# **Self-organized Multi-robot Task Allocation**

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**Outline**

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**2** **Task Allocation by Attractive Field Model (AFM)**

**3** **Communication Models**

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## Background: The EPSRC Project: "Defying the rules - How Self Regulatory Social Systems Work"

### Objectives

- Identify generic rules that allow social systems to develop sustainability through self-regulation.
- Improve the performance and robustness in the organization of social systems.

### Our collaborators

- The Applied Mathematics Research Group,
  University of West of England
- The Centre for Systems Studies,
  University of Hull
- The Condensed Matter Theory Group,
  Imperial College, London

## Multi-robot Task Allocation (MRTA)

### What is MRTA?

In a multi-tasking environment dynamically allocate appropriate tasks to appropriate robots considering the changes in task-requirements, team-performance and environment.

### Why MRTA is difficult?

In typical large distributed multi-robot teams:

- No centralized planner or coordinator
- Robots have limited ability
    - → to sense, communicate and interact locally
- Robots have limited world-views
    - → knowledge of past, present and future actions of others

## Major Approaches for MRTA

### Explicit allocation

Through explicit modelling of environment, tasks, robot capabilities. Some forms are: knowledge based, market based, role based, control theoretic.

- Pros: Straight-forward to design, implement and analyse formally[a].
- Cons: Not suitable for large teams ($> 10$), heavy dependency on explicit global broadcast communication [b].

[a]Parker, *J. of Phy. Agents*, 2:2, 2008
[b]Lerman *et. al*, *IJRR* 25, 2006

### Self-organized allocation

Through emergent group behaviour produced by the local interaction and implicit or local communication. Most common form is: response threshold based approach.

- Pros: Suitable for large teams, no explicit model, implicit/local communication[a].
- Cons: Difficult to design, implement, analyse and limited to one specific global task.[b]

[a]Pugh & Martinoli, *Swarm Intell:*3, 2009
[b]Gerkey & Mataric, *IJRR*, 23, 2004

## Self-organization

### What is Self-organization?

Pattern formation in both biological and physical systems through the local interactions internal to the system [a].

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[a]Camazine *et al.*, Self-organization in Biological Systems, 2001.

### Ingredients

- Positive feedback
  $\rightarrow$ ants' recruitments to food source.
- Negative feedback
  $\rightarrow$ overcrowding at food sources.
- Multiple interactions
  $\rightarrow$ peer-to-peer, broadcast communication
- Randomness
  $\rightarrow$ error in trail-following

### Why Self-organized approach?

- Implementing simple agent behaviours is economical
- Easily scalable for large robot-teams and tasks
- Fault-tolerant
- Energy-efficient

## Attractive Field Model (AFM)

### Features of AFM

- **Interdisciplinary:** Developed from the study of ant, human and robotic social systems[a].
- **Abstract:** Sufficiently abstract to accommodate different sensing and communication models.

[a]Arcaute *et al.* Ecol. Complexity, 6:4 2008.

### Requirements of Self-regulation

1. **Concurrence:** "The simultaneous presence of several tasks"
   $\rightarrow$ at least a single task and the option of not doing any task.

2. **Continuous flow of information:**
   $\rightarrow$ to perceive tasks and receive feedback on system performance.

3. **Sensitization:** "Individuals having different levels of preference"
   $\rightarrow$ to all available tasks.

4. **Forgetting:** "A mechanism to reduce sensitisation levels"
   $\rightarrow$ e.g. a slow general decay of sensitisation.
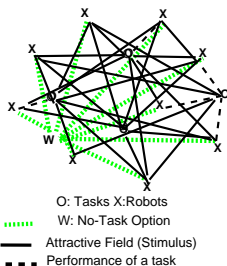
## AFM as a Bipartite Network



O: Tasks  X: Robots
W: No-Task Option
—— Attractive Field (Stimulus)
· · · Performance of a task

**Figure:** The attractive filed model (AFM)

| Source nodes (o) | tasks to be allocated |
| --- | --- |
| Agent nodes (x) | agents e.g., ants, humans, or robots |
| Black solid edges | attractive fields that correspond to an agent's perceived stimuli from each task |
| Green edges | attractive fields of no-task option shown as task (w) |
| Black dashed edges | not edges, but shows an agent allocated to a task. |

Agent's probability to choose a task:

$$P_j^i = \frac{S_j^i}{\Sigma_{j=0}^{J} S_j^i} \quad where, \quad S_0^i = S_{RW}^i \qquad (1)$$

$S_j^i$ and $S_{RW}^i$: $i$ agent's stimuli to $j$ task and random-walk.

