I am a roboticst and computer scientist who works in the area of human-robot teaming (HRT). My work explores how to solve real-world robot perception and decision-making challenges, particularly those encountered in noisy, complex settings (e.g., hospitals) [1]. My research provides transformative advances to the field of robotics, contributing new AI systems that address key technical challenges, as well as situating systems in ways that address real-world problems. My work lies at the intersection of **artificial intelligence (AI), human-robot interaction (HRI), computer vision, and health informatics**, and aims to support and empower people.

The field of robotics is growing at a vast pace with deployments in everyday environments such as hospitals, schools, and retail settings. Until recently, the HRI field has focused on dyadic interaction (i.e., one human and one robot) [2]. However, recent work highlights the importance of designing robots to interact with groups of people, in order to work alongside them, as this reflects what they will encounter in real-world settings [1, 2]. My research addresses this gap by exploring multi-agent systems that support and empower people working in teams. During my PhD, I designed new perception methods to enable robots to detect and track their teammates in real-world environments [1, 2, 3, 4, 5]. Then, I explored the use of robots in healthcare, and investigated how they can support clinical team workflow and empower stakeholders, by characterizing teaming in safety-critical environments (SCE) [6, 7], where I developed a new navigation system for robots in the emergency department (ED) [8].

My work has been published in top venues in my field, including AAAI, HRI, IROS, THRI, and CSCW, where I was honored to receive a **Best Paper Honorable Mention**. Also, I have received competitive awards for my research, including the **National Science Foundation Graduate Research Fellowship (NSF-GRFP), the Microsoft Research (MSR) Dissertation Award, the Google Anita Borg Memorial Scholarship, the GEM Consortium Fellowship, and the National Women in Information Technology (NCWIT) Collegiate Award**.

1 Teaming in Safety-Critical Environments: Robot Perception of and Interaction with Groups

In my PhD research, I designed systems that enable robots to work seamlessly in teams in real-world SCEs. This work resulted in three main contributions. First, I developed new computational models for human group perception, which resulted in a new unsupervised group detection and tracking system (RoboGEM) that outperformed state-of-the-art methods by up to 50% [1, 3, 9]. Next, I characterized a specific SCE, the Emergency Department (ED), in terms of task representation, data needed for AI systems, and patient experience to effectively place robots in this domain [7, 6]. Third, I designed a social navigation system for robots working in the ED that enables them to navigate in a safety-complaint manner in which they avoid high-acuity patients more effectively and efficiently than classic navigation methods [8].

1.1 New Computational Models for Human Group Perception

I conducted an in-depth analysis of the current state-of-the-art of group perception methods within the computer vision and social signal processing fields. This analysis identified open challenges that need addressing in order for robots to effectively collaborate and work with groups in real-world settings [2]. For example, most group perception methods employ fixed, overhead cameras (i.e., an exo-centric / third-person perspective) to sense groups of people, rendering them impractical for mobile robots working in most settings. Instead, perception methods based on an ego-centric (i.e., first-person) perspective are more suitable for mobile robots, to enable them to enter any environment and accomplish their goals without external sensing requirements [2].

Next, I proposed a theoretical framework that enables robots to perceive groups of people and their level of affiliation (a sense of belonging) [10]. This framework reflects four principles which robots can leverage to behave appropriately in groups, including: 1) the *proximity principle* which states that people tend to join groups in close proximity to them, 2) the *elaboration principle* which states that groups are dynamic systems that grow in complexity,

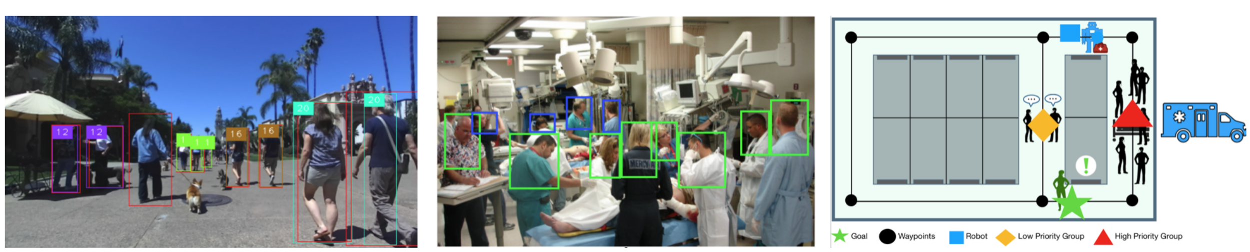

Figure 1: My research explores robot perception of groups (left), robots to support clinical teams (middle), and robot perception and decision-making in safety-critical environments (right).

