2026 ASEE ANNUAL CONFERENCE June 21–24, 2026 | Charlotte Convention Center, NC
Host Sponsor UNC Charlotte
Paper ID #53839

Designing Social Robots for Detecting and Mitigating Patterns of Inequity in Student Teams: A Conceptual Framework

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Introduction

Learning to work and communicate in collaborative teams is a core learning outcome of engineering education thought to be necessary for successful professional practice [1]. However, while collaborative and cooperative learning experiences are a cornerstone of engineering education that offer students opportunities to develop these sociotechnical skills, existing research suggests that patterns of inequities in engineering student teams, particularly those experienced by racial/ethnic and gender minoritized students, frequently undermine equitable access to learning experiences and, by extension, the degree to which students realize learning opportunities equitably [2]. Such patterns have been the subject of decades of engineering education research since scholars note that the nature of engineering teamwork (e.g., addressing ill-structured, value-laden problems) makes engineering teams particularly susceptible to patterns of inequity [3].

Researchers and practitioners have proposed numerous strategies for supporting teamwork equity in engineering education. Some have pointed to learning management systems, such as CATME and Tandem, that capture and report teamwork data capable of distilling teamwork processes for students and faculty alike [4 - 5]. However, these approaches are frequently critiqued because they support retroactive interventions that occur only after the inequities have taken place and been reported [6]. Moreover, these strategies require instructor time for monitoring, interpreting, and responding to the inequities detected by the learning management system, and instructor time is frequently reported as a barrier to effective teaching practices [6]. Others describe structural conditions of the specific engineering course, such as course policies about team formation and task allocation, that can support or undermine teamwork equity [7-8]. These studies frequently suggest that faculty should make careful choices as they form teams as these choices may have consequential, yet difficult to predict, downstream effects on student learning experiences and outcomes.

This research is part of a broader study seeking to develop interventions that support teamwork equity that can capture and address moments and patterns of inequities in real time. Specifically, the study sought to design and implement social robots capable of (a) detecting moments and patterns of inequities in student-team interactions, (b) intervening at appropriate times to support students' full participation and learning, and (c) using appropriate mechanisms to address realized inequities, as well as mitigating future inequities. The study described herein includes Phase 1 of the full research program, in which the study team sought to capture patterns of inequity using human-human data. This research is guided by the following research questions:

RQ1: How are moments and patterns of inequities manifested in student teams?
RQ2: What mechanisms can be used to detect moments and patterns of inequities manifested in student teams?

Literature Review

Unique Aspects of Engineering Teamwork in Educational Settings

This research is not the first to document moments and patterns of inequity in collaborative teams, which has been the subject of decades of research in areas such as organizational theory, athletics, psychology, and education, to name a few [9-10]. However, we contend that teamwork in engineering entails unique aspects that make the study of inequities in teamwork processes similarly unique. For example, engineers are often engaged in ill-structured, distributed projects that entail value-laden decisions, multiple solution paths, and task allocation processes that must be negotiated within the team [1, 10-11]. This is particularly true in educational settings, where structural hierarchies (e.g., managers in professional settings, coaches or captains in team sports) are frequently absent. Moreover, in educational settings, unlike professional settings, educators frequently want students to have access to all aspects of a project, which represent important learning experiences [12-13].

Perhaps most importantly, engineering teamwork entails complex interdependencies such that decisions made on one aspect of a project can shape, and be shaped by, decisions made on the other aspects of the project that may or may not include input from the entire team. As a result, even within a team, individuals may have different motivations, goals, and ideas about the final form and function of the project artifacts [14]. These motivations, goals, and ideas are then manifested in observable, measurable behavioral sequences that may support, or inhibit, full participation for all students in the team.

Further, the ill-structured, sociotechnical nature of team-based engineering design problem solving entails various interrelated social processes that shape whether, how, and to what extent different students come to participate in the team. Historically, conversational dynamics have dominated the teamwork literature, where scholars have focused on teamwork dynamics such as talk time to characterize inequities. Others point to task allocation, which represents students' access to important learning experiences. Finally, researchers describe the process of presenting, clarifying, selecting, and enacting ideas as an important site where inequities are manifested.

