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Toward Improving Human-Robot Collaboration with Emotional Awareness

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Abstract Current computational theories used for human-robot collaboration specify the structure of collaborative activities, but are weak on the underlying processes that generate and maintain these structures. We argue that emotions are crucial to these underlying processes and we have developed a new computational theory, called Affective Motivational Collaboration Theory, that combines emotion-based processes, such as appraisal and coping, with collaboration processes, such as planning, in a single unified framework. This work is implemented as part of a larger effort to build robots capable of generating and recognizing emotions in order to be better collaborators. We have investigated the mutual influences of affective and collaborative processes in a cognitive theory to support interaction between humans and robots or virtual agents. We build primarily on the *cognitive appraisal* theory of emotions and the *SharedPlans* theory of collaboration to investigate the structure, fundamental processes and functions of emotions in a collaboration. We have developed new algorithms for appraisal processes as part of a new overall computational model. We have evaluated our implemented appraisal algorithms by conducting an online user study.

Keywords Human-Robot Collaboration · Emotional Awareness · Cognitive Appraisals · Affective Motivational Collaboration Theory/Framework

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1 Introduction

A key aspect of the sociability of robots is their ability to collaborate with humans in the same environment. Collaboration is a coordinated activity in which the participants work jointly to satisfy a shared goal [24]. There are many challenges in achieving a successful collaboration between robots and humans. To meet these challenges, it is crucial to understand what makes a collaboration not only successful, but also efficient. Existing computational models of collaboration explain some of the important concepts underlying collaboration; such as the presence of a reason for collaborators' commitment, and the necessity of communicating about mental states in order to maintain progress over the course of a collaboration. The most prominent collaboration theories are based on plans and intentions [12] [24], and they support teamwork and collaboration between humans and robots or virtual agents. However, these theories 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 actions in the plan. Collaborators communicate these beliefs and intentions via utterances about actions that contribute to the shared plan. This communication leads to the incremental construction of a shared plan, and ultimately successful completion of the collaboration. In contrast, in Joint Intentions theory, the notion of joint intention is viewed as a persistent commitment of the team members to a shared goal. In this theory, once an agent enters into a joint commitment with other agents, it should communicate its private beliefs to other team members.

Although existing collaboration 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. For instance, a general mechanism has yet to be developed that allows an agent to effectively integrate the influence of its collaborator's perceived or anticipated emotions into its own cognitive mechanisms to prevent shared task failures while maintaining collaborative behavior. 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 essentially constitute a means of modifying the content of social interaction as the collaboration unfolds. The underlying processes of emotions possess these two properties, and social functions of emotions explain some aspects of the underlying processes in collaboration. This work is implemented as part of a larger effort to build robots capable of generating and recognizing emotions in order to be better collaborators.

Humans are emotional and social beings; emotions are involved in many different social contexts including collaboration. Although there are purely personal emotions, most emotions are experienced in a social context and acquire their significance in relation to this context [37]. For instance, humans are influenced by the emotions of those around them. They also have emotions about the actions of people around them. They have emotions about the events that occur in the lives of other people. Also, humans' concern about their relationships with others elicits emotion. They can feel emotion about their personal successes and failures and those of others. Moreover, socially shared and regulated emotions can provide social meanings to events happening in the environment [73].

There is also a communicative aspect of emotions. For instance, emotions are often intended to convey information to others [16]. Emotions are also involved in verbal behaviors. For instance, an utterance can include both content and relational meaning. An emotion might appear to be elicited by the content of the utterance, but in fact be an individual's response to the relational meaning [48]. The interpretation of these relational meanings are handled by the appraisal of events. Appraisal processes give us a way to view emotion as social [69]. Meaning is created by an individual's social experiences in the social world, and individuals communicate these meanings through utterances. Consequently, the meaning of these utterances and the emotional communication change the dynamic of social interactions. A successful and effective emotional communication necessitates ongoing reciprocal adjustments between interactants that can happen based on interpretation of each other's behaviors [37]. This adjustment procedure requires a baseline and an assessment procedure. While the components of the collaboration structure, e.g., shared plan, provide the baseline, emotion-related processes (e.g., appraisal) provide the assessment procedure.

