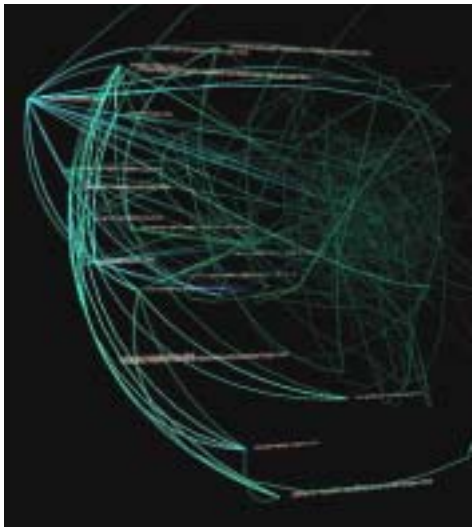


Networked Robots

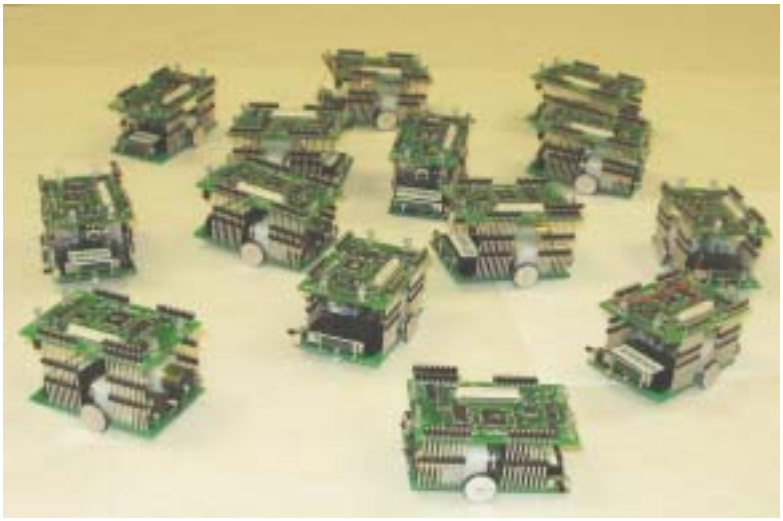
Ken Goldberg UC Berkeley
Daniela Rus MIT
Ning Xi Michigan State

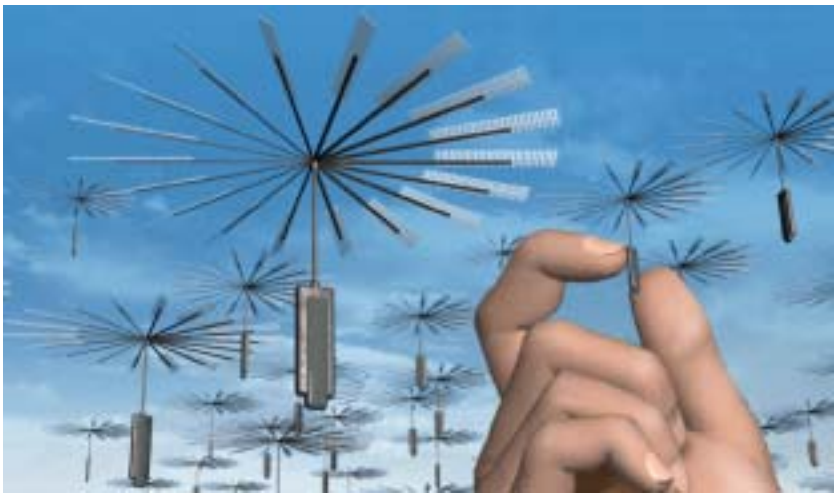
networked robots:

http://telegarden.aec.at

Live Demo of Super Media Enhanced Internet Based Teleoperation – IROS 2003

networked robots:





Smart Dust: Kris Pister, UCB

Networked Robots:

Systems that couple communication to control of one or more robots via networks which often include sensors and remote human operators.