In engineering design student teams, all these processes—task allocation, idea contribution, idea selection, and idea enactment—are the subject of complex team-based negotiations. For this reason, it can be particularly difficult to distinguish patterns of inequity from "good engineering teamwork" in engineering teams. For example, moments in which a student is allocated a technical communication task may reflect their relative skill for writing or desire for mastery experiences related to documentation. They may also reflect other students' unwillingness to participate in non-technical tasks in engineering. Similarly, a moment during which a student's ideas are scrutinized can both be a fair process of clarification during the decision-making process, which itself is an important learning opportunity [2]. It may also be a manifestation of social power, in which scrutiny is used in a bad faith effort to discard one's ideas. That is, as students ask questions, challenge, scrutinize, and negotiate engineering ideas in ill-structured problem-solving settings, legitimate, equitable social processes, such as moment during which one's ideas are scrutinized, can be confused as manifestations of social power dynamics and social inequities [2]. The purpose of this research was to begin characterizing these inequities to support accurate detection, particularly in engineering teamwork contexts, where the nature of engineering teamwork can make such detection challenging.

Patterns of Inequity in Engineering Teams

For decades, the prevailing belief amongst researchers, industry leaders, and policymakers has been that team diversity supports important team outcomes, such as creativity and innovation [15]. It was for this reason that researchers and policy makers called for immense resources that supported broadening participation in engineering—the presence and full participation of those historically excluded from engineering was thought to bolster economic output for engineering firms [16]. Simultaneously, research has consistently shown that structural diversity alone was insufficient. Instead, the degree to which engineers are fully integrated in engineering teams, affording them opportunity for full participation, is key to realizing the benefits of structural diversity in engineering teamwork [2].

Unfortunately, patterns of inequity are frequently manifested in engineering teams, in both professional and educational settings. Scholars have described attributional inequities, such as when women's contributions are instead attributed to their male counterparts [2, 14], as well communication and interactional dynamics, such as differential patterns of interruption or unequal access to the conversational floor, as mechanisms by which inequities are manifested [17]. Many of these studies have tended to focus on measures thought to be objective, such as talk-time and participation in allocated tasks, alone [18]. Moreover, these studies frequently describe features of the inequities rather than the behavioral sequences that led up to and resulted from the inequity.

However, research indicates that inequities can manifest in more nuanced ways that can be more difficult to detect. For example, Dotson [19] describes epistemic exclusion, which entails ways in which students' ideas and contributions can be systematically excluded from epistemic systems. Such exclusion occurs, for example, when one's ideas are not fully considered, unequally scrutinized, or unfairly discarded during team discussions, which can be mistaken for "good engineering teamwork" if not critically analyzed [2]. Others have pointed to discursive practices that are detectable during team discussions, such as the intonation and timbre of students' utterances, facial expressions, or patterns of (non)responses during team discussions [21]. These studies suggest that social robots designed to detect inequities must also capture the subtle, difficult to detect manifestations of inequities that occur in student teams. Still, while this portion of the research focuses on detecting patterns of inequity in student teams, the broader goal is to determine appropriate interventions, as well as appropriate timing for the interventions, for when these inequities are detected.

Methods

Data Sources

Since the purpose of this research was to characterize the types and manifestations of inequities that occur in student teams, we analyzed teamwork data from across a variety of settings to reflect different factors that may shape the form and function of inequities in engineering teams. For example, teamwork literature indicates that team size (i.e., the number of students participating in a team) can shape communication dynamics, task allocation, and team conflict. As a result, we analyzed teamwork activities in groups that varied in size from 2-4 students. Moreover, students' understandings of the key deliverables (i.e., the things on which their grades or evaluations will be based) can shape how task allocation unfolds. As a result, it was important that we seeded specific deliverables in the activity descriptions (Table 1).