There are several appraisal models (e.g., EMA [40]) contributing in different applications such as social sciences, virtual agents, and robotics. However, none of these models have focused on the appraisal processes during collaboration. A cognitive appraisal theory of collaboration is a contribution beyond existing generic appraisal theories because collaboration involves several key properties in structural and functional levels. Most collaborative situations involve participants with different beliefs and capabilities; usually collaborators only have partial knowledge of the process of accomplishing the collaborative activities; collaborative plans are more than the sum of individual plans; collaborators are required to maintain mutual (as well as private) beliefs about their shared goal; they need to be able to communicate with others effectively; they need to commit to the group activities; collaborators need to commit to the success of others; they need to reconcile between commitments to the existing collaboration and other activities; and they need to interpret others actions and utterances in the collaboration context. For instance, support, commitment, and responsiveness are prerequisites of collaborative interaction that induce changes to required underlying processes. One of these processes is appraisal which has a key evaluative and regulatory role during collaboration. We believe appraisal processes must consider factors related to the collaborative environment, rather than considering only the robot's plan. For instance, although the appraisal models mostly use utility to compute the relevance of an event, we have found new cognitive components involved in determining utility because of the influence of the collaboration. These components, such as the recurrence of a belief by the human collaborator or the influence of the human collaborator's perceived emotion on the robot's decisions emphasize the fact that collaboration requires different procedures in appraisal processes.

In this paper, first, we present two pairs of hypothetical interaction scenarios (see Section 3). Each pair contrasts an emotionally-aware with an emotionally ignorant[1] robot interacting with a human in the same situation. These scenarios highlight the necessity of giving robots the capacity to understand and regulate emotions, as well

[1] In our implementation, we always consider neutral emotion for the emotionally ignorant cases. Therefore, any human's negative or positive perceived emotion will be ignored by the robot and presumed as neutral emotion.

as to provide emotion-driven responses. We then briefly introduce Affective Motivational Collaboration Theory which explains the underlying processes of emotions and collaboration. The emotion-aware examples show how the mechanisms of this theory are involved in agreeing on a shared goal with a robot (see Section 3.3), and delegating a new task to the robot (see Section 3.5). The emotion ignorance examples are the same, except that the robot always perceives human's negative or positive emotions as neutral, and ignores the human's verbally or nonverbally expressed emotions. As we discussed above, there are certain types of emotion-regulated mechanisms with which a collaborative robot can modify and maintain a collaboration structure (e.g., shared plan). We explain these mechanisms and their corresponding operations in Affective Motivational Collaboration Theory (see Section 4). Next, we focus on the Collaboration and Appraisal mechanisms from this framework (see Section 5). We describe some methods used in our Collaboration mechanism to retrieve information from the collaboration structure; this information is used in the algorithms we provide for the relevance, desirability, expectedness, and controllability appraisals of an event in the collaboration context. Finally, we provide the results from an online user study that we have conducted to evaluate our appraisal algorithms (see Section 6).

2 Related Work

The prominent collaboration theories are mostly based on plans and joint intentions [12,24], and they were derived from the BDI paradigm developed by Bratman [8] which is fundamentally reliant on folk psychology [50]. The two theories, Joint Intentions [12] and SharedPlans [24], have been extensively used to examine and describe teamwork and collaboration. The SharedPlans theory is a general theory of collaborative planning which accommodates multi-level action decomposition hierarchies, and allows the process of generating complete plans. The SharedPlans theory shows how a group of collaborators can incrementally form and execute a shared plan, and describes how a shared plan coordinates their activities towards achieving a shared goal. Furthermore, SharedPlans theory emphasizes that collaborative plans are an interleaving of collaborators' mutual beliefs and intentions about the actions in the plan [21,22,24]. In contrast, the Joint Intentions theory as another formal theory of collaboration is based on the idea of individual and joint intentions to act as a team member. In this theory, a joint intention is a shared commitment to perform an action while in a group mental state. Joint Intentions theory describes how team members can jointly act together by sharing mental states about their actions while an intention is viewed as a commitment to perform an action [12].