Two subclasses :

1) **Tele-operated**, where human operators send commands and receive feedback via networks.
2) **Autonomous**, where robots and sensors exchange data and coordinate via networks.

Enabling Technologies:

1. Network Standards: IP, HTML, Browsers
2. Processor and Networking Chipsets
3. Compression Standards: JPG, MP2,3,4
4. Infrastructure: clients, routers, cabling
5. Bandwidth: 10 Mbps, 100Mbps, Gbps
6. Public Exhuberance: Wide Adoption
7. Wireless IP Standards and Chipsets
8. Motes, Smart Dust, Pico-Radio

Major US Laboratories and Investigators:

1. CMU: Choset, Veloso, Simmons, Coppin, Singh
2. Crossbow, Dust Inc
3. Intel Research: Culler, IRISnet, PlanetLab,
4. Irobot and Evolution : Greiner, Brooks, Pirjanian
5. Michigan State: Xi
6. Microsoft Research: Zhao
7. Minnesota: Papadopolous
8. MIT: Rus, Slotine
9. NASA: Backes, Schenker
10. Stanford: Thrun, Khatib
11. UC Berkeley: Bajcsy, Culler, Goldberg, Sastry, Wright
12. UPenn: Kumar
13. USC: Bekey, Sukhatme, Requicha, Mataric
14. U South Florida: Murphy, Valvanis
15. UW: Hannaford, Fox
16. Wash U: Tarn

Major Non-US Laboratories and Investigators:

- Japan: Tanie, Chong, Fukuda, Kosuge: $7 Million in 2004
- Korea: Ministry of Information and Communication, KAIST, Samsung, Roh,Lee, Networked Robots Initiative
- China, Taiwan, Hong Kong: Y.C. Wang, Y.H. Liu
- Australia: CSIRO, Corke, Trevelyan, Durrant-Whyte
- Canada: McMasters, UBC
- Switzerland: Federal Inst of Technology: Siegwart
- Italy: U. Pisa: Bicchi
- France: Tele-Surgery
- Germany: U. Freiburg: Burgard
- UK: U. Reading: McKee
- Spain: Valdez

International Workshops, Special Issues:

- International: IEEE Technical Committee on Networked Robots (over 130 researchers worldwide):
- Five IEEE Workshops (at IROS 1998, ICRA1999, ICRA 2002, ICRA 2003, ICRA 2004).
- Special Issue of the Autonomous Robots Journal (Dec 2003, v15)
- Special Issue of the IEEE Proceedings (March 2003, 91/3)
- Two Special Issues of the Robotics and Automation Magazine (in Spring 2000).

Influential Papers and Systems:

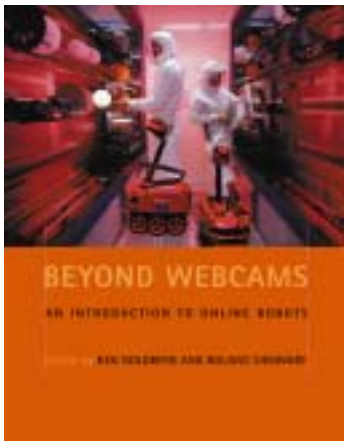
- Spong, Anderson 1989: proved stability through passivity.
- Slotine 1991: wave variables (patented)
- Goldberg 1994: web based telerobot
- Tarn & Brady, Pai, Simmons: tele-programming
- Chong, Penin: tele-simulation.
- Xi: event-based internet telerobots
- Culler 1999: motes and sensor Nets
- Rus: deployment, localization, mapping, and navigation for mobile networks; protocols with guaranteed message delivery
- Kumar: synthesizing local motion behaviors with given constraints on communication and sensing
- Slotine 2000: contraction theory
- Murray, Slotine: adaptive and distributed swarm control
- Sukhatme: networked robot deployment and dispersal

Publications:

