From I-Robot to We-Robot: Effects of Team Structure on Robotic Tasks

Alec Jacob Ranzato
Digital Analyst
Resolute Digital LLC
New York City, NY 10001 USA
aranzato@alumni.princeton.edu

Janet Vertesi
Princeton University
Princeton, NJ 08544 USA
jvertesi@princeton.edu

Abstract
This paper describes an experiment in which we varied the organizational structure of teams controlling a remote robot with the goal of maximizing exploration and exploitation. Although arranged in two groups, hierarchical and consensus, we observed the emergence of three sets of outcomes: tightly coupled hierarchical and consensus groups, and loosely coupled versions of both. Each group had divergent outcomes with respect to efficiency, communication, and teammate trust, with the loosely coupled teams emerging as the most successful.

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Human-Robot Interaction; teamwork; decision-making; organizations

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous

Introduction
Robots are increasingly used in team settings to accomplish complex tasks, from space exploration to search and rescue. But human groups that form to accomplish such tasks frequently display different organizational forms. From the flat hierarchies of scientists or Silicon Valley companies to the strong

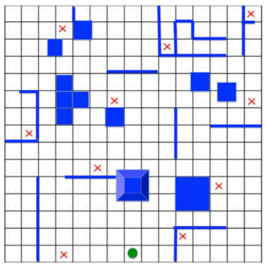

Figure 1: Experimental space of 15x15 square, with obstacles and walls.

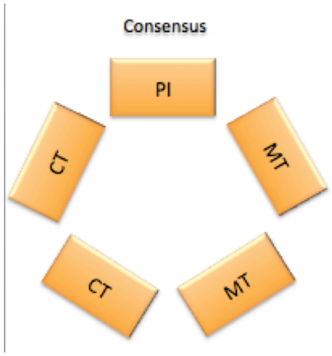

Figure 2: Seating arrangement in Consensus trials

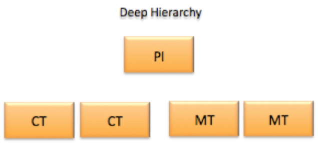

Figure 3: Seating arrangement for Hierarchy trials

chains of command in military service, this might present different possibilities for robotic action, team culture, and interaction.

Generalized research about the role of team structure on team productivity reveals that changing team structure affects aspects of teamwork, patterns of communication, and decision making processes [2,7]. Previous ethnographic work on human-robot teams at NASA [8] reveals a complex interplay between team and communication structure, and how decisions are made and tasks achieved. While studies of groups of humans commanding robots take many factors into account, social organization of decision-making and communication is typically absent from such analysis [4]. This small study therefore set out to illuminate how the varying team structures might affect team dynamics with a real robotic teammate.

Experimental Setup

The aim of this experiment was to test whether or not organizational structure matters for robotic tasks by simulating a context wherein a large team collaboratively controls a remote robot through an experimental space to achieve of number of exploratory tasks. The experimental space consisted of a grid of 15x15, with 10 objects for the robot to find (Figure 1). We deployed a three-inch-high, tread-based "rover" with camera functionality controlled via iPhone over Wi-Fi. Taking inspiration from NASA missions and urban search and rescue, we kept the robot remote from the team in control of its actions, feeding them locational information via pictures taken by the robot.

Thirty participants were recruited, and divided into 6 teams of 5, each with a 3:2 gender ratio. Each team had 90 minutes in which to find as many objects as possible and maximize exploration using "command sets" (a sequence of commands to give the robot) decided upon within maximum 10 minute intervals. However, their decision-making structures varied. Within each team, participants were randomly assigned a role: one "Principal Investigator (PI)" who lead the group, two "Camera Technicians (CT)" responsible for safeguarding memory and camera efficiency, and two "Movement Technicians (MT)" whose goal was to maximize speed and efficiency of exploration. To simulate work in a context of organizational specialization, these goals were purposefully at odds.

Each team was then assigned one of two experimental conditions: consensus or hierarchical communication structure. Under consensus, the entire group had to agree to the robotic action plan, and the PI played a supporting role in getting the group to agree. Under hierarchy, information fed up to the PI, who made the decision [3]. Participants were given customized scripts that described their team's goals, their personal goals based on their role, the information to which they had primary access, as well as their decision-making conditions (Figure 2-3). Participants were also given a grid sheet on which to create their own maps of the space and a computer on which to view pictures.

Analytical techniques

We audio recorded and transcribed all six trials and subjected them to open coding and some conversation analysis to understand how decisions were being made. We also circulated a post-experiment survey with a Likert Scale structure asking team members to judge their own and their team's performance. We tracked performance metrics inspired by [1] to measure team

	H1	H2
# Command sets	16	13
Commands/set	11.8	11.5
% explored	36.4	24.4
Objects Found	6	7
Errors	2	5

Table 1: Tightly coupled Hierarchical teams

	C1	C3
# Command sets	22	16
Commands/set	6.3	7.5
% explored	19.1	17.8
Objects Found	4	4
Errors	1	1

Table 2: Tightly Coupled Consensus teams

	H3	C2
# Command sets	18	19
Commands/set	7.9	8.6
% explored	23.1	24
Objects Found	6	7
Errors	0	1

Table 3: Loosely Coupled Teams

effectiveness, including number of objects found, errors in marking up team maps, and percentage of space explored. We also noted the number of command sets completed by each team within the 90-minute time frame, the average time to complete a command set, number of commands and pictures by each team.