There are many research focusing on different aspects of collaboration based on different collaboration theories, i.e., SharedPlans, Joint Intentions, and hybrid theories of collaboration, e.g., STEAM (a Shell for TEAMwork) [67]. Some of these works present algorithms and computational models in a teamwork environment based on the underlying structure of the SharedPlans theory [35,36,74,75], and Joint Intentions theory [10,42]. The hybrid teamwork model, STEAM [67], has also been successfully applied to a variety of domains [27,30,39,56]. There are some other works that they do not necessarily rely on a specific collaboration theory, but they emphasize on the role of emotions in human-robot collaboration [2,25,43,45]. All of the works presented in this section lack a systematic integration of collaboration theories with some theories capable of describing underlying collaboration processes. Therefore, they either do not explain the structure and the underlying processes of collaboration, or their approach in either or both of these views is application oriented. The collaboration structure of Affective Motivational Collaboration Theory is based on the SharedPlans theory [21,22,24], and it focuses on the processes that generate, maintain and update this structure based on mental states. COLLAGEN [51, 52] incorporates certain algorithms for discourse generation and interpretation, and is able to maintain a segmented interaction history, which facilitates the discourse between a human and a robot [53]. We use its latest incarnation, i.e., Disco, for our implementation.

Furthermore, there are some works focusing on the concepts of robot assistants [11], or teamwork and its challenges in cognitive and behavioral levels [44,57]. Some researchers have an overall look at a collaboration concept at the architectural level [14,15,66]. There are other concepts such as joint actions and commitments [20], and dynamics of intentions during collaboration [33] providing more depth in the context of collaboration. Some of these works emphasize the applicability of emotions in their architectures, and others emphasize the collaborative aspect of their robots. The applications of different prominent collaboration theories show the importance and the applicability of these theories in robots and collaborative systems. The following examples briefly review some of the applications of artificial emotions and appraisal theory of emotions in robots and autonomous agents.

Applications of Artificial Emotions – There are many research areas, including robotics and autonomous agents, that employ the structure and/or functions of emotions in their work with a variety of motivations behind modeling emotions [72]. Some of these works are inspired by specific psychological theories, some are freely using the concept of emotion without using the theoretical background in social sciences [68], and some are using a combination of concepts from the psychological theories [29]. We can also see the application of emotion theories in designing companion robots, robots capable of expressing emotions and social behaviors, as well as robots which can convey certain types of emotion products, e.g., empathy [9,47,61]. Robots also use emotions theories for some other purposes such as automatic affect recognition using different modalities [76], and behavior adaptation [34].

Furthermore, emotions have different intra/interpersonal functions. Motivation is one of the crucial functions of emotions, since it can initiate, direct and maintain goal-directed behaviors. The motivation mechanism in our work is inspired by Murray's theory as well as Bach's approach on Dörner's theory [4–7]. It is focused on the role of emotion-driven motives in cognitive processes, e.g., intention formation, during collaboration.

Applications of Appraisal Theory – Appraisal theories of emotion were first formulated by Arnold [3] and Lazarus [31] and then were actively developed in the early 80s by Ellsworth and Scherer and their students [54,55,58–60]. Computational appraisal models have been applied to a variety of uses including contributions to psychology, robotics, AI, and HCI. For instance, Marsella and Gratch have used EMA [40] to generate specific predictions about how human subjects will appraise and cope with emotional situations and argue that empirical tests of these predictions have implications for psychological appraisal theory [19]. However, EMA does not focus on the dynamics of collaborative contexts. There are several examples in artificial intelligence and robotics of applying appraisal theory [1,28,40]. In robotics, appraisal theory has been used to establish and maintain a better interaction between a robot and a human [28,55,71]. Appraisal theory has also been used in robots' decision making [17], or in their cognitive systems [26,38]. In the virtual agents community, empathy and affective decision-making is a research topic that has received much attention in the last decade [41,46,49,70].

