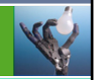

Role of Cooperation in Multi-robot Systems

Alaa Khamis, PhD, SMIEEE

http://www.alaakhamis.org/

EGYPT CHAPTER

http://www.ras-egypt.org/

Outline

- Talk Description
- Introduction to Multirobot Systems
- Benchmark Problems of Multirobot Systems
- Challenging Problems of Multirobot Systems
- Towards Cooperative Multirobot Systems

Outline

- **Talk Description**
- Introduction to Multirobot Systems
- Benchmark Problems of Multirobot Systems
- Challenging Problems of Multirobot Systems
- Towards Cooperative Multirobot Systems

Talk Description

This talk provides well-grounded and informative answers to questions like:

- What are the main features of multirobot systems (MRS)?
- What are the challenging problems of MRS?
- How to achieve different forms of cooperation in MRS?

Outline

- Talk Description
- **Introduction to Multirobot Systems**
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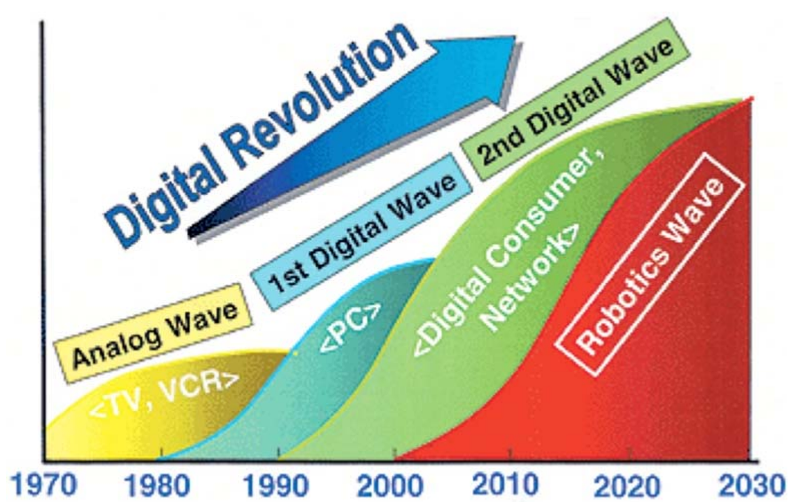
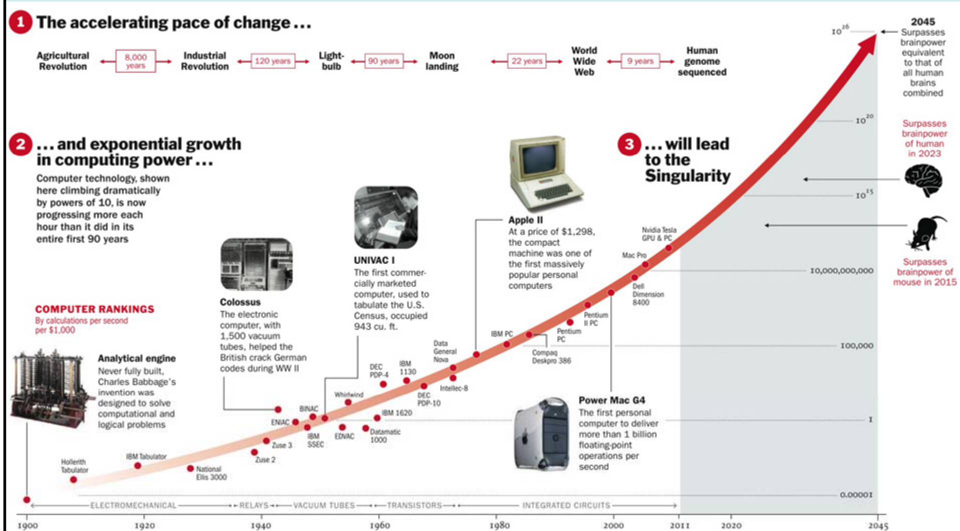
- Towards Cooperative Multirobot Systems

Introduction to Multirobot Systems



Source: Bruno Siciliano. Robots Moving Closer to Humans. IEEE Distinguished Ambassador Seminar, IEEE RAS – Egypt Chapter. Available at: http://ras-egypt.org/activities.html

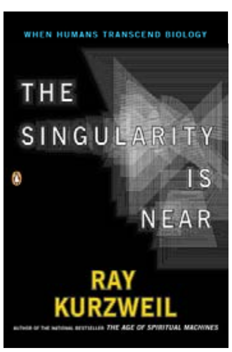
Introduction to Multirobot Systems



Source: Lev Grossman, "2045: The Year Man Becomes Immortal," TIME Magazine, February, 2011.

Introduction to Multirobot Systems

Kurzweil predicts personal computers with the power of the human brain by 2025



Emerging Technologies

Genetics | Nano-technology | **Robotics**

Introduction to Multirobot Systems

Short-term goals of Robotics:

- The object-recognition capabilities of a 2-year-old child

- The language capabilities of a 4-year-old child

- The manual dexterity of a 6-year-old child

- The social understanding of an 8-year-old child

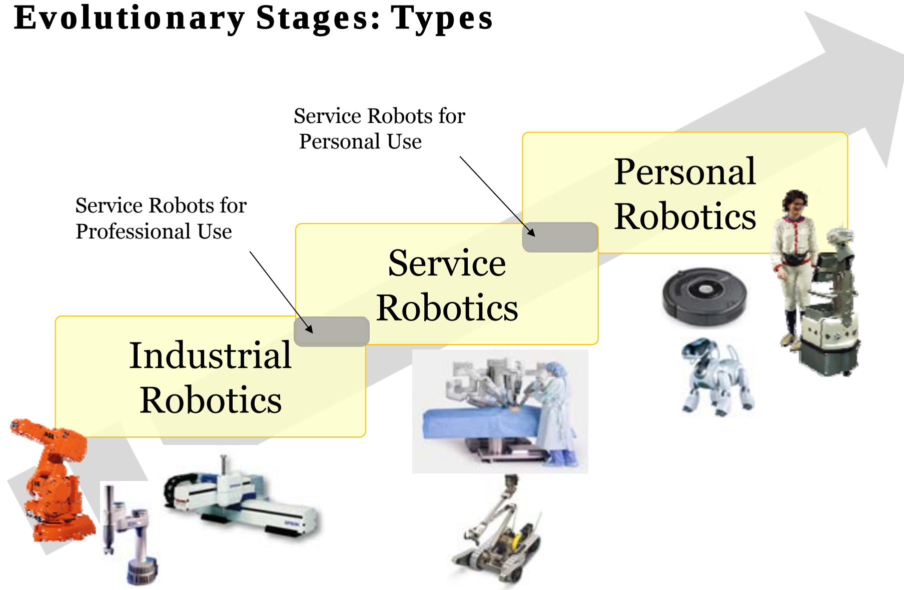
More info: http://www.springer.com/authors/author+zone?SGWID=0-168002-12-691704-0

Introduction to Multirobot Systems

- **Evolutionary Stages of Robot Systems**
  - ◇ Types
  - ◇ Market size
  - ◇ Intelligence
  - ◇ Body/Brain Evolution

