory

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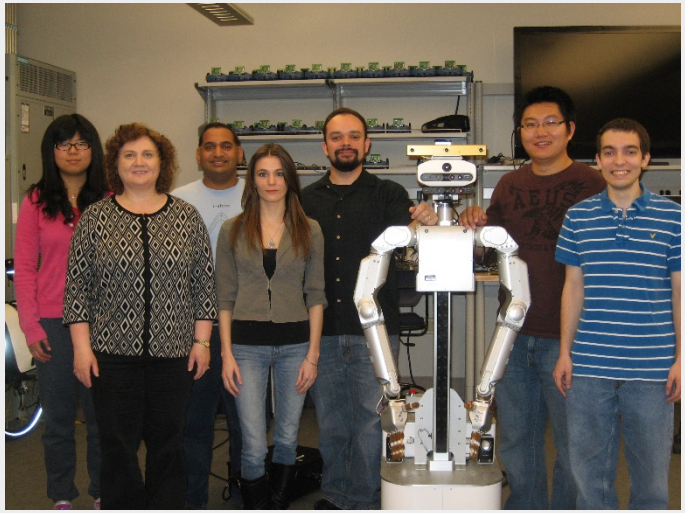

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