3) the *similarity principle* which states that people tend to stay in groups longer when they share common goals and interests, 4) the *complementarity principle* which states that people tend to stay in groups longer when they have mutually beneficial characteristics. Computationally, this framework is reflected in three stages: group perception, group detection and tracking, and path planning among groups. This laid the groundwork for the robotic systems I designed throughout my PhD [10].

First, to enable robots to detect groups of people in highly noisy, complex, real-world environments, I designed the Robot-Centric Group Estimation (RoboGEM) system [1, 3]. Historically, group perception work tends to: (1) focus on exo-centric perspective approaches, (2) use data captured in well-controlled environments which cannot support real-world operating scenarios, and (3) use supervised learning methods which may potentially fail when robots encounter new situations. In contrast, RoboGEM employs hierarchical clustering (unsupervised learning), and works well on ego-centric, real-world data, where both pedestrians and the robot are in motion at the same time. **RoboGEM outperforms the current top-performing method by 10% in terms of accuracy, and 50% in terms of recall, and can be used in real-world environments to enable robots to work in teams [1]**.

In subsequent work, I expanded the scope of RoboGEM to enable a robot to track groups over time as it works alongside them. In this project, **supported by the NSF-GRFP award**, I developed RoboGEM 2.0, which achieves human group detection and tracking in crowded environments in real-time. RoboGEM 2.0 performs well in crowded environments using a tracking-by-detection approach. RoboGEM 2.0 is based on the intuition that pedestrians are most likely in groups when they have similar trajectories, ground plane coordinates, and are in close proximity to each other. It leverages deep learning, which provides a more robust affinity representation than prior work (which employs hand-crafted feature representations). Using this representation, I developed a group data association method which enables robots to match groups of people over time. It also includes new methods for group tracking that employ Convolutional Neural Network (CNN) feature maps for group data association, and Kalman filters to track group states over time [9].

1.2 New Ways to Design Robots to Support Clinical Teams

In the next stage of my research, I explored using RoboGEM within a real-world application: teaming in healthcare. This is a dynamic setting in which teams experience coordination, communication, and decision making challenges, rendering it a well-suited application domain for my work. I was interested in how robots might be used to reduce the number of preventable patient harms, which in the US, kill over 400,000 patients annually in hospitals alone. 70% of these errors are the result of communication and collaboration breakdowns that occur in SCEs.

Nurses are the primary advocate for patients in hospitals. As such, they are uniquely positioned to identify and prevent patient harm. However, strict hierarchical structures and asymmetrical power dynamics between physicians and nurses often result in penalties for nurses who speak up to "stop the line" of behavior that causes medical errors. This inspired my work, which involved collaborating with nurses nationwide to envision how robots might empower and support them in clinical teams.

First, most participants identified that when team members had little experience performing resuscitation, they put patients' lives in danger, as they needed to rely on reference cards or their team members to tell them the steps. To address this, participants envisioned a robot that could autonomously navigate to a patient's room when a resuscitation starts, and walk a team through the steps to revive the patient. Second, they wanted a robot to perform real-time error identification, and verbally alert the team when it identifies errors. Third, participants talked about how chaotic it can be performing resuscitation and oftentimes, their teammates might block their access to the patient. To address this, participants envisioned a robot that could generate choreography for team members, and using a shared display, show them where they should position themselves around the patient's bedside. Then it could verbally alert them when someone needs to change positions.

This work provided exciting design concepts for future robot technology in acute settings, which inspired later work in my PhD. This work was published at the ACM Computer Supported Cooperative Work (CSCW) conference, where I was honored to receive a **Best Paper Honorable Mention** [6].