Strength of an attractive field:

$$S_j^i = tanh\{\frac{k_j^i}{d_{ij} + \delta} \phi_j\} \qquad (2)$$

$k_j^i$, $d_{ij}$: $i$ agent's sensitization and distance to task $j$. $\phi_j$: urgency of task $j$.

## AFM and Self-organization

- **Positive feedback** through learning
  Example: Increasing task-sensitization of agents
  With an agent's *rate of learning* tasks, $k_{INC}$:

  $$If \ task \ is \ done: \ k_j^i \rightarrow k_j^i \ + \ k_{INC} \qquad (3)$$

- **Negative feedback** through forgetting
  Example: Decreasing task-sensitization of agents
  With an agent's *rate of forgetting* tasks, $k_{DEC}$:

  $$If \ task \ is \ not \ done: \ k_j^i \rightarrow k_j^i \ - \ k_{DEC} \qquad (4)$$

- **Multiple interactions** through continuous flow of information.

- **Randomness** through stochastic task-selection.

**Related issues for using AFM in real-world application**



**Figure:** Modelling real-world application to a laboratory scenario

### Map tasks & robot capabilities

1. workload $\Leftrightarrow$ task-urgency
2. work done $\Leftrightarrow$ task-urgency decrease
3. work pending $\Leftrightarrow$ task-urgency increase

### Enable continuous flow of info

1. Centralized communication
2. Local communication
3. Stigmergic communication

### Other issues

1. Enable learning/forgetting in controller
2. Perception of distance $\Leftrightarrow$ localization

## A Manufacturing Shop-Floor Interpretation of AFM
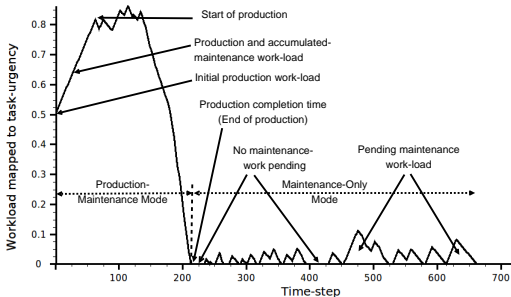


**Figure:** Production and maintenance cycles of a manufacturing shop-floor

AFM validation under a shop-floor scenario[a].

| Initial task urgency | workload x $\delta\phi_{INC}$ |
|---|---|
| If task unattended | work-load increases by $\delta\phi_{INC}$ |
| If task served | work-load decreases by $\delta\phi_{DEC}$ |
| Average Production Completion Delay (APCD) | (*Ideal production time - Actual production time*)/ *Ideal production time* |
| Average Pending Maintenance Work (APMW) | (*Total pending maintenance work in all machines*)/*Total no. of machines.* |

[a]Sarker & Dahl. *LNCS* 6234, 2010.

## **Centralized and Local Communication Models**
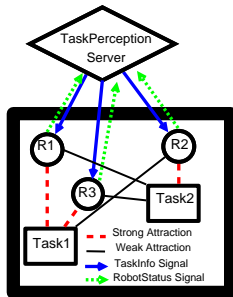


**Figure:** A centralized communication scheme

Communication models inspired by wasps[a]

| **Centralized Model** | **Local Model** |
|---|---|
|  |  |
| Modelled after *Polistes* wasps: "global sensing no peer-to-peer communication" | Modelled after *Polybia* wasps: "local sensing local communication" |
| Global broadcast messaging | Local peer-to-peer messaging |
| Communicate synchronously | Communicate when peer(s) come in close contact (inside range $r_{comm}$) |

[a]Jeanne. *Info. process. in social insects*, 1999

## A Taxonomy of MRTA Solutions
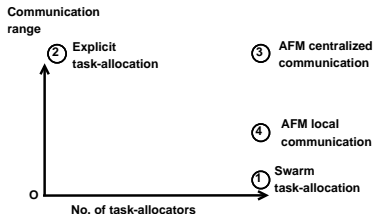


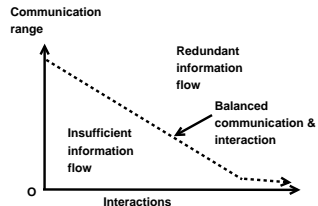**Figure:** Classification of MRTA solutions based on task-allocation and communication strategies