3 Example Scenarios

3.1 Backstory

The scenarios transpire in a lunar facility using collaborative robots working with astronauts. The mission is to finish installing the solar panels required to provide energy for the operation of the facility. Most of the panels have already been installed. However, the facility is now facing a low batteries situation, which forces the team to be cautious about energy consumption. A female astronaut is inspecting the working conditions in the field and planning the installation of the remaining panels in collaboration with the robot.

3.2 Astronaut-Robot Interaction

The Robot and the Astronaut will collaborate with each other to achieve their shared goal, which is to install two solar panels. They will face various difficulties, ranging from the task being unpleasant and challenging to conflicts between their private and/or shared goals because of a blocked or a protracted sub-task. The Robot and the Astronaut will go through a series of assessment processes to figure out a) how did the current blockage happen? b) why is the current task is blocked? and c) what is the next action they are going to take? The Robot uses its cognitive abilities and communication skills to overcome these problems, to motivate the Astronaut, and to propose alternative tasks.

3.3 Agreeing on Shared Goal (Emotion Awareness)

This hypothetical interaction and the emotion ignorant version in the next section demonstrate how the process of agreeing on a shared goal is improved by the Robot's awareness of its collaborator's emotions (here, frustration).

A1. Astronaut: Oh no! Finishing the quality check of the connector with this measurement problem is so frustrating. I think we should stop now!

A2. Robot: <u>I see. This is frustrating.</u> But, I can go on and check the impedance of the panel as it was originally planned.

A3. Astronaut: Then, I will have some time to fix the measurement tool.

A4. Robot: The next task is fixing the panel and it requires you to prepare and attach the welding rod to your welding tool. To save our time, I will connect the adaptor while you are preparing your measurement tool.

A5. Astronaut: That would be great!

The Astronaut's first turn (A1), shows her verbally conveying her frustration with respect to a malfunctioning measurement tool. In reply, the Robot's first turn (A2) shows the Robot perceiving the Astronaut's frustration and acknowledging it verbally. The underlined section of the Robot's utterances (in turn A2) shows the influence of using emotion-driven processes which lead to acknowledgement of the Astronaut's emotion[1]. In Section 4, we will show the computational mechanisms that are involved in this process. In Section 5.2, we will see how perceiving human collaborator's emotion (here, frustration as a negative emotion) can influence computing the relevance of the event.

Continuing in turn A3, the Astronaut's utterance shows a change of underlying belief from termination of the collaboration to planning to fix the measurement tool. Notice that the proper acknowledgement of the Astronaut's emotion helps to change her emotion from frustration to neutral. Now that the Astronaut is no longer expressing a negative emotion (i.e., frustration), and is instead planning to fix the problem, the Robot can provide an alternative task as a potential solution (A4). This example illustrates an advantage of emotional awareness: although the Robot, according to the shared plan, could have provided the same alternative task as a solution to the Astronaut immediately, it delayed instead, providing the potential alternative after first dealing with the Astronaut's negative emotional state. Finally, since agreeing on a shared goal is a collaborative negotiation process, emotion awareness plays a crucial role in providing a fair offer. As a result, the Astronaut's response in the last turn (A5) shows acceptance and contentment with the Robot's behavior as well as the potential solution to continue collaboration and agreement on the shared goal.

3.4 Agreeing on Shared Goal (Emotion Ignorance)

This example shows the beginning of the same process of agreeing on a shared goal as in the previous section, except that it diverges from reaching an agreement due to the Robot's emotion ignorance. It begins with the same utterance (B1) as the previous example (A1).

B1. Astronaut: Oh no! Finishing the quality check of the connector with this measurement problem is so frustrating. I think we should stop now!

B2. Robot: I can help you with the connector, or we can terminate this task. <u>What do you want me to do?</u>

B3. Astronaut: As I said the measurement tool does not work properly. We can not continue!

