ALLIANCE: An Architecture for Fault Tolerant Multi-Robot Cooperation

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Problem

- To develop a software architecture that facilitates fault tolerant cooperative control of teams of heterogeneous mobile robots working towards a common goal.

- The software architecture should be robust, reliable and flexible in dynamic and unpredictable environments.

- The architecture should be distributed.
Solution

- ALLIANCE developed by Lynne E. Parker

**Key Features of ALLIANCE**

- Fully Distributed Architecture.
- Behavior-based Architecture.
- Heterogeneous robot teams.
- Fault tolerant Architecture; in terms of dynamic task-reallocation.
- Reduced communication overhead; no negotiations.
- Use of mathematical motivation models, *impatience* and *acquiescence*, towards adaptive action selection.
- Implemented on a team of physical robots.
Assumptions

- The robot can detect the effect of their own action.
- Robot \( r_i \) can detect the actions of other team members through explicit communication.
- Robots on the team are not intentionally adversarial.
- The robots do not possess perfect sensors.
- Any of the robot subsystems can fail.
- The communication medium is not guaranteed to be available.
- Robot failure cannot be necessarily communicated to other robots.
- The robots do not have the complete world knowledge.

Note: The assumptions are made with respect to small to medium sized team of multi-robots.
Overview of ALLIANCE

- Overall mission is decomposed into a set of high-level tasks.
- High-level tasks are achieved by means of a number of behavior sets that an individual robot is capable of executing.
- The set of behaviors consists of higher-level behaviors, map-building, exploring, and lower-level behaviors, obstacle avoidance, etc.
- The output of the lower-level behaviors can be suppressed or inhibited by the higher-level when necessary.
- Behavior sets are classified as active, if robot is executing that behavior set, or hibernating, if otherwise.
- Only one behavior set is active at any point in time.
- The selection of the behavior set is done by means of motivational behaviors, each of which controls the activation of one behavior set.
ALLIANCE Architecture

The ALLIANCE Architecture

Inter-Robot Communication

Motivational Behavior

Motivational Behavior

Behaviors Set 0

Layer 2

Layer 1

Layer 0

Sensors

Motivational Behavior

Motivational Behavior

Behavior Set 1

Behavior Set 2

Actuators
Motivational Behaviors

- ALLIANCE uses motivation for task monitoring and dynamic task reallocation.

- Each motivational behavior receives input from a number of sources including sensory feedback, inter-robot communication, inhibitory feedback, and internal motivations. These inputs are used to generate the output at any point of time.

- The output defines the activation level of each behavior.

- Once the activation level exceeds the preset threshold for each behavior, the behavior is activated.

- ALLIANCE uses 2 types of internal motivation: impatience and acquiescence
  - **Impatience**: enables the robot to handle situations external to itself.
  - **Acquiescence**: enables the robot to handle internal situations.
Motivational Behavior

- **Working**
  - A robot’s motivation value to activate a behavior is initialized to 0.
  - Over a period of time the robot’s motivation level increases at a rate that depends on the activities of its co-workers.
    - If no robot is accomplishing a behavior then the motivation level increases at a fast rate of impatience.
    - If another robot is working on the behavior then the motivational level increases at a slower rate of impatience.
  - At the same time the robot’s willingness to give up a task increases over time as long as the sensory task indicates the task is not being accomplished.
Formal Model of ALLIANCE

- Set of n heterogeneous robots in the team
  \( R = \{r_1, r_2, ..., r_n\} \)

- \( m \) independent subtasks which form the mission.
  \[ T = \{t_{sk_1}, t_{sk_2}, ..., t_{sk_m}\} \]

- Behavior set possessed by robot \( r_i \).
  \[ A_i = \{a_{i1}, a_{i2}, ...\} \]

- Set of \( n \) functions where \( h_i(a_{ik}) \) indicates the task that robot \( r_i \) is working on when it activates behavior \( a_{ik} \)

Parameters

- Activation threshold: \( \theta \). This determines the level of motivation beyond which a given behavior set becomes active.
Formal Model of ALLIANCE

- Sensory Feedback:
  \[ sensory\_feedback(t) = \begin{cases} 
  1 & \text{if the sensory feedback in robot } r_i \text{ at time } t \\
  0 & \text{otherwise} 
\end{cases} \]

- Inter-robot communication:
  \[ \text{comm\_received}(I,k,j,t_1,t_2) = \begin{cases} 
  1 & \text{if robot } r_i \text{ has received message from robot } r_k \\
  0 & \text{otherwise} 
\end{cases} \]