In full, we analyzed data from 9 teams across 3 activities, each of which was completed during class sessions in various engineering classrooms. Full descriptions can be found in Table 1 below. Before each activity, all students (i.e., research participants and non-participants) were assigned group and individual ID to (a) preserve confidentiality during the transcription process and (b) ensure that instructors could not distinguish participants from non-participants, potentially applying undue influence on participants. Students were also asked to complete a pre-activity survey that captured demographic characteristics, prior engineering experiences, learning goals, and prior experiences with each team member. Each activity lasted 1-2 class sessions, and each session was video and audio recorded for analysis. Video and audio recordings were then transcribed for further analysis.

Teamwork Activity Settings

While the specific activities students participated in across the settings differed, they shared characteristics related to deliverables and task allocation processes. For example, given the literature that suggests gender informs some task allocation processes in students teams (e.g., women are more likely to be allocated secretarial tasks, and men are more likely to be allocated more technical tasks), each activity was designed to ensure that there were both technical artifacts (e.g., a built robot) and documentation deliverables (e.g., a report or presentation). For example, in one task, students were asked to design and build a LEGO food delivery robot capable of navigating to the appropriate assigned “home” on a floor map. Each team was then asked to submit documentation and a short presentation about their designs addressing a series of sociotechnical questions related to accessibility, navigation, and human-robot interaction, to name a few. We did this to ensure that there were a variety of tasks that students could be allocated, thus affording us an opportunity to document inequities that occur during the task allocation processes across teams.

Table 1
Activity Descriptions

Course Context (Academic Level)	**Activity Description**	**Deliverables**
Introduction to Computing for Engineers (first-year engineering students)	Design, build, and test a LEGO delivery robot capable of navigating a map and delivering a payload to the appropriate address. Document your design decisions in a short presentation that addresses issues related to accessibility, navigation, and human-robot interaction.	● Built robot ● SPIKE source code ● 10-minute Video-recorded presentation ● Video of final robot testing
Human-Robot Interaction (fourth year and graduate student engineers)	Program and test a food delivery Sphero robot capable of navigating a map and delivering a payload to the appropriate address. Document your design decisions in a short presentation that addresses issues related to social navigation.	● Sphero source code ● Presentation
Human-Robot Interaction (third- and fourth-year undergraduates, graduate students)	Program the Misty II robot. In Session 1, design a Wizard-of-Oz GUI interface that experimenters can use to remotely control the robots behaviors. In Session 2, integrate LLMs to allow a robot to have a back-and-forth conversation with a human participant.	● Video of the GUI in action (Session 1) ● Video of the LLMs controlling robot dialogue ● Source Code (for both sessions)

Data Analysis

Data analysis proceeded in two phases. First, the study team began by reviewing video data individually, documenting critical incidents that we believed captured moments of inequities in student teams across the teams in the activities. We then met to discuss individual interpretations of the incidents, which entailed watching short video excerpts of the teams in the study, and summarizing the mechanisms of inequality that we observed in the data. Still, we note that these summaries were not necessarily included in the final codebook. Rather, the purpose of the process was to begin developing a format for the codebook. For example, as the goal was both to characterize the patterns of inequity that were manifested in student teams, as well as to document the mechanism for detection (e.g., text alone, audio alone, video alone, some combination of text, video, and audio data), we chose to include a column in the codebook that documented the manner in which moment or pattern was detected.

In Phase 2, the study team began developing individual codebooks by reviewing a subset of the video, audio, and transcript data. During this process each of the six study team members were assigned three videos to code. As the purpose of this process was to characterize behavioral sequences that occur after some initiating event (e.g., an idea contribution), this process entailed process coding, which Miles, Huberman, and Saldaña argue is particularly appropriate for research that extracts participant actions, interactions, and the consequences of those actions and interactions [21]. For example, the team coded for a series of behavioral sequences that occur after a student makes an idea contribution (Table 2). That idea contribution may be acknowledged or ignored. Acknowledgements may be followed by reflections, positive or negative feedback, and ultimately enactment (i.e., the team implements the idea) or rejection (i.e., the team does not implement the idea).