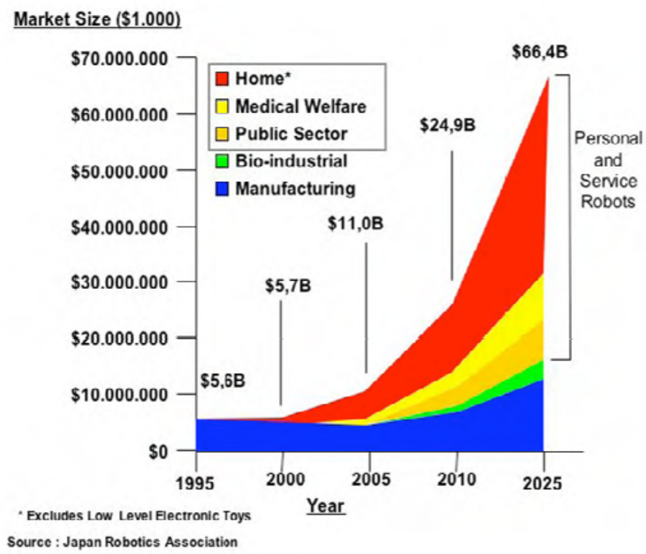
Introduction to Multirobot Systems

- **Evolutionary Stages: Types**



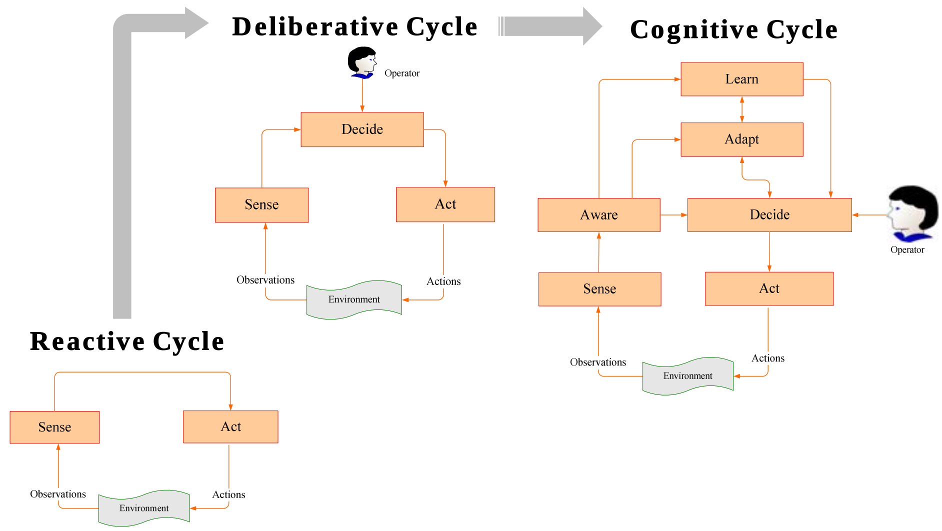
Introduction to Multirobot Systems

- **Evolutionary Stages: Market Size**



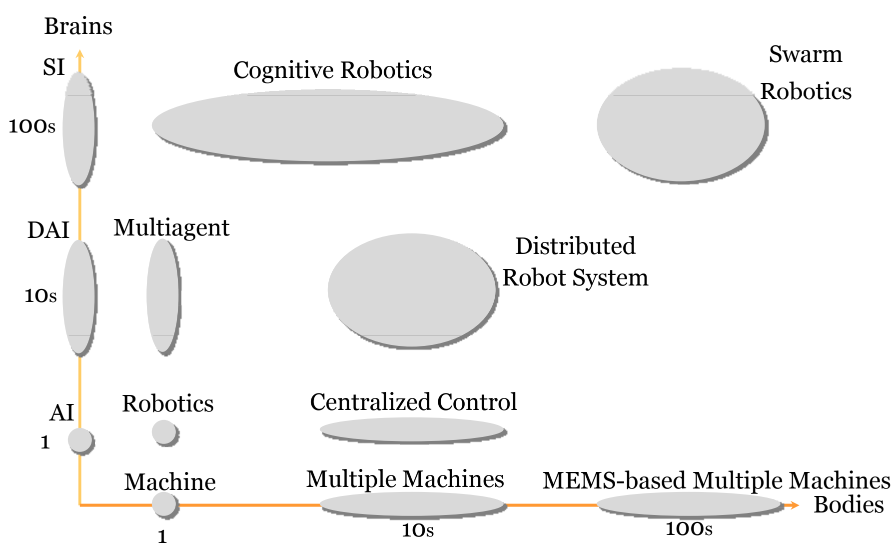
Introduction to Multirobot Systems

- **Evolutionary Stages: Intelligence**



Introduction to Multirobot Systems

- **Evolutionary Stages: Body/Brain Evolution**



Introduction to Multirobot Systems

- **Multirobot Systems**

  Multirobot systems (**MRS**) are **a group of robots** that are designed aiming to perform some **collective behavior**.

  The MRS is gaining great interest because of the following reasons:

  ◇ Resolving task complexity

  ◇ Increasing performance

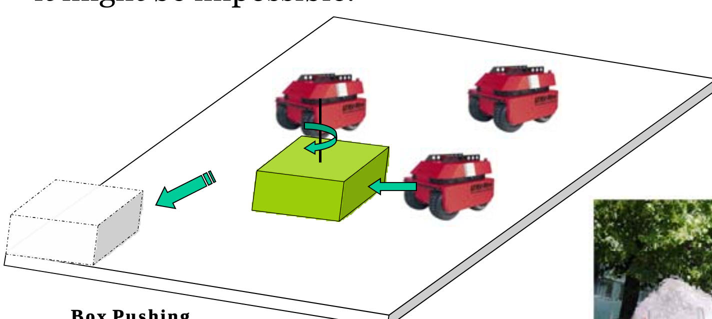
  ◇ Reliability

  ◇ Simplicity in design

Introduction to Multirobot Systems

- **Why Multirobot Systems?: Resolving task complexity**

  Some tasks may be quite complex for a single robot to do or even it might be impossible.



Box Pushing

Crossing a gap

Introduction to Multirobot Systems

- **Why Multirobot Systems?: Resolving task complexity**

Some tasks are inherently distributed.

Heterogeneous team of an air and two ground vehicles that can perform cooperative reconnaissance and surveillance

Introduction to Multirobot Systems

- **Why Multirobot Systems?: Resolving task complexity**

Some tasks are diverse and required **different capabilities**.

A robot in every home

"As I look at the trends that are now starting to converge, I can envision a future in which robotic devices will become a nearly ubiquitous part of our day-to-day lives.

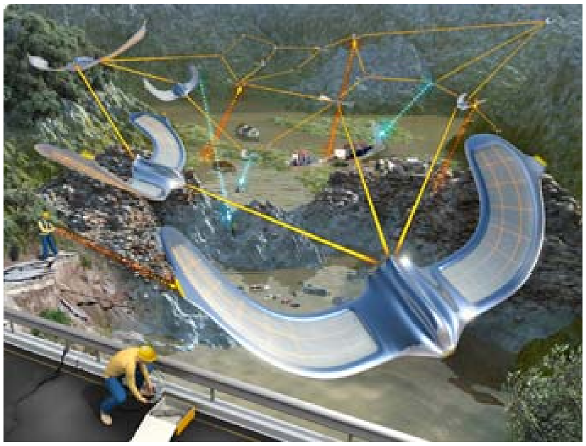
The challenges facing the robotics industry are similar to those we tackled in computing three decades ago."

Bill Gates, 2007
Scientific American

Introduction to Multirobot Systems

- **Why Multirobot Systems?: Increasing performance**

  Multiple robots can solve problems faster using parallelism.



Minimize:

- Task completion time

Maximize:

- Area Coverage
- Object Coverage
- Radio Coverage

Introduction to Multirobot Systems

- **Why Multirobot Systems?: Reliability**

The introduction of multiple robots **increases robustness** through **redundancy**.

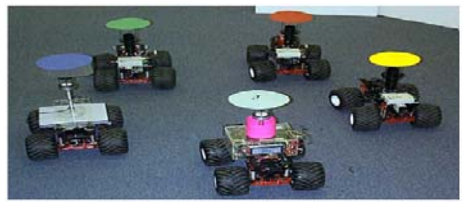
Increasing the system reliability because having only one robot may work as a bottleneck for the whole system especially in critical times.

But when having multiple robots doing a task and one fails, others could still do the job.

Introduction to Multirobot Systems

- **Why Multirobot Systems?: Simplicity in design**
  Building several resource-bounded robots is much easier than having a single powerful robot

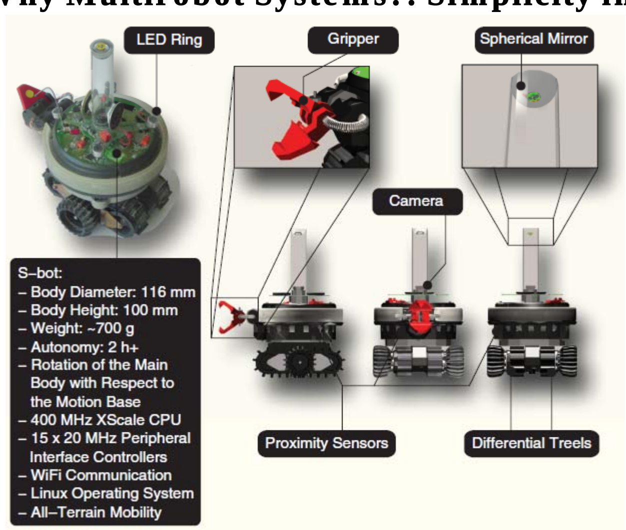
Powerful single robot



Several resource-bounded simple robots

Introduction to Multirobot Systems

- **Why Multirobot Systems?: Simplicity in design**



S-bot: an autonomous, mobile robot capable of self-assembly

ANDERS LYHNE CHRISTENSEN, REHAN O'GRADY, AND MARCO DORIGO, "Morphology Control in a Multirobot System: Distributed Growth of Specific Structures Using Directional Self-Assembly", IEEE Robotics & Automation Magazine, December 2007.