[1] Notice the absence of these utterances as the consequence of ignoring the Astronaut's emotions in the corresponding turn (B2) in the next example.

B4. Robot: Okay. Do you want me help you with the connector?

B5. Astronaut: How can you help me with the connector?

B6. Robot: I cannot fix your measurement tool, but I can fetch another one for you if you want?

B7. Astronaut: No, I don't want another measurement tool! We don't have time for that!

B8. Robot: Okay. You want me to terminate this task. Terminating this task can influence the quality of installation of this solar panel which can cause the mission to fail. Or, do you want us to work on another task? We can install the panel using your welding tool, but I do not know whether the quality of our installation will be acceptable.

B9. Astronaut: I told you we have this problem and we should terminate the mission! We cannot continue without the measurement tool!

As mentioned earlier, emotional awareness is beneficial in collaboration by channeling the collaboration process towards the shared goal. Without emotional awareness a collaborative robot will try to maintain the status of the shared goal and protect it from failure without considering its collaborator's negative emotion. In this example, the emotionally ignorant Robot does not acknowledge the Astronaut's frustration (compare B2 with A2 above), since it does not perceive that emotion as a negative one. This ignorance of negative or positive emotions influences the robot's behavior by misinterpreting the perceived emotions as a neutral one. Then, while negotiating the shared goal, the Robot fails to offer a potential solution with respect to the Astronaut's emotional state. As a result, it causes the failure of the negotiation process during collaboration.

The Robot in this example does not perceive the Astronaut's emotion, and therefore does not include the Astronaut's emotion (frustration) as an influential factor in its computational mechanisms (see details in Section 4). Hence, in the Robot's first response (B2), it does not acknowledge the Astronaut's emotion, and instead immediately conveys two available alternative actions according to the existing shared plan, and asks the Astronaut to select between them. As shown in the Astronaut's response (B3), this immediate proposal does not result in any progress in collaboration. As a result, the Astronaut repeats herself about the task status while still expressing frustration. The Astronaut's response does not change the Robot's mental state and this causes the Robot to try to repeat its own question while still missing the Astronaut's frustration (B4). The Robot's utterance creates an ambiguous assumption for the Astronaut about whether the Robot can fix the broken measurement tool for her. This ambiguity makes the Astronaut even more frustrated and causes her to ask a question to remove the ambiguity of the Robot's proposal (B5). In return, the Robot not only misses the Astronaut's intensified frustration, but also nullifies the Astronaut's assumption about fixing the malfunctioning measurement tool and proposes the potential solution of replacing the tool, and asks whether the Astronaut agrees on that

(B6). As we shall see, the Robot's reasoning is different in B6 because its assessment of the Astronaut's cognitive state and its strategies for motivating the Astronaut are different.

In B7, the Astronaut modifies its assumption and announces the shortage of time as justification for expressing her anger. At this point, the Robot's response becomes more crucial since its wrong method of interaction and emotionally ignorant behavior shifted the Astronaut's emotional and mental states into a noncollaborative status. Consequently, the Robot again attempts to revive the collaboration process; it provides more information about the repercussions of terminating the collaboration process, to see whether the Astronaut can pursue another task (B8). Notice the underlined section of the Robot's turn B8 indicates its reasoning about the problem dissociated from the Astronaut's mental state. Finally, the poor interaction of the Robot caused by its emotionally ignorant behavior leads to an unsuccessful termination of their collaboration (B9).

3.5 Task Delegation (Emotion Awareness)

In this and the next section, a different collaborative behavior, task delegation, is used to illustrate how collaboration critically depends on understanding how worried the other collaborator is. This example shows that when the Robot is aware of the Astronaut's worry, it can use its own Motivation mechanism driven by emotions to come up with a way to alleviate her worry. Its solution is to postpone all questions as long as possible.

C1. Astronaut: I still have some problems with attaching the first panel! We do not have enough time. You should begin to install the second panel.

C2. Robot: Okay. Don't worry. I can handle that.