**Figure:** Information flow caused by different levels of communication and interaction

## **Multi-robot control architecture**

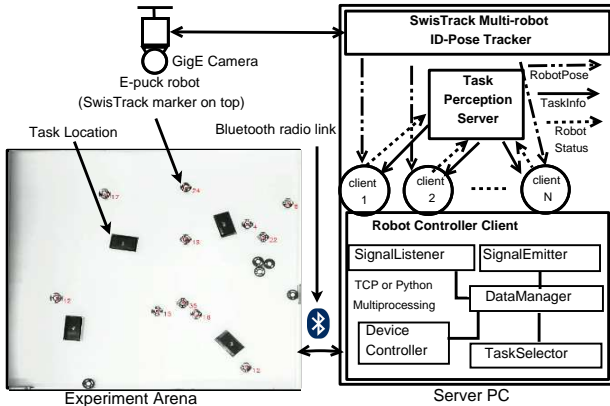Based on our Hybrid-event Driven Architecture on D-Bus[1]



**Figure:** Hardware and software setup for centralized communication experiments

[1]Sarker & Dahl. *Proc. of UKACC Int'l Conference on Control, Coventry, UK* 2010.

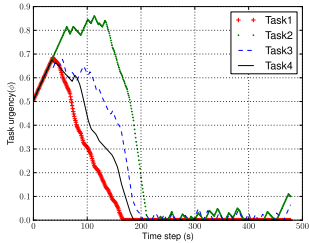## Results: Shop-floor Work-load and Active Workers



**Figure:** Changes in task-urgency

Shop-floor work-load:
Sum of changes in task-urgencies of all $M$ tasks at $(q+1)^{th}$ step:

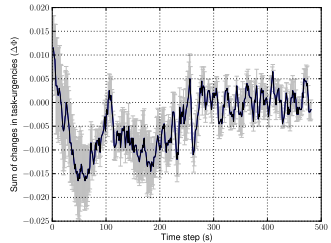$$\Delta\Phi_{j,q+1} = \sum_{j=1}^{M}(\phi_{j,q+1} - \phi_{j,q}) \qquad (5)$$



**Figure:** Shop-floor work-load

Active worker ratio:

$$\frac{\textit{Active workers in all tasks}}{\textit{Total available workers}} \qquad (6)$$

## Results: Shop-floor Work-load and Active Workers Ratio in 4 tasks experiments with 16 robots
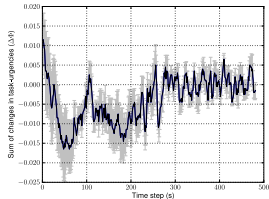


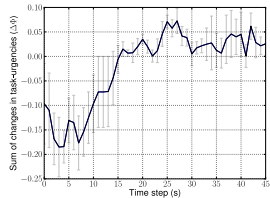**Figure:** Shop-floor work-load under centralized comms.



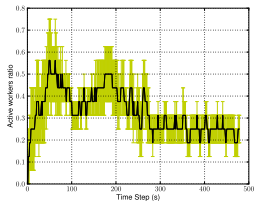**Figure:** Shop-floor work-load under local comms.



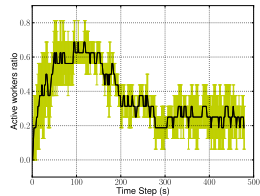**Figure:** Active worker ratio under centralized comms.



**Figure:** Active worker ratio under local comms.

## Results: Task-Performance

**Table:** Shop-floor production and maintenance task performance

| Experiment Series | Production delay (SD) s | p-value 1-tailed t-test (confidence) | Pending maintenance time (SD) s | p-value 1-tailed t-test |
|---|---|---|---|---|
| 8 robots, 2 tasks, centralized, sample n=5 | 555 (50) | 0.0 | 5 (5) | 0.0 |
| 16 robots, 4 tasks, centralized, sample n=5 | 825 (360) | 0.2 (60%) | 15 (65) | 0.0 |
| 16 robots, 4 tasks, local with range=0.5m, sample n=3 | 605 (180) | N/A | 25 (85) | N/A |
| 16 robots, 4 tasks, local with range=1m, sample n=3 | 615 (200) | 0.0 | 10 (35) | 0.0 |

## Results: Task-specialization

Overall group task-specialization in terms of peak values of sensitization of all robots:

$$K_{avg}^{G} = \frac{1}{N} \sum_{i=1}^{N} \max_{j=1}^{M} \left( k_{j,q}^{i} \right) \quad (7)$$