The study team then met in sub-teams to reconcile our codes, capturing overlapping definitions across our individual codebooks before reconciling code definitions, inclusion/exclusion criteria, and detection mechanisms. In this paper, these codes are not standalone features of complex teamwork dynamics, but tokens in behavioral sequences that lead up to, and follow from, teamwork inequities. For example, Table 2 below includes example parent and child codes related to idea contributions and the potential behavioral sequences we documented that occur after idea contributions. Importantly, not all sequences result in teamwork inequities, and our codebook was designed to capture both normal, positive teamwork processes, wherein ideas are shared, clarified, and enacted, as well as mechanisms of inequity, wherein ideas are systematically discarded.

Table 2
Example Codes – Idea Contributions

Parent Code	**Child Code**	**Definition**	**Detection Mechanism**
Idea Contribution	Idea Contribution Made	A team member proposes an idea.	Transcript
	Idea Contribution Ignored	Student(s) do not address a team member's idea contribution	Transcript + Video
	Idea Contribution Acknowledged	Students acknowledge (either verbally or non-verbally) a teammate's ideas.	Transcript + Video
	Idea Contribution Reiterated	A student proposes an idea that was already proposed	Transcript
	Idea Contribution Reflected	A student's (Student A's) idea is reflected to them by another student (Student B) who either restates the idea or repeats the idea in new terms.	Transcript
	Idea Contribution Response - Positive	After an idea contribution is made by Student A, another student or students respond positively (either verbally or non-verbally) to Student A's ideas.	Transcript + Video
	Idea Contribution Response - Negative	After an idea contribution is made by Student A, another or students respond negatively (either verbally or non-verbally) to Student A's idea.	Transcript + Video
	Idea Contribution Acceptance	A student proposes an idea to the group and the group agrees to pursue the idea.	Transcript
	Idea Contribution Rejection	A student proposes an idea to the group and the group does not agree to pursue the idea.	Transcript
	Idea Enactment	A student's idea is implemented by the team (either individually or collectively).	Transcript + Video
	Idea Contribution Deferred	After an idea contribution (Idea A) is made, acknowledged, and accepted, a different idea (Idea B) is chosen.	Transcript

In this paper, we characterize these behavioral sequences in terms of paths that lead from one initiating incident (i.e., an idea contribution) to some culminating incident (i.e., the idea is implemented or discarded) (Figure 1).

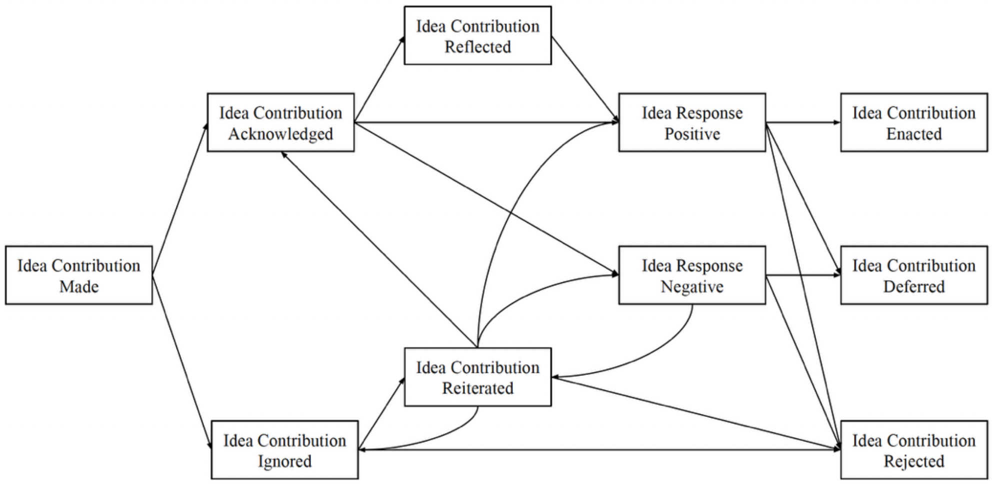


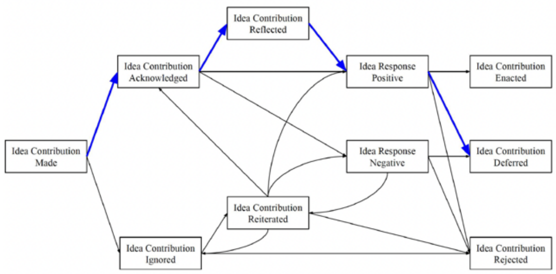
Figure 1. Example behavioral sequences occurring following an idea contribution.