Introduction to Multirobot Systems

- **Applications**
  - ◇ Intelligent carts
  - ◇ UXVs
  - ◇ Cube sats
  - ◇ Space-based construction
  - ◇ Agricultural Foraging
  - ◇ Killing Cancer Tumors in Human Body
  - ◇ Search and Rescue
  - ◇ Humanitarian demining
  - ◇ Distributed monitoring

Introduction to Multirobot Systems

- **Applications: Intelligent Carts**

Unintelligent carts are commonly found in large airports. Travelers pick up carts at designated points and leave them in arbitrary places. It is a considerable task to re-collect them.

It is, therefore, desirable that intelligent carts (intelligent robots) **draw themselves** together autonomously.

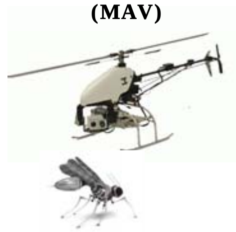
Introduction to Multirobot Systems

- **Applications: UXVs**

Unmanned Vehicles (UXVs)

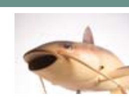
Unmanned Ground Vehicles (UGV)

Unmanned Aerial Vehicles (UAV) & Micro Aerial Vehicles (MAV)



Unmanned Surface Vehicles (USV)

Unmanned Underwater Vehicles (UUV)



Introduction to Multirobot Systems

- **Applications: UAVs**
  - ◇ Military Applications: Drones
    - Congress has mandated that by 2015, 1/3rd of all US military missions should be unmanned.
    - There are 17,300 drones in the US army inventory.
    - These drones can carry up to 3000 pounds of weapons.
    - Fabricated by Boeing

A forward looking infrared (FLIR) camera onUAV

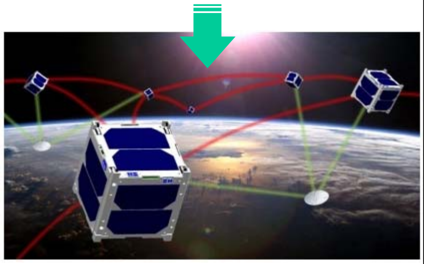
UAV carrying Viper Strike Weapon System

Source: http://www.marketresearchmedia.com/?p=509

Introduction to Multirobot Systems

- **Applications: Cube Sats**
  - ◇ Small and Pico Satellites
    - Small satellites are artificial satellites of lower weights and smaller sizes (under 500 kg).
    - Small satellites can be Minisatellite, Microsatellite, Nanosatellite, Picosatellite or Molecularsatellite.
    - Picosatellite or "picosat" is an artificial satellite with a wet mass between 0.1 and 1 kg.

Giant Solar-powered Satellite



Network of CubeSat

More info: Klaus Schilling, IEEE Distinguished Lecture. Available at: http://ras-egypt.org/activities.html

Introduction to Multirobot Systems

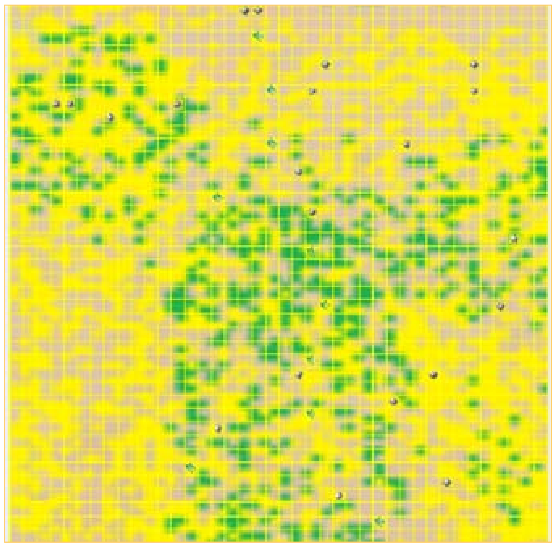
- **Applications: Search & Rescue Operations**

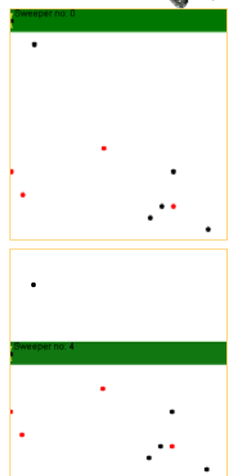
Companion slides for the book Bio-Inspired Artificial Intelligence: Theories, Methods, and Technologies by Dario Floreano and Claudio Mattiussi, MIT Press

Introduction to Multirobot Systems

- **Applications: Humanitarian Demining**

GPR-based Minesweeper





…

Alaa Khamis and Asser ElGindy "Minefield Mapping using Cooperative Multirobot Systems", Journal of Robotics, 2012.

Cooperation in Multirobot Systems

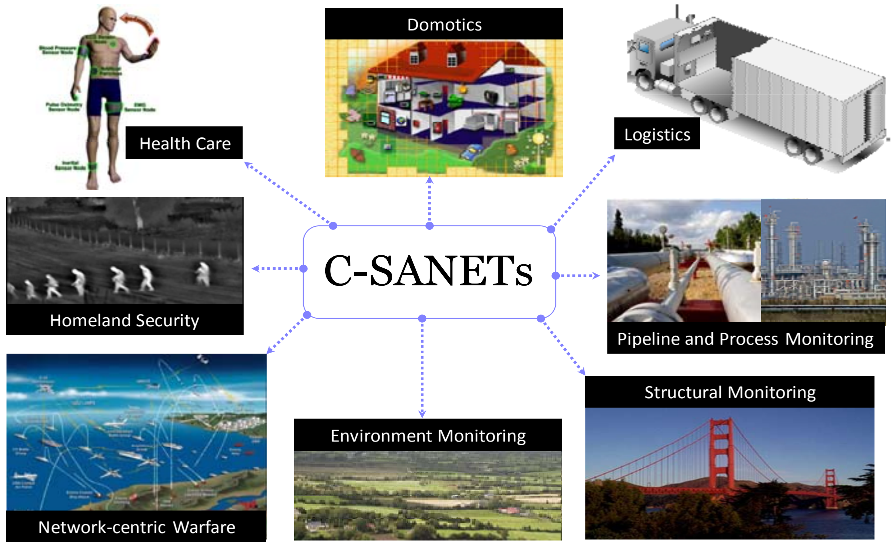
- **Applications: Distributed Monitoring**

Dimensions of Recent Trends

Multiplicity | Multimodality | Mobility

Cooperation in Multirobot Systems

- **Applications: Distributed Monitoring**



Outline

- Talk Description
- Introduction to Multirobot Systems
- **<u>Benchmark Problems of Multirobot Systems</u>**
- Challenging Problems of Multirobot Systems
- Towards Cooperative Multirobot Systems

Benchmark Problems of MRS

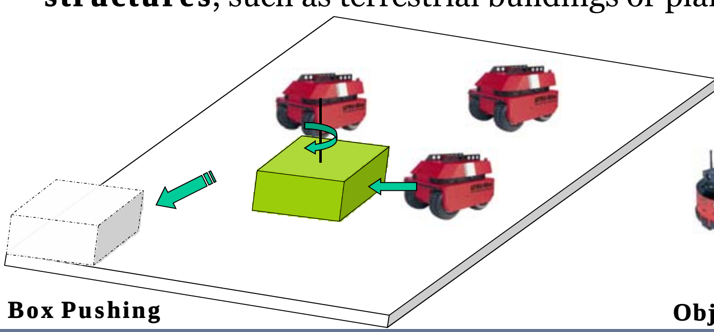
- Box Pushing and Object Transportation
- Exploration and Formation Control
- Division of Labor
- Foraging
- Object/Area/Radio Coverage
- Soccer Tournaments
- Cooperative perception
- Cooperative Target Cueing and Handoff
- Cooperative Mapping
- …

Benchmark Problems of MRS

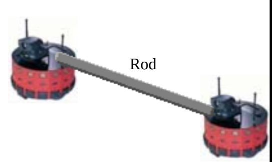
- **Box Pushing and Object Transportation**

  This problem's concern is about a group of robots try to **push a box** to a certain point.

  Applications include **transportation of heavy objects** in industrial environments or **assembly of large-scale structures**, such as terrestrial buildings or planetary habitat.



Box Pushing



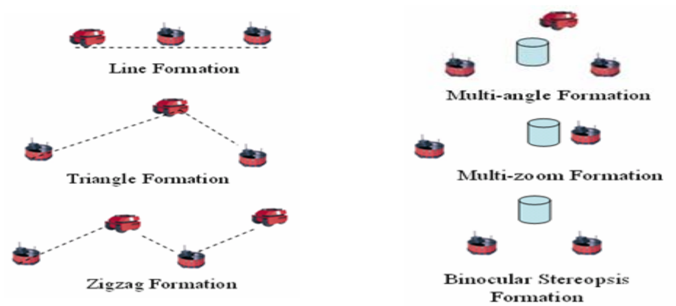
Object Transportation

Benchmark Problems of MRS

- **Exploration and Formation Control**

  In the **exploration** task the robots must be **spread in the environment** in order to collect as much information as possible about the surrounding area.