Results

Hierarchy-based groups on average completed fewer command sets than consensus based groups, averaging at 15.67 sets versus 19 completed command sets in 90 minutes. The highest number of completed command sets achieved by a team was 22, and that was under the consensus condition. This appeared to support our initial intuition that consensus-based groups would be able to complete more command sets, perhaps due to more efficient communication and greater capacity to develop shared mental models and resolve conflict [5]. However, although consensus-based groups completed more command sets in the allotted 90 minutes, hierarchy-based groups had command sets that were notably longer. Qualitative analysis revealed that achieving consensus was a difficult process and that command sets were easier to agree upon if they were shorter, undermining any claim to efficiency.

Hierarchy-based groups also *moved* the robot much more than consensus based groups. The hierarchical conditions' lengthy command sets were dominated by movement based commands rather than pictures. This is supported by the percentage of physical space covered by the robot for each group. Consensus based groups explored an average of 20.3% of the experimental space while hierarchy groups averaged 28.0% of the map, ranging from 24 to 36%. While not possible to call this statistically significant due to the limited trials, the difference is notable.

The number of objects found was also higher for hierarchical teams, who discovered an average of 6.33 objects while consensus teams found an average of 5 objects during the 90 minutes. However, consensus teams made fewer errors: only 1 error each versus an average of 2.33 errors under hierarchy. Qualitative data suggested that consensus based teams were very concerned with detail and certainty throughout the spatial mapping process, as compared to hierarchy based groups which were more willing to make riskier decisions based on approximations. The shortened command sets in addition to the few errors made by consensus group suggests that consensus was easier to achieve in planning sessions if action was geared toward confirmation rather than exploration. Indeed, the transcripts of both consensus trials revealed many of interruptions, reiterations, and multiple confirmations that occurred during the discussions, indicating a "free-for-all" style.

Tight and Loose Coupling

Two groups under each condition did appear to function as formally laid out, but the remaining two created hybrid organizational structures, embedding a hierarchy within consensus or vice-versa. Organizations with "gaps in formal structure and actual work activities" are described as loosely coupled in order to maintain efficiency in the face of uncertainty or to address a lack of efficiency embedded in the formal structure [5].

Hierarchy teams 1 and 2 comprise a tightly coupled cluster (Table 1). Across the performance data they had a low total number of command sets as well as near identical average numbers of commands per command set. These two groups also explored the most space (up to 36.4% of the map), and made the most errors in object placement. Consensus teams 1 and 3 (Table 2) also had very similar average number of commands per command set and amount of space explored with those command sets. These two teams explored the least amount of space and only discovered 4 objects within the experimental space; however, they only made 1 error in object placement on the map. We also saw consensus teams use their decision-making style at sites beyond command set confirmation, reinforcing a close relationship to that style. From the quantitative results as well as comparison of qualitative analysis, then, we are confident that these four experimental conditions represent a tightly coupled formal and informal organizational condition, one where the team's culture of decision making mirrored its structure.

Hierarchical team 3 and consensus team 2 operated in ways that reflected their opposite conditions (Table 3). Qualitative analysis of transcripts indicated that the consensus team established a hidden power dynamic and "experts" emerged within the group to whom others deferred judgment. Meanwhile, in the hierarchical team the group experienced a lateral flow of information, acute attention to detail, shortened command sets, and a desire for more immediate gratification.

The quantitative performance data seems to support that there is a relation between these two groups. Both of these groups completed a similar number of command sets (19 and 18), and the average number of commands in each set was around 8. These numbers fall *between* the two other clusters. Further, both of these teams achieved exploratory success reminiscent of the tightly coupled hierarchical teams, both exploring greater than 23% of the map and finding 7 and 6 objects respectively, but also demonstrated a low number of object placement errors. Thus their "middle of the road" approaches, in respect to condition, seemingly allowed them to reap the benefits attributed to either organizational structure.

Trust, Value, & the Robot

Survey results showed a difference between clusters in how an individual believed his/her teammates valued his/her contribution. In loosely coupled groups, trust and teammate value were lower across the board and ideal team size was smaller. This may be because on both teams, the social order is inherently unclear. Fewer teammates might reduce this confusion. Tightly coupled groups had higher values place on trust and the value of team-members' contribution.

However, loosely coupled teams also had the most positive views toward their robotic teammate. The same ethnographic research that inspired this study [8] demonstrates how important this relationship is towards success. Without clear intra-team social order, loosely coupled teams were embraced their robotic teammate as a single point of unity among them.

Conclusions

The emergence of three informal orders for these groups indicate that there is measurable variability in team outcomes *depending on both their organizational structure* -- and what we might call their organizational culture as well. Tightly coupled hierarchical teams explored and discovered the most but made more errors. Tightly coupled consensus-based teams explored the least and discovered the least but made few errors in the process.

Loosely coupled teams emerged as the most successful in terms of productivity, exploring the most space and finding the most objects with the fewest errors. For the given task, this was enough to deem them the most successful. However, given that team effectiveness is not only a factor of success but also of satisfaction, loosely coupled teams acting within informal structures featured lower levels of trust and value on their teams likely because the social order was unclear, and this raises questions of team longevity, and long term team effectiveness.

Not all groups are created equal. The present small study suggests avenues for future research that consider the organizational structure or culture of a team operating a remote robot. Whether in search and rescue or scientific tasks, communication and decision-making structures appear to matter for outcomes. Exploratory tasks may demand a more hierarchical approach, while tasks that require near-perfection in execution may benefit from consensus-based teams. A middle ground between the two is possible but there are trade-offs. We may even build robots that are best fit for one or the other environment, or that encourage hierarchical versus consensus planning. If so, we must keep flexibility in mind, to enable loose coupling in order to best achieve local goals. More attention to the organizational conditions of robotic work is essential if we are to maximize for task, team, and robotic success.

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