Specifically, some paths in the graph captured full participation, depicting the process by which students presented, discussed, negotiated, and selected engineering ideas. Other paths in the potential behavioral sequences captured unambiguous processes of marginalization, such as when one's ideas are ignored and implicitly discarded. This research was most concerned with ambiguous patterns in student-student interactions. That is, the team did not assume that an idea being discarded necessarily reflected marginalization. Some interactions entailed good faith discussions of engineering ideas, the systematic identification of problems with those ideas, and the collective decision to discard those ideas (i.e., good engineering teamwork).

Findings: A Framework for Capturing Inequities in Student Teams

We describe the behavioral sequences in terms of three categories, with implications for the design and implementation of interventions for supporting student participation and learning. In Category 1, students' conversations reflected normal teamwork processes, wherein idea contributions were acknowledged, discussed, negotiated, and selected collaboratively. This did not necessarily suggest that one's ideas were always elevated. Rather, episodes in Category 1 reflected teamwork processes in which core learning outcomes—communication, application of knowledge from the engineering sciences, iterative design thinking—were exhibited, even if an idea was not selected. For example, in the episode depicted in Figure 2 below, after Speaker 9.1 presented an idea. Speaker 9.2 engaged with the idea, soliciting clarification and acknowledging the idea's potential utility. Though Speaker 9.1 eventually deferred to Speaker 9.2, we suggest that such an exchange represented an opportunity for all students to participate in the engineering design process.

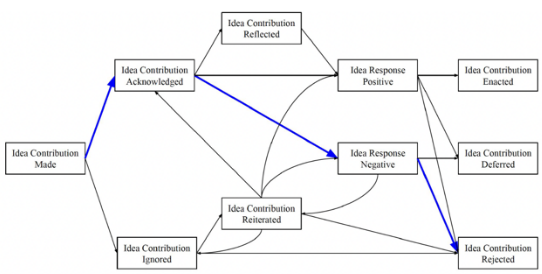
We describe these moments and patterns in three categories: (a) passive marginalization, (b) constrained inclusion, and (c) overt exclusion.



Speaker 9.1: I was thinking of something a little bit different. I guess we can go on with the discretization first.
Speaker 9.2: What was your idea?
Speaker 9.1: The camera sees that the ArUco code is in the gray area. It moves forward and I guess we can move forward for a certain distance. And then it goes here and it sees the gray are again and it goes down.
Speaker 9.2: I think because we have the map of this whole thing, the Sphero will always have information in the whole map. So, I guess your idea is for it to run forward until it hits some black tile?
Speaker 9.1: Yeah. And then it would turn 90 degrees, keep going until it sees gray again.
Speaker 9.2: I see.
Speaker 9.1: I think maybe you can go with your idea first.

Figure 2. Student dialogue during team negotiations about project solution paths.

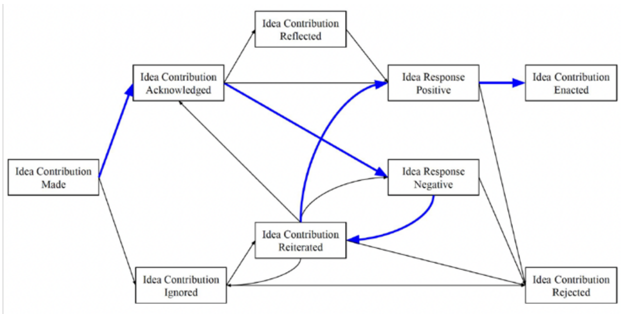
Conversely, episodes in Category 2 captured moments in which students' ideas were not necessarily explored before being discarded. These episodes were frequently marked by negative evaluations, unilateral decision making, interruptions, and other indicators of teamwork inequity. For example, in the episode depicted in Figure 3, Speaker 5.3 presented an idea, which was met with skepticism from Speaker 5.4. The episode was marked by the fact that Speaker 5.3 was not offered an opportunity for rebuttal or clarification, which may have supported their learning even if the idea was not selected. Instead, Speaker 5.3's idea was discarded in favor of Speaker 5.4.