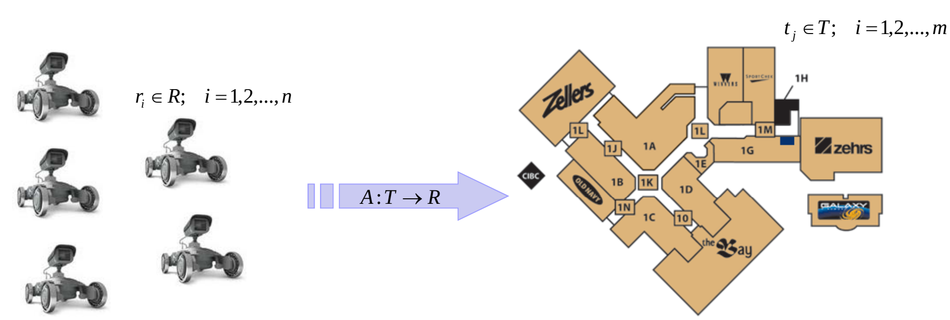
  The **formation** task is focused on having the robots move in the environment **forming particular shapes**.



Benchmark Problems of MRS

- **Division of Labor**

  This cooperative behavior addresses how to dynamically assign a set of tasks to a set of robots to maximize overall expected performance.



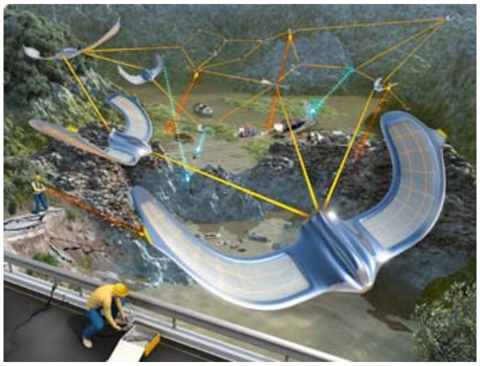
A set of n mobile Sensors: R **A set of m surveillance tasks: T**

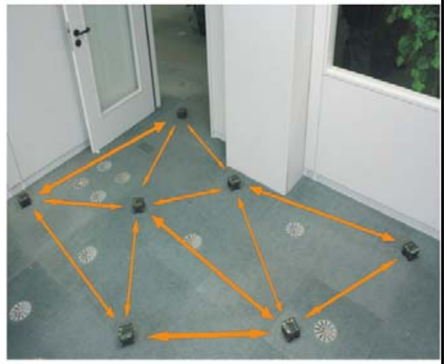
Alaa Khamis, Ahmed Elmogy and Fakhreddine Karray, "Complex Task Allocation in Mobile Surveillance Systems," Journal of Intelligent and Robotic Systems, Springer, DOI: 10.1007/s10846-010-9536-2, 2011 .

Benchmark Problems of MRS

- **Communication Relaying**

  This cooperative behavior consists in establishing communication through relaying in order to dramatically increase **radio coverage** or expand communications links, primarily over rugged, mountainous or urban terrains.





Benchmark Problems of MRS

- **Soccer**

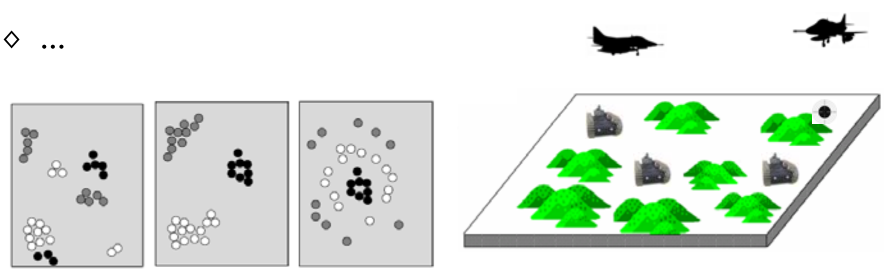
  Soccer playing is challenge problem for studying coordination and control in multirobot systems. This domain incorporates many challenging aspects of multirobot control, including:

  ◇ Collaboration,
  ◇ Robot control architectures,
  ◇ Strategy acquisition,
  ◇ Real-time reasoning and action,
  ◇ Sensor fusion,
  ◇ Dealing with adversarial environments,
  ◇ Cognitive modeling, and
  ◇ Learning.

http://www.robocup.org/ & http://www.fira.net/

Benchmark Problems of MRS

- **Other problems**
  - Sorting
  - Cooperative perception in robotics
  - Cooperative Mapping
  - Collective Robotic Search
  - …



Outline

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- Introduction to Multirobot Systems
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- **Challenging Problems of Multirobot Systems**
- Towards Cooperative Multirobot Systems

Challenging Problems of MRS

- **Algorithm Design**
- **Implementation and Test**
- **Analysis and Modelling**

Challenging Problems of MRS

- **Algorithm Design**

Algorithm–based Behaviour

Individual Behaviour
i-Level

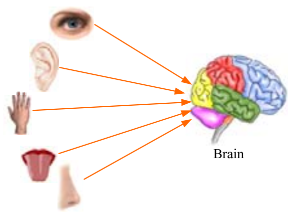
Group behaviour
g-Level

Challenging Problems of MRS

- **Algorithm Design: *i*-Level Algorithm**

Brain Functions

Low-level functions



- Fully understood
- Localized

High-level functions

Perception, situation awareness, reasoning, decision making, learning, etc.

- Partially understood
- Not fully localized

Challenging Problems of MRS

- **Algorithm Design: *g*-Level Algorithm**

Roboticists face the problem of designing both the physical morphology and behaviours of the individual robots such that when those robots interact with each other and their environment, the desired overall collective behaviours will emerge. At present there are no principled approaches to the **design of low-level behaviours** for a given **desired collective behaviour** [1].

"**collective behavior** is NOT simply the sum of each participant's behavior, as others emerge at the society level" [2].

[1] E. Sahin and A. Winfield, "Special issue on swarm robotics," Swarm Intelligence, 2: 69–72, Springer Science, 2008.
[2] Pasteels et al. From Individual to Collective Behavior in Social Insects. Pages 155-175, 1987.

Challenging Problems of MRS

- **Algorithm Design: *g*-Level Algorithm**

Main decisional abilities:

- Mission planning,

- Task allocation and

- Coordinated task achievement
  - Management the task allocation,
  - Scheduling,
  - Cooperation/collaboration between the entities,
  - Conflict avoidance, etc.

Challenging Problems of MRS

- **Implementation and Test**

To build and rigorously test a swarm of robots in the laboratory requires a **considerable experimental infrastructure**. Real-robot experiments thus typically proceed **hand-in-hand with simulation** and good tools are essential [1].

[1] E. Sahin and A. Winfield, "Special issue on swarm robotics," Swarm Intelligence, 2: 69–72, Springer Science, 2008.

Challenging Problems of MRS

- **Implementation and Test**
  - ◇ **Advanced Robotics Interface for Applications (ARIA):** Robotic Sensing and Control Libraries.
  - ◇ **Open Robot Control Software (OROCOS):** open-source real time control architecture for different machines.
  - ◇ **Microsoft Robotics Studio:** is a Windows-based environment for robot control and simulation.
  - ◇ **Player/Stage/Gazebo:** PSG is open source software that used and developed by an international community of researchers from over 30 universities/companies.
  - ◇ **Robot Operating System (ROS)**

Challenging Problems of MRS

- **Analysis and Modelling**

A multirobot system (specially swam systems) is typically a **stochastic, non-linear and partially observable system** and constructing **mathematical models** for both validation and parameter **optimization** is challenging.

Such models would surely be an essential part of constructing a safety argument for real-world applications [1].

[1] E. Sahin and A. Winfield, "Special issue on swarm robotics," Swarm Intelligence, 2: 69–72, Springer Science, 2008.