- R. Anderson, M. Spong, "Asymptotic Stability for Force Reflecting Teleoperators with Time Delay," The International Journal of Robotics Research, Vol. 11, April 1992.
- Imad Elhajj, Ning Xi, Wai Keung Fung, Yun hui Liu, Y. Hasegawa, T. Fukuda, "Supermedia Enhanced Internet Based Telerobotics", Proceedings of the IEEE, Vol. 91, No. 3, pp. 396-421, March 2003.
- Q. Li and D. Rus, "Sending Messages in Disconnected Ad-hoc Networks", in Mobicom 2000 and Journal of Parallel and Distributed Computing 6(1), pp 75--86, 2003
- C. Belta and V. Kumar, "Abstractions and control policies for a swarm of robots", IEEE Transactions on Robotics and Automation

Publications:

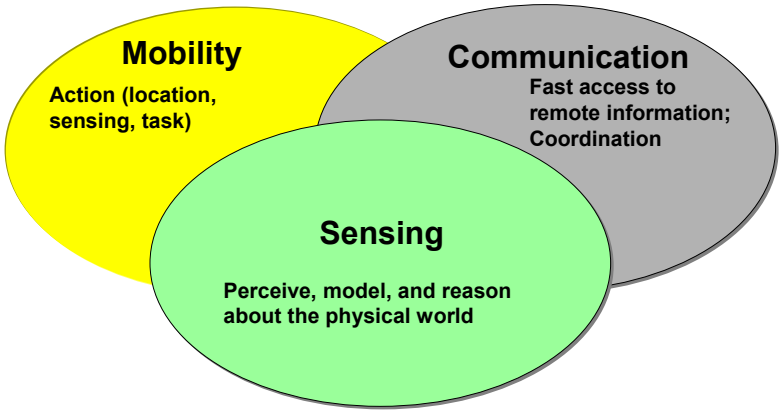
- Paulos, E. and Canny, J. (99)
- Tanie, K., Arai, H. et al. (00)
- Lynch, K. and Liu, C. (00)
- Fukuda, Xi, Liu, et al. (00)
- Tanie, Chong, et al. (00)
- Fong, T., Thorpe, C., et al(01)
- Tanie, K., Chong, N. et al(01)
- Jia, S. and K. Takase (01)
- Hu, Yu, Tsui, Zhou (01)
- Safaric, R. et al. (01)
- Goldberg and Siegwart (02)



Research Challenges

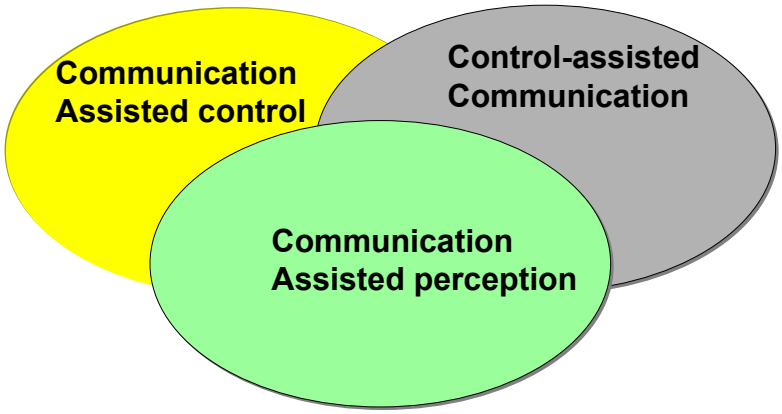
Embed numerous distributed devices to monitor and interact with physical world

Network devices to coordinate and perform higher-level tasks



Exploit spatially and temporally through sensing and actuation

Research Challenges



Research Challenges:

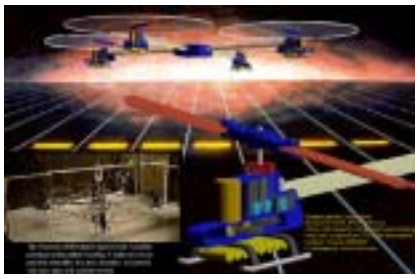
- Communication
  - Variable Time Delays, Packet Effects
  - Latency, Congestion, Bursting
  - Protocol Design: UDP vs. TCP
  - Dynamic Routing
  - Access Control, Security, Privacy
  - Low Latency Video, Tactile
  - Noise, Error Detection and Recovery
- Coordination, Algorithms
  - Collaborative, Distributed Control
  - Deployment, Localization, Mobility
  - Mapmaking and Network Self-Organization
- Systems
  - Human Interfaces
  - Power Management
  - Hybrid Architectures, Interoperability
  - Hardware (sensors, power, size, cost)

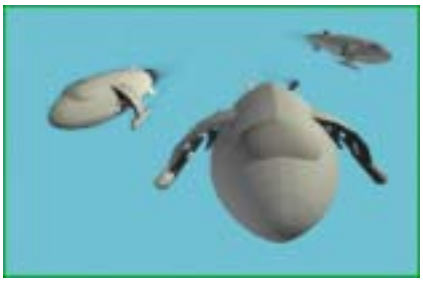
Grand Challenge Applications for 1) Tele-Operated Networked Robots

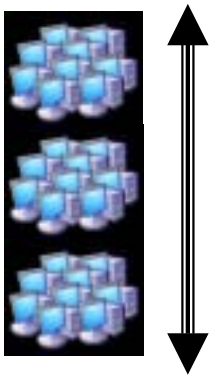
- Journalism: access to remote political events, floods
- Entertainment: access to live concerts, games,
- Tele-Meetings and Tele-Visits
- Tele-Work: diagnosis, repair, supervising, medical monitoring, rehab, warehousing, security
- Shared access to research testbeds: AFMs, biotech labs, particle accelerators, telescopes, fMRI,
- Remote exploration: Antarctica

Grand Challenge Applications for 2) Autonomous Networked Robots

- Entertainment: Robocup!
- Environmental study: rainforest, reef, ocean, caves
- Emergency response: hazardous search and rescue
- Traffic Coordination
- Nano, Micro-Scale Assembly, Monitoring
- Space, Field Exploration: teams of robots
- Manufacturing: semiconductors, bio/pharma
- Process Control: petroleum, agriculture
- Security: monitoring, patrolling