1.3 Methods for Acuity-Aware Robot Decision-Making in Safety-Critical Settings

To further investigate how robots can support clinical teams, I explored the use of robots in the Emergency Department (ED). Commercially available robots already work in hospitals to help clinicians deliver and stock materials, clean and sanitize rooms after procedures, and lift patients. Robots also serve as receptionists, assist with rehabilitation, support teams in surgery, and support remote care via telepresent robots. Despite these recent efforts in deploying robots in hospitals, it will be difficult for robots to execute the simplest tasks in the ED, which is a more challenging environment than in-patient units. The ED is more crowded, chaotic, and has patients with higher levels of acuity. Also, providers are overburdened, overworked, and have limited resources to do their jobs [7].

To address this challenge, I explored how robots could support teams in the ED, by relieving providers of non-value added tasks (e.g., submitting labs, restocking supplies) and enabling them to spend more time on patient care. I conducted research to characterize ED staff workflow and patient experience, and identified key considerations for situating robots in the ED, including safety and physical constraints. I also explored task representation, and data needed for robots to work within ED contexts, based on domain knowledge from key stakeholders [7].

A key challenge I identified occurs when patient rooms fill up, and patients are stationed and treated in hallways. Thus, ED hallways are often cluttered, over crowded, and clinicians are treating highly acute patients, working under severe time constraints. To place robots in these complex spaces, robots need to understand many features of the environment in order to operate safely and effectively, including patient acuity. This knowledge might enable them to navigate more intelligently and safely.

To address this, I developed the Safety-Critical Deep Q-Network (SafeDQN), a new reinforcement learning system that enables robots to socially navigate while taking patient acuity levels into account [8]. SafeDQN visually detects a patient's acuity level from video and encodes this in a neural network, which learns to avoid areas of high-acuity patients. I compared SafeDQN to three classic navigation methods, and found that SafeDQN generates the safest, quickest path in a simulated ED environment [8]. **I was honored to be one of only 11 students to receive a Microsoft Research Dissertation award, which supported this work.**

2 Future Research Directions

There are several new directions of research that I am excited to explore in the future. These include technological advances in robotics and AI to enable adaptive multi-human multi-robot coordination to improve team workflow, deploying physical multi-robot systems longitudinally in real-world settings, and creating new immersive experiences using Extended Reality in telehealth to broaden access to healthcare.

2.1 Designing Adaptive Multi-Human Multi-Robot Systems

The COVID-19 pandemic has killed over 260,000 people in the US alone, and has overwhelmed hospitals, resulting in ventilator and bed shortages. Healthcare Workers (HCWs) are experiencing burnout from the risk of COVID-19 exposure, physical exhaustion, considerable psychological strain. Robots have the potential to mitigate this crisis. For example, robots are assisting HCWs by serving as mobile telehealth platforms to reduce virus exposure risk, delivering supplies, and sanitizing patient rooms. One major gap in prior work is that these efforts are disparate - robotic systems need to be scaled up so they can assist multiple people, and coordinate with multiple robots, in order to work effectively with their human teammates. For example, consider two robots working with two different clinical teams. In some cases, one team can have a light workload while the other team is treating multiple patients with high-acuity conditions. In this case, the robot with a lighter load should assist the team with a higher load so that resources are allocated to patients that need it the most.

In my prior work, I developed perception systems to enable robots to detect and track groups of people in real-world settings [1, 9]. In the future, I plan to broaden this line of research further and scale this work to multiple robots that detect and track distributed teams. A key challenge these robots will encounter is how to leverage information from their perception systems in order to allocate resources to teams that need the most assistance. I will explore techniques for robots to coordinate among themselves (e.g., one robot searching for another robot's team to provide assistance) and task allocation systems (e.g., one team is treating a highly-acuity patient while another robot is treating a low-acuity patient).

I will also develop new learning and vision methods to enable robots to predict the intentions of human teammates based on prior experience with the team. This raises exciting new questions. For instance, what are effective ways to predict task completion times to adaptively coordinate with teams in the future? How can robots forecast teammate activities, and use that knowledge to predict what they will do next or when they will need assistance? How can we design perception systems that enable scheduling of robot assistance and enable robots to adapt to team workflow in order to optimally assist people?