- Suppression from active behavior:
  \[ \text{activity\_suppression}_{ij}(t) = \begin{cases} 
  0 & \text{if another behavior set } a_{ik} \text{ is active, } k \neq j, \text{ on robot } r_i \text{ at time } t \\
  1 & \text{otherwise} 
\end{cases} \]

- Impatience:
  \[ \text{Impatience}_{ij}(t) = \begin{cases} 
  \min_k (\delta\_slow_{ij}(k,t)) & \text{if } (\text{comm\_received}(i,k,j,\ t-\tau_i,t) = 1) \\
  \delta\_fast_{ij}(t) & \text{otherwise} 
\end{cases} \]
Impatience_reset\_ij (t) = \begin{cases} 
0 & \text{if } \exists k.((\text{comm\_received}(i, k, j, t - \delta t, t) = 1) \text{ and } \\
& (\text{comm\_received}(i, k, j, 0, t - \delta t) = 0)) \text{, where } \\
& \delta t = \text{time since last communication check} \\
1 & \text{otherwise} 
\end{cases}

Robot Acquiescence:

\text{acquiescence}_{ij}(t) = \begin{cases} 
0 & \text{if } ((\text{behavior set } a_{ij} \text{ of robot } r_i \text{ has been active } \\
& \text{for more than } \psi_{ij}(t) \text{ time units at time } t) \text{ and } \\
& (\exists x.\text{comm\_received}(i, x, j, t - \tau_i, t) = 1)) \text{ or } \\
& \text{behavior set } a_{ij} \text{ of robot } r_i \text{ has been active } \\
& \text{for more than } \lambda_{ij}(t) \text{ time units at time } t) \\
1 & \text{otherwise} 
\end{cases}

Motivation Calculation:

\begin{align*}
\text{m}_{\text{ij}}(0) &= 0 \\
\text{m}_{\text{ij}}(t) &= [\text{m}_{\text{ij}}(t - 1) + \text{impatience\_reset}_{ij}(t)] \\
& \times \text{sensory\_feedback}_{ij}(t) \\
& \times \text{activity\_suppression}_{ij}(t) \\
& \times \text{impatience\_reset}_{ij}(t) \\
& \times \text{acquiescence}_{ij}(t)
\end{align*}
L-ALLIANCE

- Dynamically updates the parameter settings based upon knowledge learned from previous experiences.

- Each robot 'observes', evaluates and catalogues the performance of any team member whenever it performs a task of interest to that robot.

- These 'learned' observations allow the robot to adapt their action selection over time.

- The underlying algorithm is distributed across the behavior sets of ALLIANCE.
Experiments

- Experiments conducted on physical robots: teams of 3 R-2 robots were used in all experiments.

- **Hazardous waste cleanup mission**
  - Mission requires two artificially 'hazardous' waste spills in an enclosed room to be cleaned up by a team of three robots.
  - The robot team must locate the two waste spills, move the spills to a goal location, while also periodically reporting the team progress to humans monitoring the system.
The cooperative team under ALLIANCE was robust. The team was able to respond autonomously to various types of unexpected events either in the environment or in the robot team without the need for external intervention. The cooperative team need not have a priori knowledge of the abilities of the other team members to efficiently complete the task. It allows the robot teams to accomplish their missions even when communication system breaks down.
## Comparisons

<table>
<thead>
<tr>
<th>ALLIANCE</th>
<th>Negotiation Based Approaches</th>
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<tbody>
<tr>
<td>Fully Distributed</td>
<td>Not completely distributed, some centralized decision maker.</td>
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<tr>
<td>Reduced communication overhead as there is no negotiation</td>
<td>Communication overhead is higher.</td>
</tr>
<tr>
<td>Each robot has to know about the capabilities of other robots</td>
<td>Each robot does not have to know about the capabilities of other robots.</td>
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Conclusion

- ALLIANCE is a fully distributed, behavior based approach for fault tolerant mobile-robot cooperation.

- ALLIANCE enhances team robustness through usage of motivational behavior mechanism.

- Physical redundancy can be used to enhance fault tolerance of the system.

- The L-ALLIANCE enhances ALLIANCE architecture by using learning algorithm to fine tune the impatience and acquiescence parameters.

- The architecture has been implemented on a team of physical robots, thereby illustrating its feasibility.