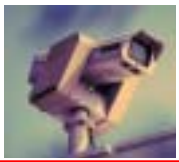




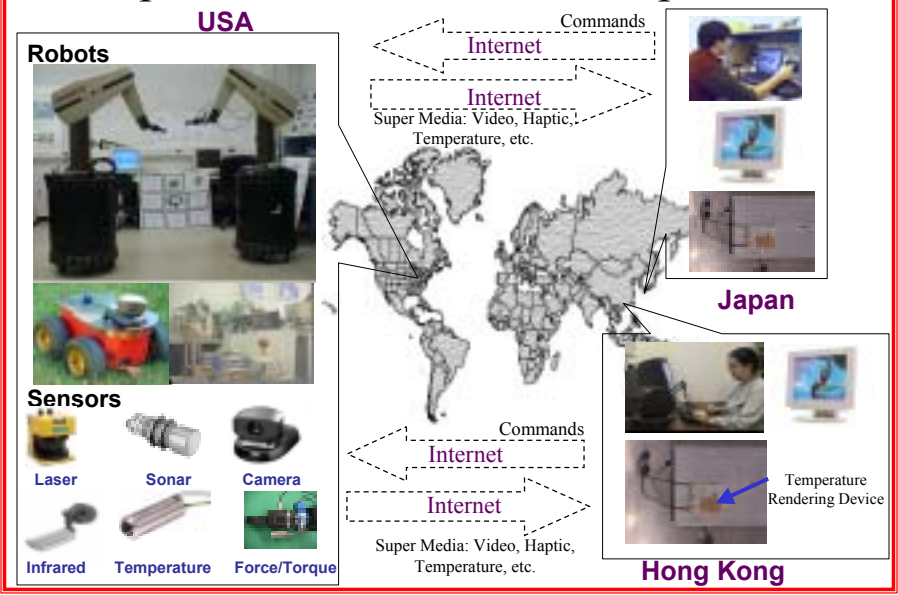


Networked Robots: Tele-Operation

Networked Robots: Autonomous



Super Media Enhanced Teleoperation



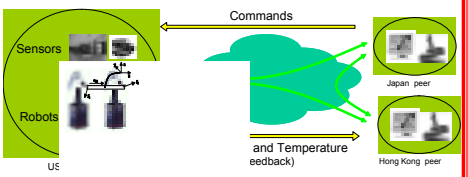
Super Media via Overlay Network

Difficulties

- Communication media is unreliable
- Available node-to-node bandwidth constantly changes is even hardly measurable

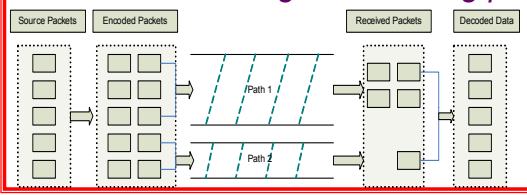
Measured End-to-End available bandwidth between MSU and Berkeley for 24 hours

Overlay Networks



"Virtual Link States" choose alternate paths in case of path failure or performance degradation

Solution: Stretching and sending packets over multiple paths



Source data encoded with stretch factor 2 and sent over two disjoint paths. Six packets sent over path 1. Four packets sent over path 2.

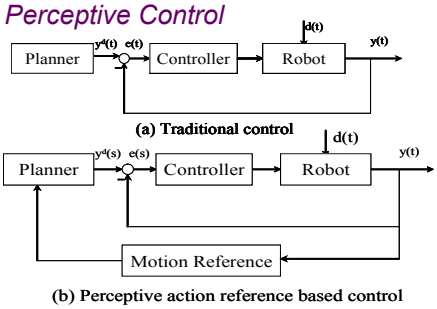
Perceptive Control for Internet Based Teleoperation

Difficulties

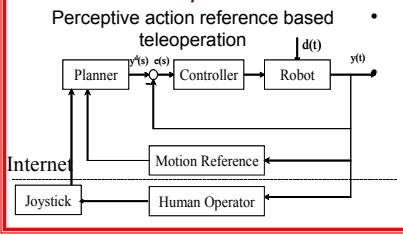
- Random time delay effects
  - Instability
  - Desynchronization
  - Loss of transparency

Measured random time delay between MSU and Hong Kong for 6 hours

Perceptive Control



Solution: Perceptive reference to overcome random time delay



- System stability under random time delay

Conditions for stability

- Asymptotically stable time based system
- Action reference must be a monotonic increasing function of time

- Event transparency and synchronization:
  - Condition for event-transparency

$$\frac{F_h(s)}{V_h(s)} = C\frac{F_e(s)}{V_e(s)}$$

$$F_e(s)_{rd} = F_e(s)_{hd}$$

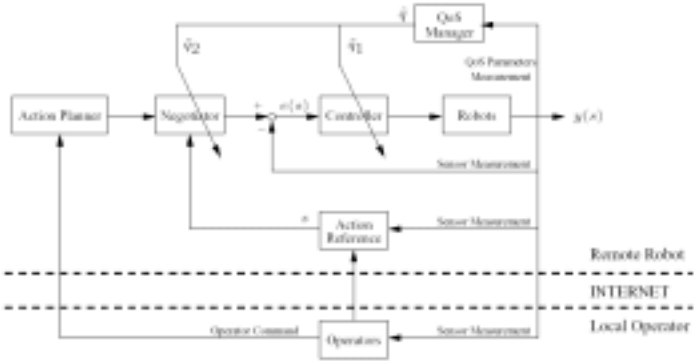
  - Event based multiple media stream synchronization