Outline

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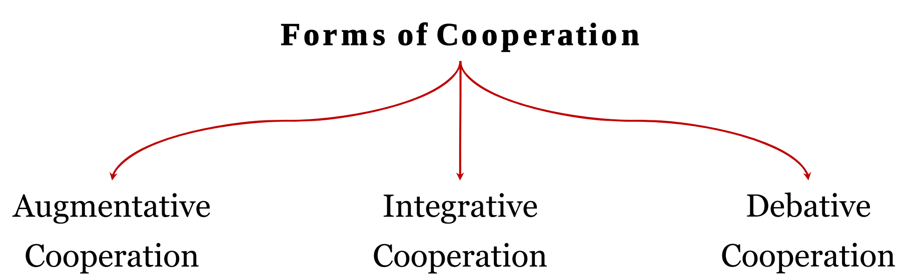
- **Towards Cooperative Multirobot Systems**

Towards Cooperative Multirobot Systems

- **Forms of Cooperation in MRS**

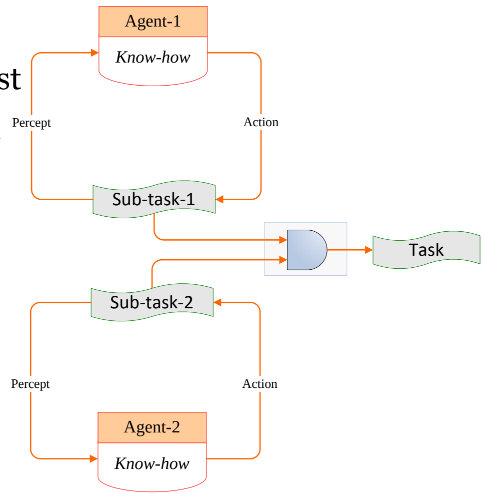


Alaa Khamis, "Cooperative Sensor and Actor Networks in Distributed Surveillance Context," 10th International Conference on Practical Applications of Agents and Multi-Agent Systems (PAAMS'12), Salamanca, Spain, 2012.

Towards Cooperative Multirobot Systems

- **Augmentative Cooperation**

When agents have a **similar know-how** but the agents must be multiplied to perform a task too demanding for only one agent. This task is then shared into **similar sub-tasks.**

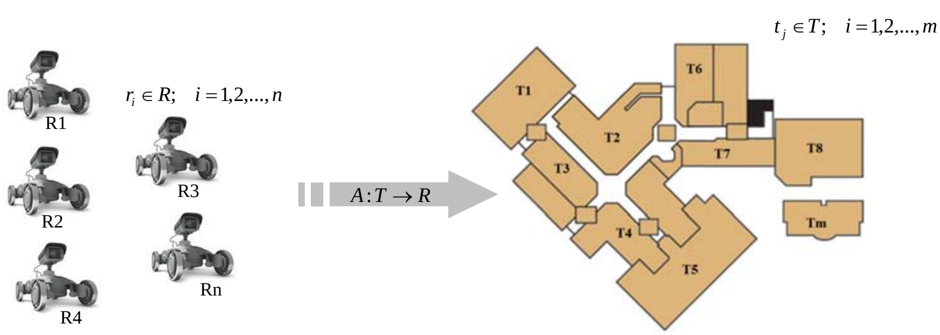


Examples:

- ◇ Task Allocation
- ◇ Target Cueing and Handoff
- ◇ Optimal Deployment
- ◇ Group Formation
- ◇ Cooperative Mapping

Towards Cooperative Multirobot Systems

- **Augmentative Cooperation: Task Allocation**



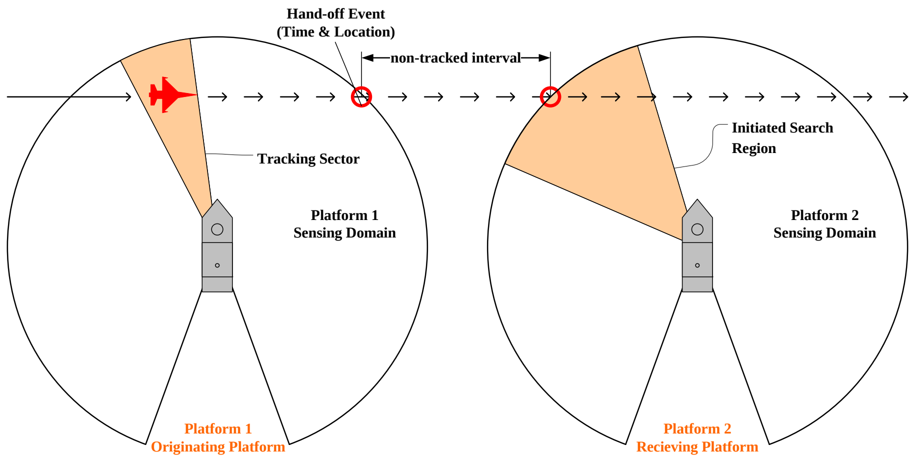
A set of n mobile Sensors: R

A set of m surveillance tasks: T

Alaa Khamis, Ahmed Elmogy and Fakhreddine Karray, "Complex Task Allocation in Mobile Surveillance Systems," Journal of Intelligent and Robotic Systems, Springer, DOI: 10.1007/s10846-010-9536-2, 2011

Towards Cooperative Multirobot Systems

- **Augmentative Cooperation: Target Cueing and Handoff**

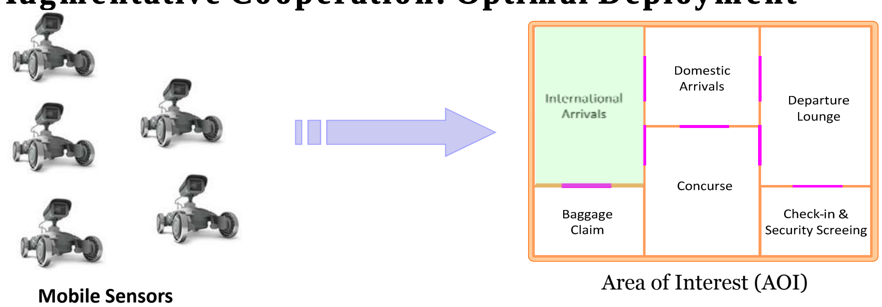


Inter-platform Handoff

A. Benaskeur, **A. Khamis**, H. Irandoust, "Augmentative Cooperation in Distributed Surveillance Systems for Dense Regions," International Journal of Intelligent Defence Support Systems, 4(1): 20-49, 2011

Towards Cooperative Multirobot Systems

- **Augmentative Cooperation: Optimal Deployment**



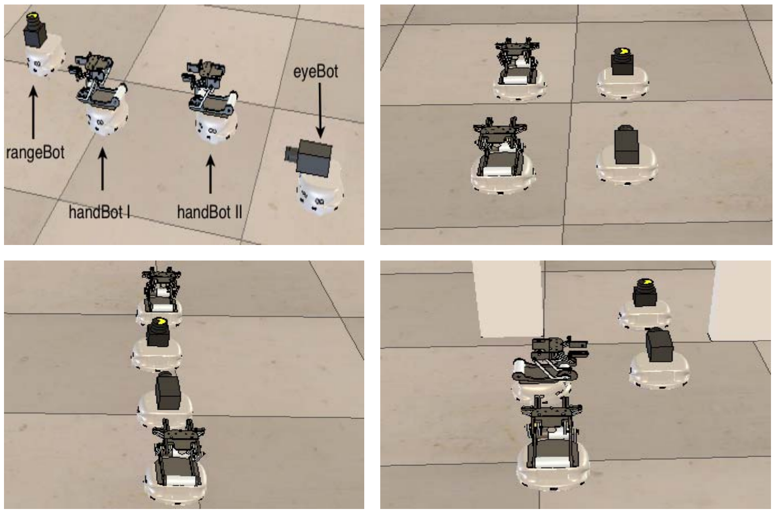
Optimal strategy to deploy a set of mobile sensors in AOI:

- ◇ Maximize the area coverage;
- ◇ Maximize target detection rate;
- ◇ Minimize detection time.

Yun-Qian Miao, **Alaa Khamis**, Mohamed S. Kamel, "Novel Mobility Model for Mobile Sensors Deployment in Surveillance Systems", International Journal of Robotics and Automation, 2012

Towards Cooperative Multirobot Systems

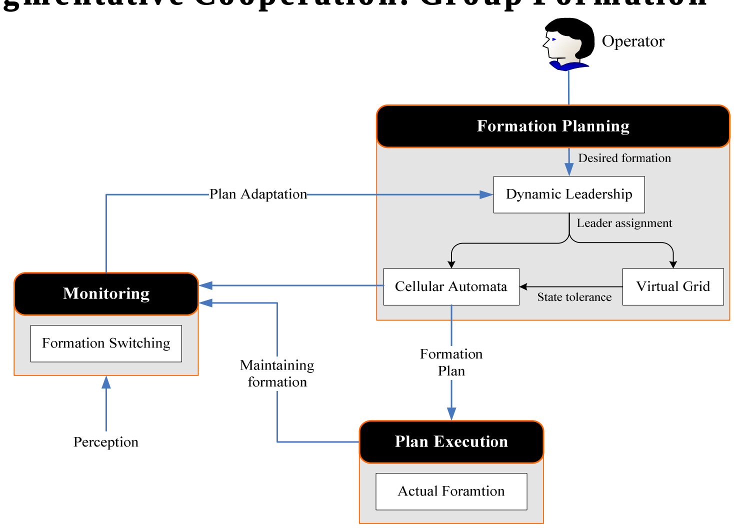
- **Augmentative Cooperation: Group Formation**



Ahmed Shehata and **Alaa Khamis**, "Adaptive Group Formation in Multi-robot Systems," Advances in Artificial Intelligence Journal, 2013.

