Multiple Human-Robot Collaboration with AURA Sharing

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Abstract

Multi-robot collaboration needs proximity that knows the task by adapting to interaction intent, not just geometric distance. Awareness of Uncertainty in Robot Actions (AURA) defines a continuous, actor-based proximity field from perception and internal state estimation to model spatial influence and anticipate intrusion. **AURA Sharing**, a mode-aware extension in which multiple robots reinterpret their outer AURA fields according to the collaboration mode: coexistence, cooperation or collaboration. The inner hard core remains private while the outer field becomes the interface for task-dependent spatial coordination.

Motivation

Presently, the multi-HRC scenario is,

- **Task-blind** – distance ignores the collaboration mode
- **Unshared** – partners look like unknown obstacles
- **Unscalable** – fixed margins break down with more actors [2]
- **Training-dependent** – Signed Distance Fields (SDF) [3] require offline network training per robot, with no real-time adaptation to dynamic partners

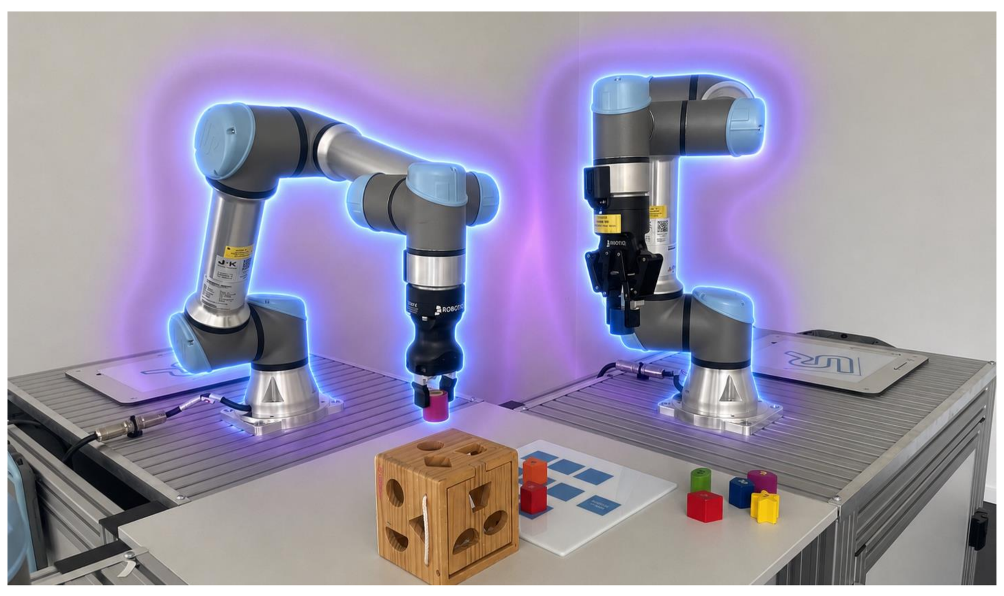
→ **Need**: proximity that adapts to the interaction intent

Background

Human-robot collaboration is classified into three interaction modes based on spatial separation:

- **Coexistence:** human and robot share a workspace but work independently on separate tasks; no direct interaction.
- **Cooperation:** human and robot work concurrently on the same workpiece, requiring spatial awareness of each other.
- **Collaboration:** human and robot work interdependently on the same task; one cannot proceed without the other [1, 4].

(a)
Coexistence mode – Separate fields, each robot doing their own tasks



(b)
Cooperation mode – Overlapping fields, working on the same workpiece, concurrent but independent actions

(c)
Collaboration mode – Merged outer field, jointly handling the same object in a shared workspace

Figure 1. AURA Visualization in different Collaborative Modes

Approach

Mode-Aware AURA Sharing Mechanism:

1. **AURA specific to each Robot**
   Each robot maintains an AURA field through GMM and the joint-state estimation.

$$A_i(p) = \sum_{k=1}^{N_i} \exp\left(-\frac{\|p - c_{ik}\|^2}{2\sigma_i^2}\right)$$

$where,$
$p \quad \rightarrow query\ point\ in\ the\ workspace$
$c_{ik} \quad \rightarrow sampled\ link\ point\ of\ robot\ i$
$\sigma_i \quad \rightarrow spatial\ spread\ of\ robot\ i's\ AURA$

2. **Mode Selection by Robot IDs**
   Assignment of tasks that have been classified into different modes and selection of robots.

Selection of Robots (IDs) by Operators → Task Assignment and Collaboration Mode selection → Activation of AURA Sharing Policy

3. **AURA Sharing Rule:**

Layer	Implication	Sharing Rule
Inner field	Hard collision boundary	Never shared
Outer field	Spatial influential zone	Mode-dependent
Intrusion region	Obstacle candidate	Sent to RRT for replanning

4. **AURA Sharing Policy**
   The collaboration mode controls only the outer field. The inner hard field remains private in all modes.

$$\mathcal{A}_i = \mathcal{H}_i \cup \mathcal{O}_i$$

where, $\mathcal{H}_i \rightarrow Hard\ inner\ layer,\ \ \mathcal{O}_i \rightarrow Outer\ layer$

- $Coexistence \quad \rightarrow \mathcal{O}_i \cap \mathcal{O}_j = \emptyset$
- $Cooperation \quad \rightarrow \mathcal{O}_i \cap \mathcal{O}_j \neq \emptyset, d_{ij} \leq \delta$
- $Collaboration \quad \rightarrow \mathcal{O}_i \cup \mathcal{O}_j = \mathcal{O}_{ij}^{shared}$
- $Invariant\ Rule \quad \rightarrow \mathcal{H}_i \cap \mathcal{H}_j = \emptyset \quad \forall i \neq j, \forall modes$

5. **Reactive Planning Interface**
   Any observed foreign point inside the active AURA is converted into an obstacle for reactive replanning.

$$p_{obs} \in \mathcal{A}_{active} \Rightarrow AABB(p_{obs}) \rightarrow RRT$$

References

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