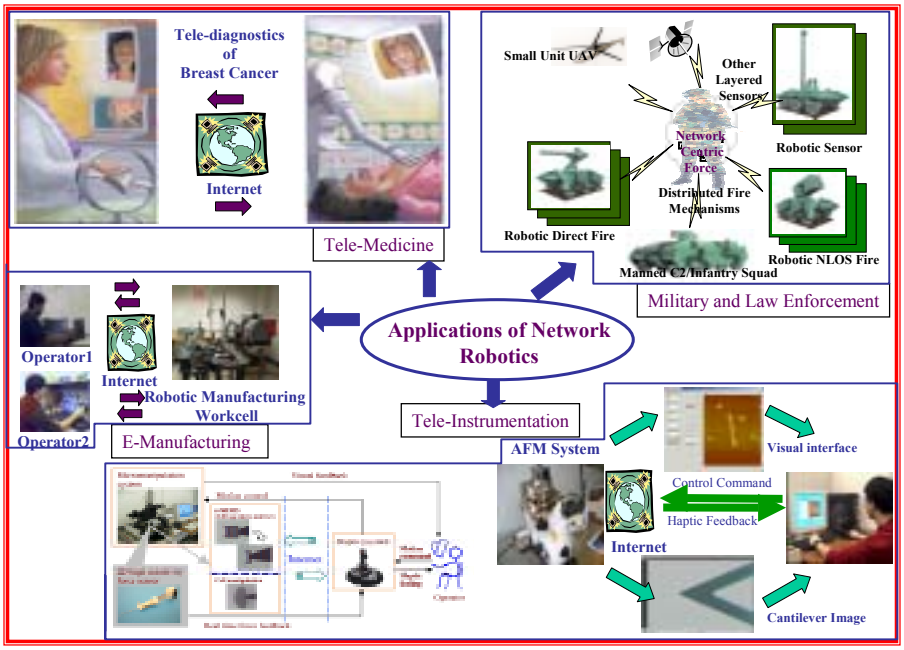
Network QoS Based Control

Based on online measured QoS Parameters, **Adjust**

- Controller Gains
- Resource Allocation

for improving teleoperation systems efficiency



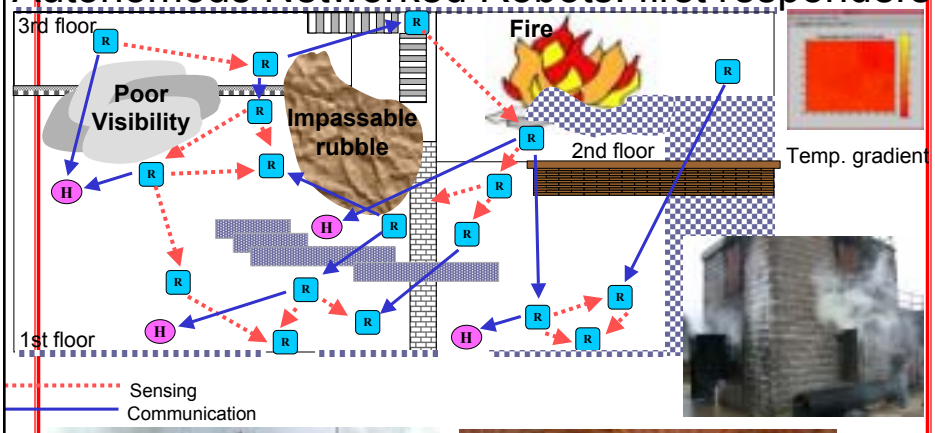


NSF Workshop on Status of Robotics in the US

Scouts: Nikos Papanikolopoulos, U. Minn