Time spent to reach peak sensitization values for all robots:

$$Q_{avg}^{G} = \frac{1}{N} \sum_{i=1}^{N} q_{k=k_{max}}^{i} \quad (8)$$

**Table:** Task-specialization values of the robots

| Experiment Series | $K_{avg}^{G}$ (SD) | *p-value* 1-tailed t-test (confidence) | $Q_{avg}^{G}$ (SD) | *p-value* 1-tailed t-test (confidence) |
|---|---|---|---|---|
| 8 robots, 2 tasks, centralized, n=5 | 0.40 (0.08) | 0.0 | 38 (13) | 0.001 (99.8%) |
| 16 robots, 4 tasks, centralized, n=5 | 0.30 (0.03) | 0.2 (60%) | 18 (5) | 0.2 (60%) |
| 16 robots, 4 tasks, local with range=0.5m, n=3 | 0.39 (0.17) | N/A | 13 (7) | N/A |
| 16 robots, 4 tasks, local with range=1m, n=3 | 0.27 (0.1) | 0.0 | 11 (5) | 0.0 |

## Results: Energy-usage

**Table:** Sum of translations of robots in our experiments.

| Experiment Series | Average translation (SD) m | *p-value* 1-tailed t-test (confidence) |
|---|---|---|
| 8 robots, 2 tasks, centralized, n=5 | 2.631 (0.804) | 0.05 (90%) |
| 16 robots, 2 tasks, centralized, n=5 | 13.882 (3.099) | 0.001 (99.8%) |
| 16 robots, 4 tasks, local with range=0.5m, n=3 | 4.907 (1.678) | N/A |
| 16 robots, 4 tasks, local with range=1m, n=3 | 4.854 (1.592) | 0.0 |

**Results: Communication Loads in terms of Frequency of `TaskInfo` signalling**
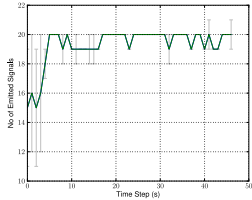


**Figure:** Under 8 robots, centralized communication
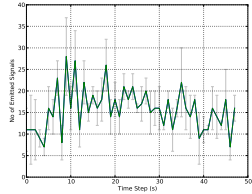


**Figure:** Under 16 robots, local communication, range=0.5m
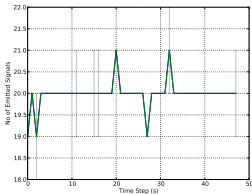


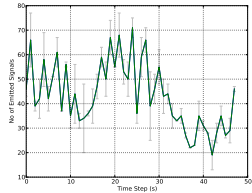**Figure:** Under 16 robots, centralized communication



**Figure:** Under 16 robots, local communication range=1m

## Conclusions & Future works

### Conclusions

- AFM solves the MRTA issue for a relatively large group.
- Task-performance varies under different strategies
  → for a reasonably large group, local communication achieves similar task-performance and task-specialization comparing with a centralized counterpart, but *significantly* reduces motions.
- AFM can model complex multi-tasking environment
- Maximizing information flow may not be useful

### Future works

- Deploy our task-allocation model in various task settings
- Relate communication range as a property of self-regulation
- Real-world implementation: e.g. warehouse automation
- Study the role of formal structure on informal self-organization.

**General Contributions**

- Self-organization
  $\rightarrow$ Self-organized allocation may produce specialized workers even when the group size is *small* ($< 10$), unlike assuming generalist workers prevents specialization in small groups[2].

- Task-allocation
  $\rightarrow$ Local communication in task-allocation may outperform centralized one in terms of energy usage.

- System development
  $\rightarrow$ Bottom-up de-coupled construction of *large* artificial system yields higher advantages particularly, flexibility and integration with inter-operable elements.

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[1]Garnier *et al.* Swarm Intelligence 1:1, 2007.

## Specific Contributions

- Interpreted AFM
  → as a basic mechanism for multi-robot task-allocation
- Validated the effectiveness of AFM
  → with reasonably *large* number of real robots
- Compared centralized & local communication in MRTA
  → modelled after social wasps: *Polistes* and *Polybia*
- Developed a *flexible* multi-robot control architecture
  → using *D-Bus* inter-process communication
- Classified MRTA solutions focusing three major issues:
  1. Organization of task-allocation
  2. Communication and
  3. Interaction