Towards Cooperative Multirobot Systems

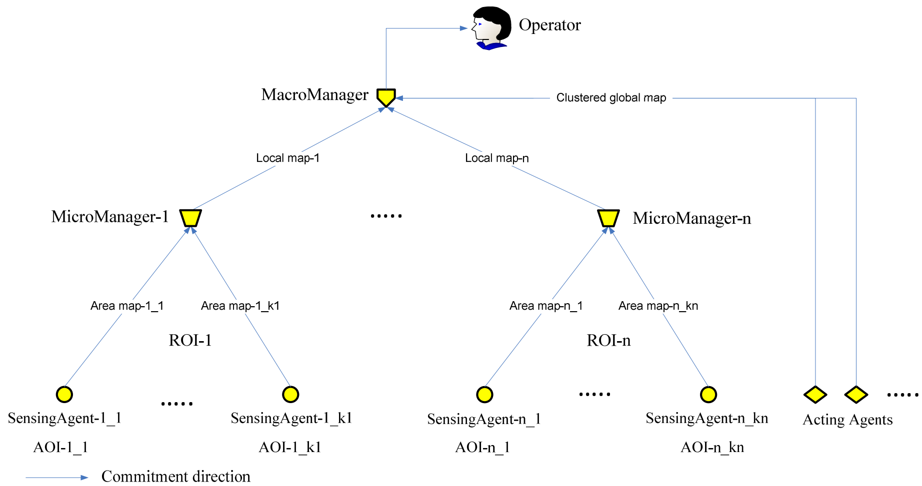
- **Augmentative Cooperation: Group Formation**



Ahmed Shehata and **Alaa Khamis**, "Adaptive Group Formation in Multi-robot Systems," accepted to be published in Advances in Artificial Intelligence Journal, 2013.

Towards Cooperative Multirobot Systems

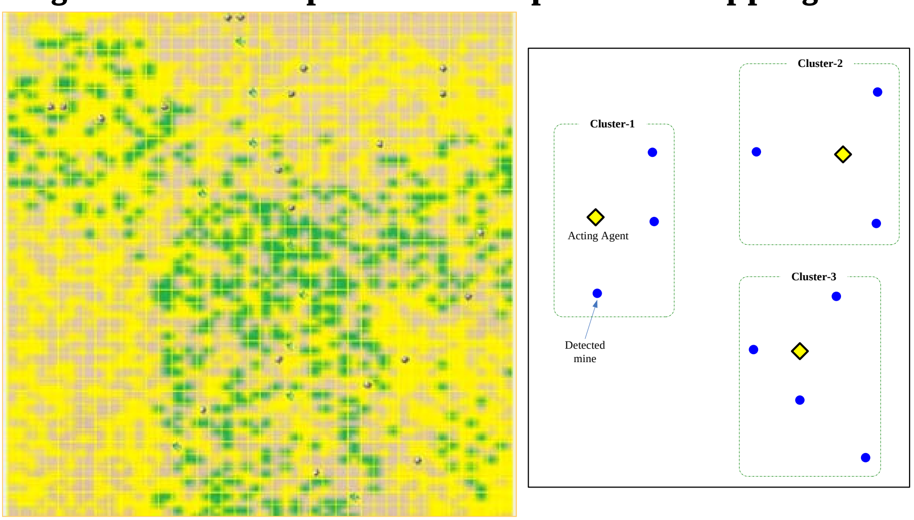
- **Augmentative Cooperation: Cooperative Mapping**



Alaa Khamis and Asser ElGindy "Minefield Mapping using Cooperative Multirobot Systems", Journal of Robotics Volume 2012, http://dx.doi.org/10.1155/2012/698046.

Towards Cooperative Multirobot Systems

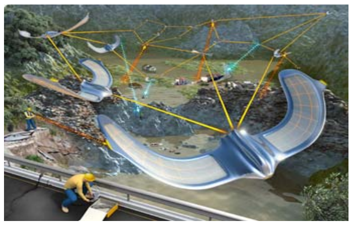
- **Augmentative Cooperation: Cooperative Mapping**

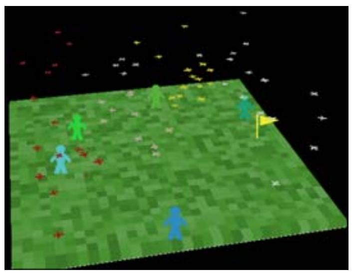


Alaa Khamis and Asser ElGindy "Minefield Mapping using Cooperative Multirobot Systems", Journal of Robotics Volume 2012, http://dx.doi.org/10.1155/2012/698046.

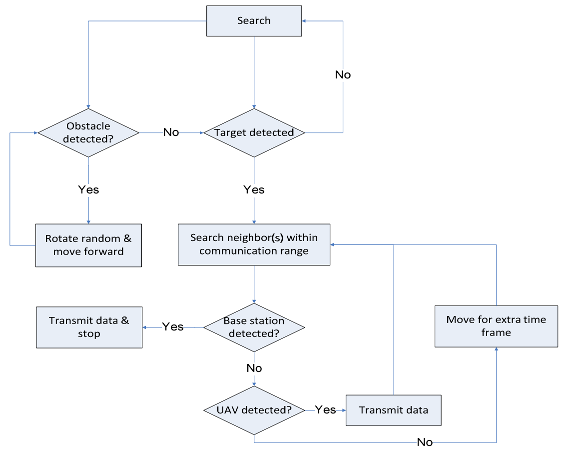
Towards Cooperative Multirobot Systems

- **Augmentative Cooperation: Communication Relaying**





NetLogo simulation environment with 60 UAVs, 5 ground targets and a base station



Mohamed Wakid and Alaa Khamis. *Communication Relay for Unmanned Aerial Vehicles in Autonomous Search and Rescue Mission.* Research Project, RAS Research Group, GUC.

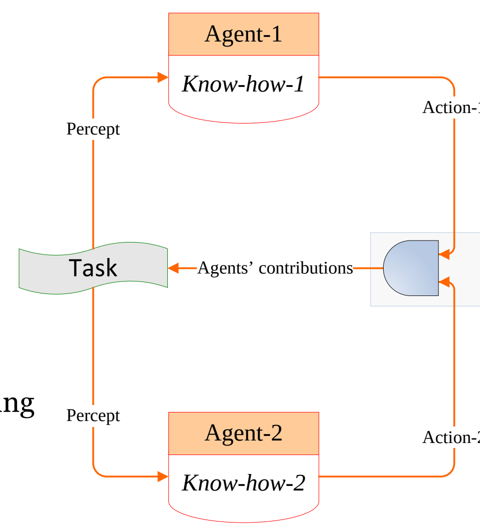
Towards Cooperative Multirobot Systems

- **Integrative Cooperation**

Agent have different **complementary know-how** and it is necessary to integrate their contribution for achieving a **task**.