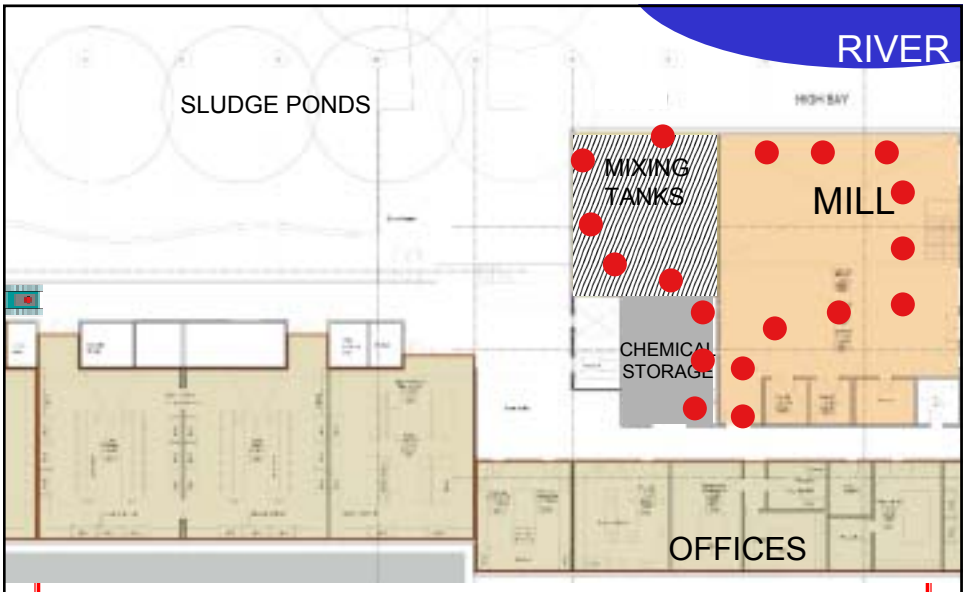
NSF Workshop on Status of Robotics in the US

Autonomous Networked Robots: first responders

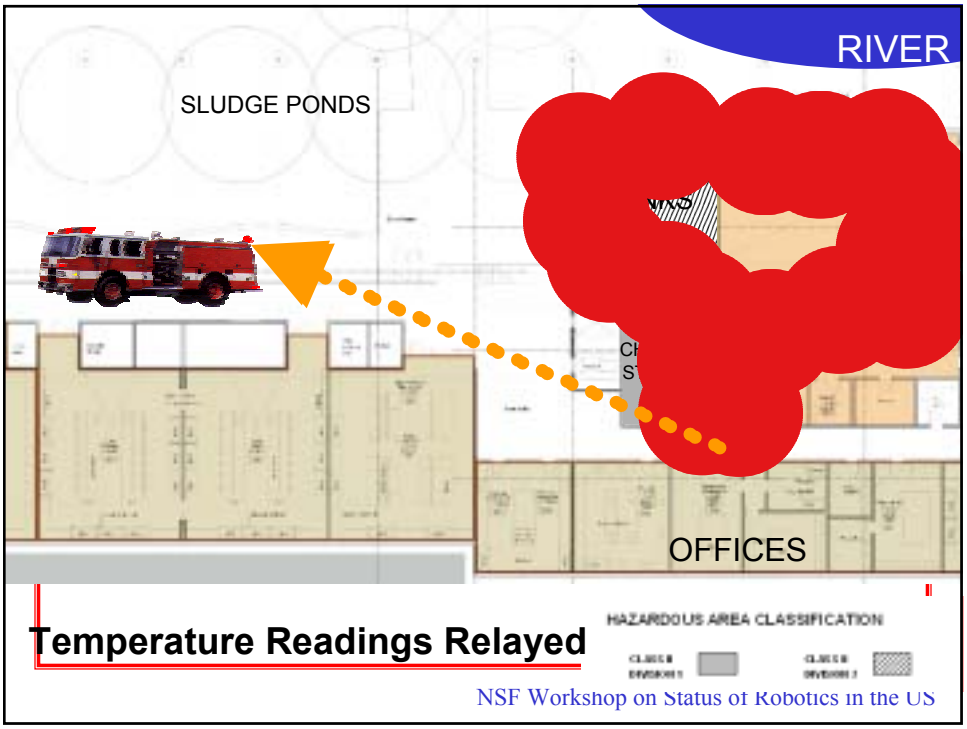


Temp. gradient

Allegheny Fire Academy, Aug 23, 2002 (Kumar, Rus, Singh)



Rapid Deployment of Sensors



Temperature Readings Relayed