CHAPTER 1
INTRODUCTION

1.1 Motivation

The idea of robots or other intelligent agents living in a human environment has been a persistent aspiration from science fiction books to artificial intelligence and robotic laboratories. Collaborative robots are expected to become an integral part of human environments to accomplish their industrial and household tasks. In these environments, humans will be involved in the robots' operations and decision-making processes. The involvement of humans influences the efficiency of robots' interaction and performance, and makes the robots sensitive to human cognitive abilities and behaviors.

Computational collaboration theories are too task-driven. These theories explain some of the important concepts underlying collaboration; they focus on tasks, their constraints and their requirements such as the presence of a reason for the collaborators' commitment, and the necessity of communicating about mental state in order to maintain progress over the course of a collaboration. However, a key aspect of collaborative robots is being able to show behaviors which can make them more likable, trustworthy, and satisfactory. We believe that these aspects of collaborative behaviors can influence the performance of a collaboration. Therefore, collaborative robots need to take into account human collaborator's internal state, and not only focus on executing different actions with respect to their plan to maintain the collaboration process.

Accoring to [103] collaboration is a coordinated activity in which the participants work jointly to satisfy a shared goal. We believe that beside the status of the shared plan, mutual mental state, or other task-driven details of the collaboration, human's decisions are also influenced by affect-driven functions. In fact, humans perceive, assess, and interpret their collaborator's activities to be able to coordinate their own acts throughout the collaboration. Therefore, collaborators need to adopt proper mechanisms to a) perceive their counterpart's affective states (and perhaps their meanings), and b) communicate their own understanding of these perceptions. This aspect of reasoning is missing in the existing computational collaboration theories and their applications.

From a different point of view the most prominent computational collaboration theories, i.e., SharedPlans [101, 103] and Joint Intentions [54], explain only the structure of a collaboration. For instance, in SharedPlans theory collaborators build a shared plan containing a collection of beliefs and intentions about the tasks in the plan. Collaborators communicate these beliefs and intentions about tasks that contribute to the shared plan. This communication leads to the incremental construction of a shared plan, and successful completion of the collaboration. Although these theories explain the important elements of a collaboration structure, the underlying processes required to dynamically create, use, and maintain the elements of this structure are largely unexplained. In particular, a general mechanism has yet to be developed that allows an agent to effectively integrate the influence of its collaborator's perceived or anticipated affective state into its own cognitive mechanisms to prevent shared task failures. Therefore, a process view of collaboration must include certain key elements. It should inherently involve social interactions, since all collaborations occur between social agents, and it should contain a means of modifying the content of social interaction as the collaboration unfolds. The social functions of emotions explain some aspects of the underlying processes in collaboration. This thesis makes the case for affect-driven processes within collaboration and demonstrates how it furthers collaboration between humans and robots.

1.2 Thesis Statement and Scope

In this thesis, we develop and validate a framework called *Affective Motivational Collaboration* (AMC) which can improve the effectiveness of collaboration between agents/robots and humans based on a structure maintained by collaboration manager called *Disco*[1]. This thesis focuses on the reciprocal influence of the collaboration structure and the appraisal processes in a dyadic collaboration. We address only two-participant collaboration; teamwork collaboration is out of our scope. Furthermore, this work focuses on a) the influence of affect-regulated processes on the collaboration structure, and b) prediction and interpretation of the observable behaviors of the other during a collaborative interaction.

We describe the cognitive processes involved in a collaboration in the context of a computational framework. This framework theoretically relies on the collaboration structure described by SharedPlans theory, and its implementation is built on top of the collaboration manager, Disco, which provides and mainitains all the details of the collaboration structure. The existing implementation of SharedPlans theory does not focus on the processes involved to mainatain a collaboration structure. *Affective Motivational Collaboration* theory deals with the major affect-driven processes having an impact on the collaboration structure and ultimately a collaborative robot's behavior. This theory is informed by research in psychology and artificial intelligence which is reviewed in Chapter 2. Our contribution, generally speaking, is to synthesize prior work on appraisal[2], SharedPlans theory's description of collaboration, and motivation to provide a new computational theory of an affect-regulated goal-driven dyadic collaboration.

[1]Disco is the latest incarnation of COLLAGEN [203, 204] which incorporates certain algorithms for discourse generation and interpretation, and is able to maintain a segmented interaction history, which facilitates the collaborative discourse between a human and a robot.

[2]We have chosen appraisal-based modeling of emotions among several theories of emotions.

1.3 Contributions

Throughout this work we aim to show how a robot can leverage affect-driven processes using appraisal algorithms to improve collaboration with humans. As such, in this thesis, first we introduce our foundational theoretical concepts under the title Affective Motivational Collaboration theory, and then we introduce a novel framework, called Affective Motivational Collaboration framework, which allows a robotic agent to collaborate with a human while incorporating underlying affect-driven processes and the affective expression of the human collaborator. This framework is based on computational models of collaboration and appraisal allowing for task-driven interaction with robots or other agents. The theoretical foundation, computational models and algorithms, as well as the overall framework, and the end-to-end evaluation of the framework make the following contributions:

1. **Introducing *Affective Motivational Collaboration* theory:**

   (Chapter 3) As mentioned earlier, since the theoretical foundation of AMC framework is built on the combination of SharedPlans theory of collaboration [103] and cognitive appraisal theory of emotions [162] [223], one of the contributions of our work is to introduce theoretical concepts incorporating key notions of both theories in a dyadic collaboration context. Applying cognitive appraisal theory in the collaboration context described by the SharedPlans theory is novel. Another theoretical concept involved in AMC theory is incorporation of different functions of emotions to generate particular collaborative behaviors. These functions of emotions are *Goal Management, Motivation, Social Regulation*, and *Attentional Focus*.