Speaker 5.3: Can we just predefine this here instead of using the computer vision to see it?
Speaker 5.4: Yeah, so we can try that. The issue that I've experienced before is that the errors stack up, so if like it goes straight, but the heading is like one degree off, then it's just going to go like into the void. And there's a reason why they gave us like the ArUco code or whatever the code mark is. I mean, we can try this. It's easy and fast to test. So, you only just for now just try to use like hard code. The path.
Speaker 5.1: Yeah. I like that idea.
Speaker 5.4: I'm just going to like screw around.

Figure 3. Behavioral sequence depicting idea rejection in a student team.

However, our work was most concerned with ambiguous exchanges that may well be interpreted as either indicators of good engineering teamwork or mechanisms of exclusion in student teams. These episodes were marked by disagreements and ambiguous decision-making structures. For example, in the episode depicted in Figure 4, Speaker 7.4 presented an idea which was met with disagreement from Speaker 7.2. Though the team appeared to be engaged in earnest discussions about the idea, Speaker 7.2's argument was interrupted and, eventually, Speaker 7.4's idea prevailed. We identify this episode because it undermines the assumption that moments in which ideas are acknowledged and discussed necessarily point to full participation. Moreover, the episode undermines the idea that moments when the skepticism and interruptions that are usually documented as moments of inequities may be indicators of full participation.



Speaker 7.3: How about the syntax for this?
Speaker 7.4: I'm going to set the heading to this as well. Left is 270, right is 90.
Speaker 7.2: Actually, that might not work correctly because the reason why they're getting the current heading is that it will always turn 45 degrees from where it's currently looking.
Speaker 7.4: Yes.
Speaker 7.2: Whereas if you say 270, no matter where it's looking, it's going to try and turn 270 from there.
Speaker 7.4: Really? I thought that was...[interrupted]
Speaker 7.3: It won't turn 270, it will just start moving in the direction of 270.
Speaker 7.4: No, whatever zero heading, I'm pretty sure it turns it to the 270 heading instead of adding 270. You don't want it to turn 270 because then you were confused on what is left and what isn't.
Speaker 7.2: Right, exactly.
Speaker 7.4: So, I think it is just, yeah.
Speaker 7.3: It just turns to the 270.
Speaker 7.4: Yeah.
Speaker 7.3: Yes, you're right.

Figure 4. Behavioral sequence depicting idea enactment in inequitable team context.

We suggest that such ambiguous episodes are particularly difficult to detect and represent moments of *constrained inclusion* in which students appear to be full participants but only to the extent that referent others do not impede full participation. Such moments pose conceptual and methodological challenges for the design and implementation of automated social robots.

Discussion and Future Directions

This analysis is the first step in the design and implementation of social robots for detecting and responding to teamwork inequities in engineering student teams. We suggest that the literature is rife with examples of inequities that exist in two extremes–moments so overt that most observers would interpret them as moments of inequity or exclusion, or moments so covert that various observers may draw opposite conclusions. Our goal in this first phase of the study was both to characterize the nature of inequities, as well as capture the types of data necessary for detecting the inequities. The three categories described above are not new, yet they may be informative in the design of social robots. That is, we asked, "What interpretations can be drawn based on various data sources alone and in combination with each other, and how can we leverage these ideas to design social robots?"

Our future work entails coding additional teams across activities. We also plan to test various intervention mechanisms. We presuppose that different patterns require different interventions–what the social robot does to mitigate patterns of interruption may be different than what the robot does to mitigate inequities in task allocation. Still, to make these determinations, understanding the mechanisms of marginalization, as well as the data necessary to detect them, was an important first step.

Acknowledgements

This study was supported by the National Science Foundation under Grant NSF Award Number 2402899. The opinions expressed here do not reflect the opinions of NSF, and no official endorsement should be inferred.

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