Another challenge robots will encounter is how to identify various tasks that their human teammates perform. To enable the deployment of robots at scale, they need the ability to generalize to new tasks. One potential approach to this problem is to use transfer learning, which is the process of using a model developed for one task and reusing it to learn a new task. I will leverage this to enable robots to adaptively identify new tasks employed by their teammates thereby adapting to new task scenarios. This work will enable robots to coordinate among each other and with humans to improve team workflow by leveraging adaptive learning techniques.

2.2 Longitudinally Deploying Multi-Human Multi-Robot Systems

Another area of research that I am interested in pursuing is the long-term deployment of multi-human multi-robot systems in SCEs. There is prior work that explores the long-term use of robots in both private and public settings, such as people's homes and airports. However, significant work is needed to understand the long-term impacts of multi-human multi-robot systems in SCEs (e.g., weeks and months at a time), particularly with multi-robot systems.

My future work will explore this under-addressed problem and explore how to deploy multi-robot systems for months at a time. I am particularly motivated to explore this within clinical care domains. I will investigate several research questions such as: what tasks should multi-robot systems take on? What are the major failure cases of multi-robot systems? What healthcare interventions or technical advances can work as effective ways to address reliability challenges? This work will also explore how multi-robot systems impact clinician workflow and patient outcomes.

2.3 Extended Reality for Remote Telehealth

According to National Nurses United (NNU), over 1,700 HCWs have died in the US alone from COVID-19 and related complications. These frontline workers are placed at risk when treating COVID-19 patients. In some cases, HCWs are forced to work without protective gear to perform their jobs safely. To address this crisis, we need technology to support and enable HCWs to treat patients remotely in which they are physically distanced, i.e., remote telehealth. This will reduce the number of HCWs that contract the virus, and improve the safety of patients and HCWs.

In my prior work at Facebook AI Research (FAIR), I designed a virtual agent to improve remote team interactions in the context of an online multiplayer game (Minecraft) [11]. I developed a virtual agent that interacts with players as they build structures in Minecraft, with the goal to mediate onboarding a new team member. Building on this prior work, I will explore how to leverage Extended Reality (XR) to create immersive remote interactions between clinicians and patients. XR encompasses augmented reality (AR), virtual reality (VR), and mixed reality (MR) technologies to enhance human senses by creating simulated worlds for people to experience together.

I am interested in creating clinician-patient experiences by bringing them together in a simulated world where the clinician can meet with a patient in a similar way that they would in in-patient units. I will explore ways to enhance our senses by leveraging haptic technology to simulate touch; in other words, how can we leverage haptic technology to create sensory feedback in clinician-patient interaction? For example, when a clinician lifts a patient's leg, the patient should feel the force of the clinician's hand lifting their leg up and in return the patient should naturally lift their leg as they would in a physical world. However, XR technology is far from being able to accomplish this level of sensor feedback in remote interactions. Using XR, computer vision, and sensor technology, I want to create these realistic experiences that enable clinicians to examine and diagnose patients. With companies like Google, Microsoft, and Facebook expanding their research agendas to AR/VR, I intend to seek funding and partnerships through their academic funding programs.

3 Conclusion

My research is critical to addressing fundamental challenges in robot perception and decision-making, to enable them to work with people in high-risk environments. My Ph.D. work connects approaches from various disciplines, including computer science, robotics, mathematics, and to tackle complex problems to enable robots to intelligently interact with and support people in real-world settings. Moving forward, I am excited to build a **strong research program centered around the core idea of building robots to better our society and improve automation and teamwork in real-world settings.**

In the next stage of my career, I will build on my ability to secure funding from government agencies and foundations, and will seek support for my research from organizations such as the NSF, the National Institutes of Health (NIH), the Air Force Office of Scientific Research (AFOSR), and the Robert Wood Johnson Foundation (RWJF). I also plan to collaborate with academic and industry partners, which will provide unique opportunities to deploy robots in real-world environments. I look forward to collaborating with faculty and students with interests in robotics, AI, and health informatics to explore these exciting new areas.

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