# Enabling Efficient Team Cooperation by Understanding Modes of Human-robot Interactions

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## I. Introduction

An important piece of solving the problem of enabling human-robot teaming at and beyond operational speeds in dynamic, unstructured environments lies in how interaction and communication take place within the team and what information is communicated in support of the shared goals of the team. It is critical to identify and define a structure classifying what drives interaction such that teammates in these scenarios can heuristically know what to communicate with which teammate, when to communicate it, and what depth of information should be provided. To this end, we address a subset of the problem of defining such a structure by highlighting three primary factors impacting interactant dynamics as they relate to an example operational context. Furthermore, we ground these factors into a mission model including a hierarchy of state description levels to support efficient and effective communication between human and robot teammates working at and beyond human operational speeds.

The operational context that we use to ground our approach is the RoboFlag testbed domain introduced by D'Andrea and Babish [1]. This domain demonstrates human-robot interaction at high speeds in dynamic, unstructured environments and thus provides a rich context for exploration of these topics. The RoboFlag testbed emulates a capture-the-flag scenario in which two teams of 6-10 robots and 2 people apiece in a hybrid simulated-physical environment are each trying to cross into the opponents territory, capture their flag, and return to their own territory while evading the enemy team. In this domain, the human and robot teammates need to interact at speed in an environment with limited sensing capabilities, distributed processing of information, and limited bandwidth capabilities In our analysis, we divide this scenario into "scout" and "defend" stages with subteams dedicated to each stage.

## II. Underlying Dimensions of Cooperative Communications in a Team

We make the case that for real-time cooperation it is essential to understand the local dynamics of the interactants and adjust the *mode of communication* accordingly. In this section we use examples from within the outlined domain to reflect the importance of following factors:

- Goal interdependence [2]
- Task Workflow [3]
- Human-robot Roles [4]: Supervisor, Operator, Mechanic, Peer and Bystander.

We assume full-communication between the agents and a mixed planning schema, where task are assigned ahead of time but contingencies need to be planned for online.

**A. Amongst Scouting Agents.** Scouting agents work in parallel to map the grounds while locating adversarial agents and their flag. An example of a shared goal and parallel task-flow, which entails that whenever an agent finishes its individual task, that should be communicated to trigger a rearrangement of duties such that they can cooperate better. Note that this is different than their passive communication of sharing data for a fused map.

**B. Between Scouts and Defense.** Defending agents are tasked with the mission to guard their own flag and fend off adversarial agents. Their actions not only depend on their own perception of the area but also on the information communicated by the scouts who encounter any adversaries. The mapped representation of the grounds helps in projecting the location information to angle and time-of-attack metric. An example of sequential task-flow where goals of one depend on output of the other. For efficient communication it is necessary to understand underlying dependencies of the information flow.

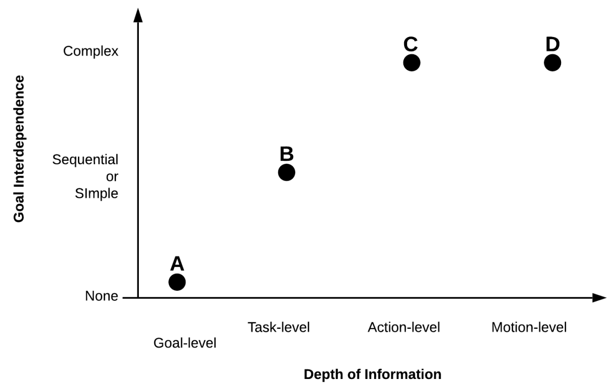


Fig. 1. Depth of Information versus Goal Interdependence for Example Scenarios

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This work was supported by the DCIST Collaborative Research Alliance at the Army Research Lab

**C. Within Defense During Adversarial Attack.** This is the most complex scenario within the outlined domain requiring faster communication, and an assessment of own as well as the other team to plan the right moves. Due to the almost dialog-like quality of this interaction it is an ideal example of a reciprocal task-flow with complex goal dependencies. Cooperation here requires a dialog-like back and forth between the agents and can go up from communicating sub-goals to communicating motion-level plans such that each agent can reactively plan around the other. Even within this a sub-team of the defense might break-off to form an inner guard team, that exclusively guards the flag and tackles those agents who break through the outer defense. At this point, all agents within outer defense team require a dialog like communication to tackle offense but only need to communicate with the inner sub-team when an adversary slips past.