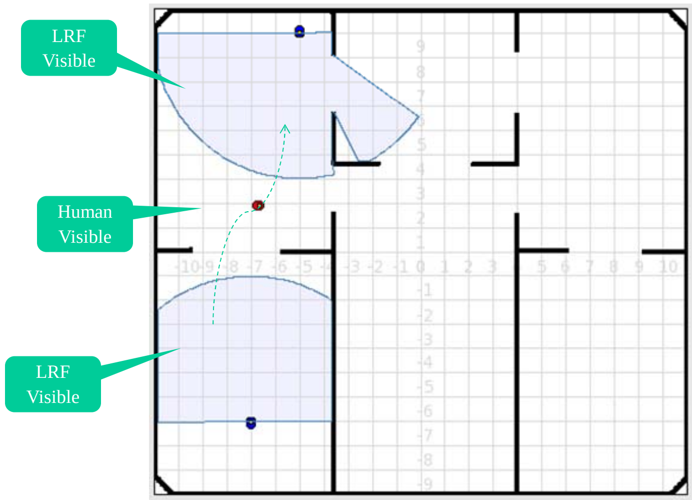
Examples:

- ◇ Multimodal Fusion
- ◇ Target Detection and Tracking
- ◇ Human-assisted Tracking
- ◇ Search and Rescue



Towards Cooperative Multirobot Systems

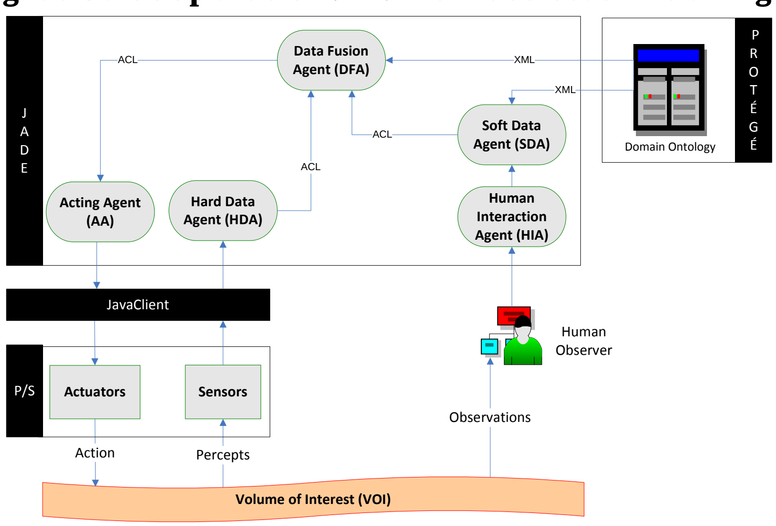
- **Integrative Cooperation: Human-assisted Tracking**



Bahador Khaleghi, **Alaa Khamis**, Fakhreddine Karray, "Random Finite Set Theoretic Soft/Hard Data Fusion: Application to Target Tracking", IEEE 2010 International Conference on Multisensor Fusion and Integration for Intelligent Systems, 2010

Towards Cooperative Multirobot Systems

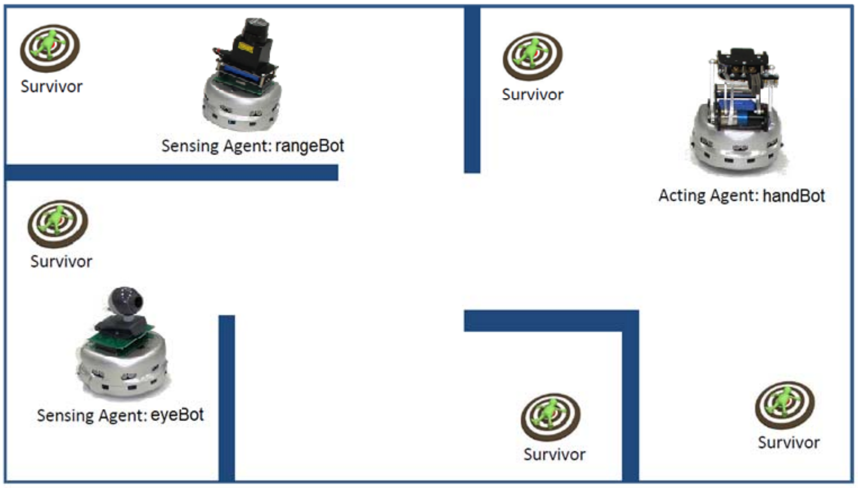
- **Integrative Cooperation: Human-assisted Tracking**



Bahador Khaleghi, **Alaa Khamis**, Fakhreddine Karray, "Random Finite Set Theoretic Soft/Hard Data Fusion: Application to Target Tracking", IEEE 2010 International Conference on Multisensor Fusion and Integration for Intelligent Systems, 2010.

Towards Cooperative Multirobot Systems

- **Integrative Cooperation: Search and Rescue**



Mohamed Badreldin, Ahmed Hussein and **Alaa Khamis**, "A Comparative Study between Optimization and Market-based Multi-robot Task Allocation Approaches," accepted to be published in Advances in Artificial Intelligence Journal, 2013.

Towards Cooperative Multirobot Systems

- **Integrative Cooperation: Search and Rescue**

Algorithm	SA-based	GA-based	Market-based
Optimal Allocation Found			
Small-scale	✓	✓	✓
Medium-scale	✓✓✓	✓✓	✓
Large-scale	✓✓✓	✓✓	✓
Capabilities matching	✓	✓	✓✓
Time matching	✓✓✓	✓✓	✓
Heavily constrained	✓✓✓		✓✓
Computational Cost			
Static Allocation [Extended Time]	✓✓✓	✓✓	✓
Dynamic Allocation [Limited Time]	✓✓	✓✓✓	✓

Mohamed Badreldin, Ahmed Hussein and **Alaa Khamis**, "A Comparative Study between Optimization and Market-based Multi-robot Task Allocation Approaches," accepted to be published in Advances in Artificial Intelligence Journal, 2013.

Towards Cooperative Multirobot Systems

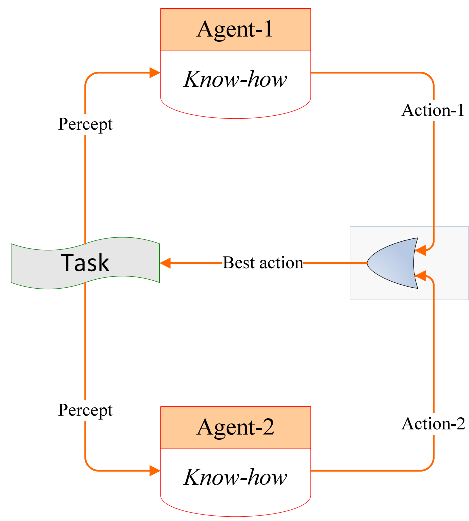
- **Debative Cooperation**

When agent have a **similar know-how** and are faced with a unique task, and they compare their results for obtaining the **best** solution.

Examples:

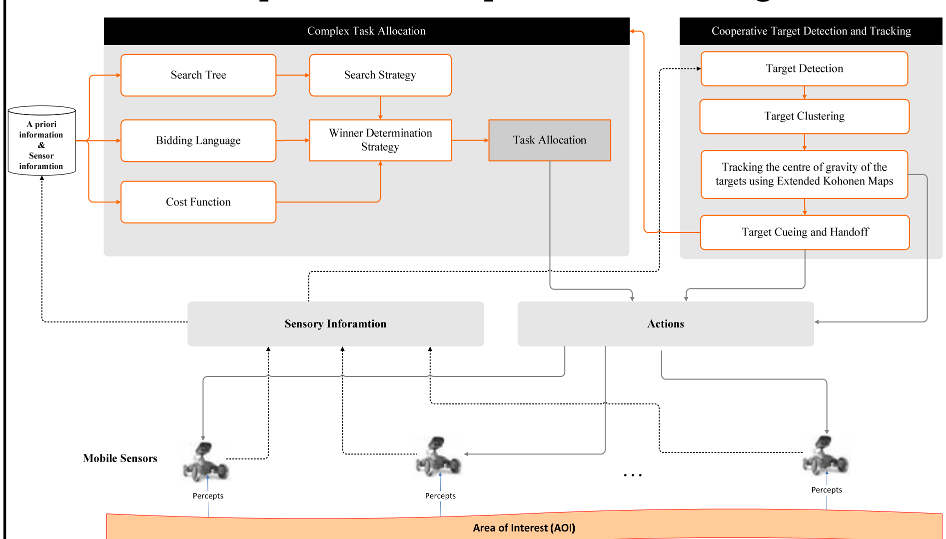
◇ Uncertainty Reduction

◇ Multisensor Single Target Cooperative Tracking



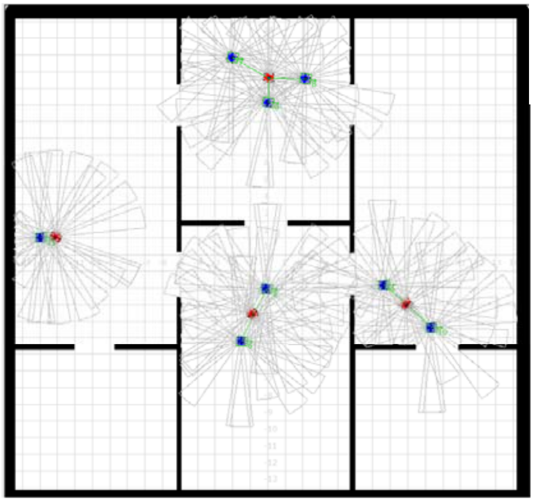
Towards Cooperative Multirobot Systems

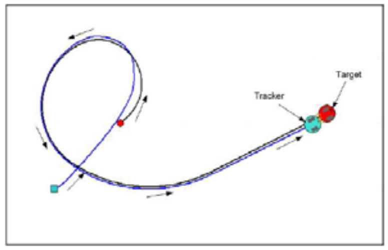
- **Debative Cooperation: Cooperative Tracking**