2. **Developing new computational models and algorithms for *Affective Motivational Collaboration* framework:**

   (Chapter 4) Another contribution of our work is to create computational models and algorithms to compute the value of appraisal variables based on the

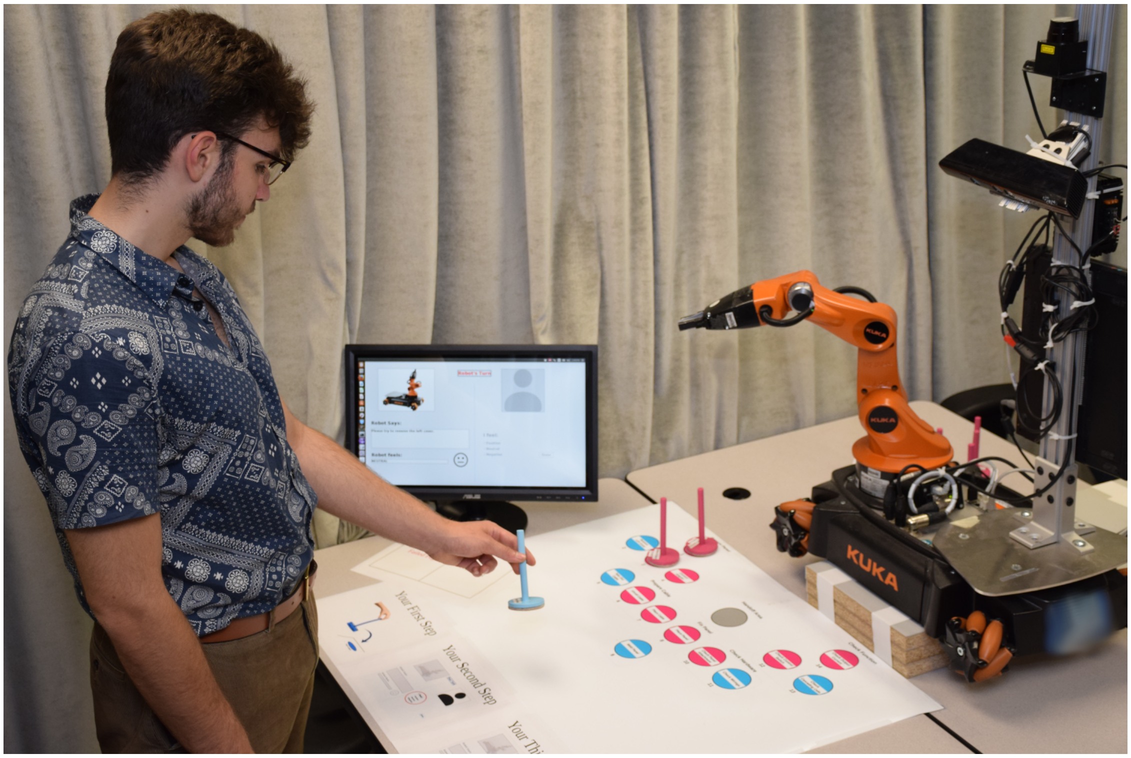

Figure 1.1: A robotic arm collaborating with a human to achieve a shared goal using *Affective Motivational Collaboration* framework.

collaboration structure in a dyadic collaboration. We use Disco as our collaboration manager to receive and maintain the collaboration structure. Reciprocally, we use the evaluative nature of the appraisal to make changes to the collaboration structure as required. We have also developed a new algorithm for affect-driven goal management in the context of collaboration. Goal management is one of the important functions of emotions during collaboration. Existing models and implementations of appraisal focus only on how the outcome of appraisal regulate and control internal processes and sometimes behaviors. This part of our work shows how the outcome of appraisal of the self and the human collaborator contribute to goal management as an emotion function.

3. **Implementing a computational system based on *Affective Motivational Collaboration* framework:**

In order to evaluate our computational models and algorithms within an interaction with human collaborators, we needed an overall functional system to perceive, process and act in a collaborative environment. We have implemented a computational system which employs our models and algorithms in *Affective Motivational Collaboration* framework. Our computational system implements the key concepts related to *Affective Motivational Collaboration* theory as well as minimal implementation of other processes which are required for validation of the model but are not part of this thesis' contributions. The emphasis of the implementation is on the underlying cognitive processes of collaboration and appraisal, however the implementation also includes the Perception and the Action mechanisms.

4. **Validating *Affective Motivational Collaboration* theory:**

   (Chapter 5) We have conducted two user studies a) to validate our appraisal algorithms before further development of our framework, and b) to investigate the overall functionality of our framework within an end-to-end system evaluation with participants and a robot (see Figure 1.1). The second user study was also conducted to evaluate the benefit of using our computational framework in human-robot collaboration. In the first user study, we crowd-sourced questionnaires to test our hypothesis that our algorithms will resonate with humans' decisions by providing answers similar to humans' responses to questions related to different factors within our appraisal algorithms. In the second user study, we investigated the importance of affect-awareness in human-robot collaboration, and the overall functionality of the AMC framework with the participants in our study environment.