**D. Effect of Human-robot Roles.** Human-robot roles were formulated by assessing errors at various levels-of-design of a robot such that the human can resolve it. Therefore there is a tight coupling between level of the contingency and the role of human who should be involved. Supervisors tend to know about mission priorities and constraints, and are ideal for resolving goal conflicts, e.g. should a scout switch to defense role under a heavy attack. At lower levels, peers are better for asking for any physical help, however, if the robot senses any conflicts at control-level the operator is the only one equipped with enough training to understand and troubleshoot such a problem. Interestingly, operator and robot are a micro-example of complex goal interdependencies since they need tight coupling and dialog for efficient motion execution.

## III. Grounding Factors into Mission Description

To ground the abstract concepts mentioned previously we need to define structures which can encapsulate the basic data and functions associated with the mission and description levels of the agent. We define a simple mission decomposition as following:

$$
\begin{aligned}
M &\rightarrow \{\vec{G} = (G_0, G_1, G_2, \ldots),\ \vec{G_p},\ \mathbf{G_c} : |\vec{G}|X|\vec{G}|\} \\
G_j &\rightarrow \{t_0^j, t_1^j, \ldots\} \mid \mathbf{G_c}^j \\
t_k &\rightarrow \{a_0^k, a_1^k, \ldots\} \\
a_k^r &\rightarrow \{u_0^k, u_1^k, \ldots\}
\end{aligned}
$$

The mission $M$ is defined by a goal vector, a matrix $\mathbf{G_c}$ which defines the constraints and $\vec{G_p}$ which defines the priorities over the goal-space. $\mathbf{G_c}^j$ symbolises the $j^{th}$ column of the matrix. A goal in turn can be decomposed into ordered vector of assignable tasks $t_k^j$, which are further decomposed into actions $a_l^k$ by the acting agent. The last decomposition is specific to the robotic agent where actions are further broken-down into joint controls.

Next, going from most detailed to least, we impose the following descriptive definitions on the hierarchical levels of state description by the robot:

1) *Control* - Lower-level details like joint-speed, joint-torques, current strength, battery-levels, etc.

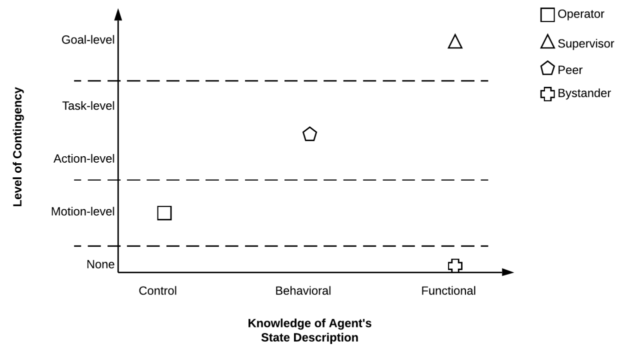


Fig. 2. Level of State Knowledge versus Level of Contingency for Team Roles

2) *Behavioral* - This level correlates with the task decomposition above and consists of state-description at the level of planned actions, e.g. forward-motion by $x$ meters, pick-object $O_i$, place-object $O_j$ at location $x_j, y_j, z_j$, etc.
3) *Functional* - Higher-level plans incorporating projections, relations, goal-level and object/landmark-level information, e.g. pick the red object, move to the kitchen, estimated battery time, etc.

Figure II provides a summary of how goal interdependencies mentioned in the previous section affect information-depth requirement between agents for efficient cooperation. Figure III summarises how the roles are broken-down into expected task and agent knowledge which can help to create heuristics about whom to involve in a particular kind of contingency.

## IV. Conclusion and Future Work

This paper assimilates previous literature to highlight underlying factors driving cooperative communication in a mixed human-robot team. A quantized scale is imposed onto these factors grounding them in mission decomposition schema. Note that we assumed several global conditions which allowed us to evaluate local dynamics of the interaction. We plan on evaluating generalization ability of our heuristics using a collaborative manipulation experiment under varying human-robot role assignments, collocated and remote robot-operation setups, and different task-flow constraints.

## References

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