Towards Cooperative Multirobot Systems

- **Debative Cooperation: Cooperative Tracking**



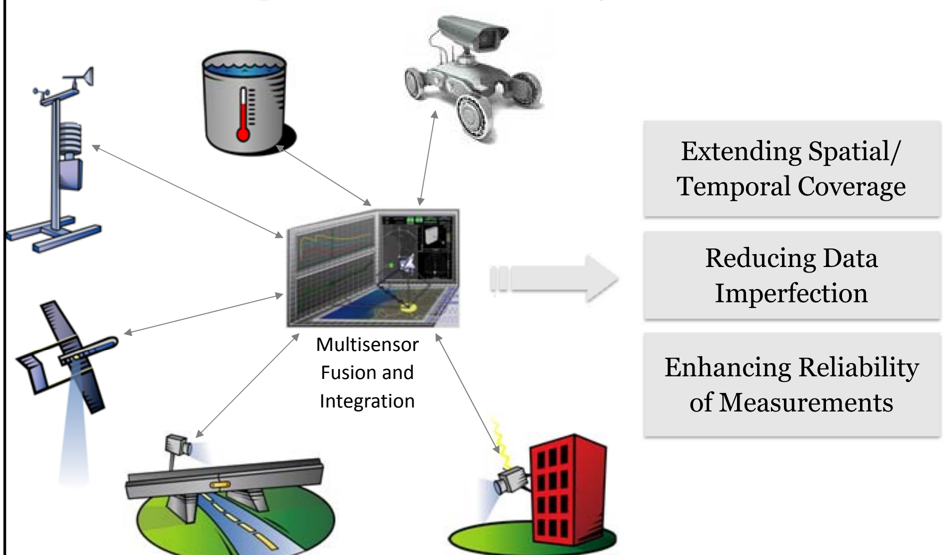


Case	Energy saving in EKM
n=m	20-40%
n=(3/4)m	12-31%
n=(1/2)m	8-23%

Ahmed Elmogy, Fakhreddine Karray, and **Alaa Khamis**, "Auction-based Consensus Mechanism for Cooperative Tracking in Multisensor Surveillance Systems,"' Journal of Advanced Computational Intelligence and Intelligent Informatics, Vol.14, No.1 pp. 13-20, 2010

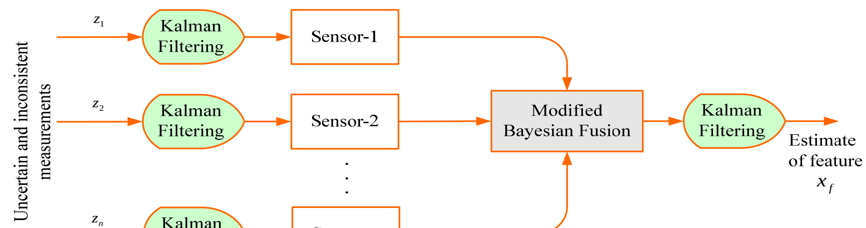
Towards Cooperative Multirobot Systems

- **Debative Cooperation: Uncertainty Reduction**



Towards Cooperative Multirobot Systems

- **Debative Cooperation: Uncertainty Reduction**



Algorithm 3: The Pre- and Post-Filtering Algorithm (F-MB-F)

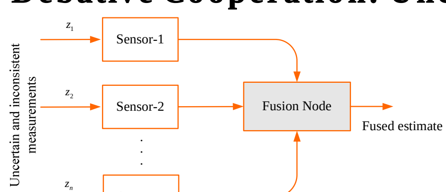
Input : σ_1, σ_2, $z_1(k)$, $z_2(k)$, $x_1(k-1)$, $x_2(k-1)$, $x_f(k-1)$, $P_1(k-1)$, $P_2(k-1)$, $P_f(k-1)$
Output: $x_f(k)$, $P_f(k)$

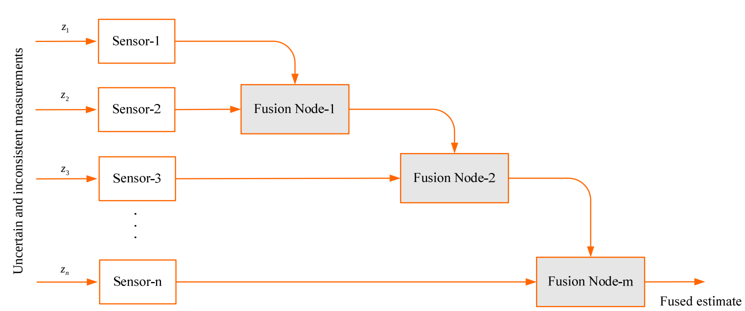
```
begin
    ξ ← σ1/σ2;
    for j ← 1 to 2 do
        x_j(k) ← Call Kalman Filter Algorithm;
    x_int(k) ← x1(k)/(1 + ξ^2) + x2(k)/(1 + ξ^-2);
    Calculate f as in (6);
    σ^2_int(k) ← (σ1^-2 f^-1 + σ2^-2 f^-1)^-1;
    (x_f(k), P_f(k)) ← Call Kalman Filter Algorithm;
```

Waleed Abdulhafiz and **Alaa Khamis**, "Handling Data Uncertainty and Inconsistency using Multisensor Data Fusion,"Advances in Artificial Intelligence Journal, 2013.

Towards Cooperative Multirobot Systems

- **Debative Cooperation: Uncertainty Reduction**





Waleed A. Hafiz and **Alaa Khamis**, "Bayesian Approach to Multisensor Data Fusion with Pre- and Post-Filtering", 10th IEEE International Conference on Networking Sensing and Control, 2013.

Towards Cooperative Multirobot Systems

- **Debative Cooperation: Uncertainty Reduction**

CPU Running Time

Residual sum of squares (RSS)

Variance (P)

Coefficient of Correlation

Criterion Function (CF):

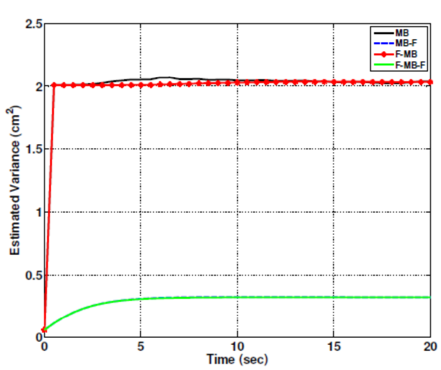
$$CF = w_1 \times \frac{c_1}{c_{1max}} + w_2 \times \frac{c_2}{c_{2max}} + w_3 \times \frac{c_3}{c_{3max}}$$

Fusion	Time (s)		RSS (cm^2)		P (cm^2)		Criterion Function	
Techniques	Centralized	Decentralized	Centralized	Decentralized	Centralized	Decentralized	Centralized	Decentralized
MB	0.056	**0.029**	76.076	**70.288**	2.607	**2.038**	0.917	**0.701**
F-MB	0.072	**0.046**	31.338	**28.764**	2.555	**2.034**	0.795	**0.603**
MB-F	0.063	**0.034**	50.838	**49.956**	0.363	**0.322**	0.499	**0.378**
F-MB-F	0.077	**0.051**	25.108	**23.666**	0.364	**0.322**	0.455	**0.339**
c_{max}	0.077		76.076		2.607			

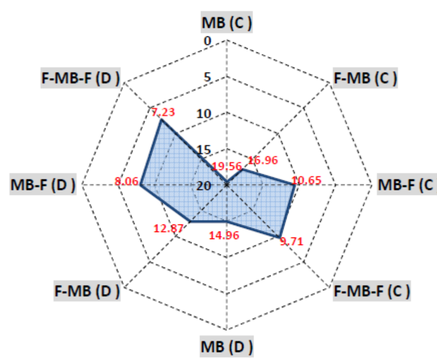
Waleed A. Hafiz and **Alaa Khamis**, "Bayesian Approach to Multisensor Data Fusion with Pre- and Post-Filtering", 10th IEEE International Conference on Networking Sensing and Control, 2013.

Towards Cooperative Multirobot Systems

- **Debative Cooperation: Uncertainty Reduction**



Estimated Variance using Decentralized Fusion



Waleed A. Hafiz and **Alaa Khamis**, "Bayesian Approach to Multisensor Data Fusion with Pre- and Post-Filtering", 10th IEEE International Conference on Networking Sensing and Control, 2013.

Thank you for your attention

Questions?