C3. Astronaut: I will try to fix it ASAP.

C4. Robot: I might need to ask some questions while I am installing the second panel.

C5. Astronaut: That's fine. Just let me know.

At the beginning of this example the Astronaut (C1) is worried because of the lack of time to achieve the shared goal (finishing installation of solar panels). She proposes that the Robot begin installing the second panel, since the first one still has some problems. The Robot in its first turn (C2), perceives the Astronaut's emotion (i.e., worry) and, using the same cognitive mechanisms (see Section 4.1), acknowledges the Astronaut's emotion just as it did in Section 3.3. The underlined utterance in the Robot's turn C2, shows the Robot's awareness of the Astronaut's emotion. Also, because of perceiving the Astronaut's worry the Robot does not ask her if it is okay to leave the current task (which was helping the Astronaut to install the first panel). The reason is that the Robot knows redirecting the Astronaut's attention away from the object of worry will create frustration, as the function of worry is to resolve the object of worry.

For this reason, the Robot also postpones asking questions until it is necessary (C4). Thus, the Robot not only prevents overwhelming the Astronaut with many questions, but its utterance implicitly reveals its knowledge of the tasks' requirements to the Astronaut. As a result, the Robot's approach to acceptance of the delegated task mitigates the Astronaut's negative emotion (i.e., worry) which makes her respond positively to the Robot's proposal.

3.6 Task Delegation (Emotion Ignorance)

This last example illustrates how ignoring the collaborator's emotions in a task delegation situation can negatively impact the progress of a collaboration. In this example, the emotionally ignorant Robot is planning in its most efficient manner (because time is short) and therefore asking a lot of questions so that it can work out the plan. But asking questions exacerbates the Astronaut's worry which leads to an unsuccessful collaboration due to the lack of time.

D1. Astronaut: I still have some problems with attaching the first panel! We do not have enough time. You should begin to install the second panel.

D2. Robot: Okay. I can handle that. Is it okay if I leave the current task though?

D3. Astronaut: Yes, that's fine. I can finish it on my own.

D4. Robot: Okay. But according to the plan, I need your help when we need to weld the panel. Will you be able to help me?

D5. Astronaut: Yes, I will.

D6. Robot: We also need your welding tool and supplies as well as the measuring tool to install the second panel.

D7. Astronaut: Just let me know whenever you need something!

D8. Robot: Thanks. I will. How about the conflict that might occur while I am trying to fix the second panel? You are going to need my help at the same time.

D9. Astronaut: Robot, I really don't understand what you are talking about!

D10. Robot: Do you want me to provide some examples?

D11. Astronaut: We don't have time for this anymore!

The Astronaut's very first utterance above (D1) is the same as the first utterance in the previous example (C1). The Astronaut is worried and expresses her worry. However, the Robot does not perceive and consequently does not acknowledge the Astronaut's emotion. As a result, the Robot responds to the Astronaut by trying to determine a proper solution for an action selection problem. The action selection problem is primarily caused by the shift in the Robot's focus of attention from an unfinished ongoing task (unsatisfied postconditions) to a new partially known non-primitive task (i.e., installing the second panel). Therefore, the Robot immediately tries to confirm leaving the current unfinished task (D2). Notice the absence of acknowledgment of the Astronaut's emotion by the Robot in this turn (compare C2 above and D2 here).

This absence of emotion awareness is the beginning of the failure of the task delegation process. Throughout the remainder of the interaction, the Astronaut constinues to express worry, and later, frustration. The Robot repeatedly fails to perceive the Astronaut's emotions, and asks numerous questions about the new delegated task (D4, D6, D8, D10), preventing the Astronaut from resolving the object of her worry, and ultimately leading to the failure of the collaboration.

4 Computational Framework

In this section, we briefly describe Affective Motivational Collaboration Theory [65] and the five underlying emotion-regulated mechanisms in this theory. Each mechanism constitutes one or more processes which are involved in generating collaborative behaviors for the Robot. We also explain different types of mental states in our computational framework. Notice in Fig. 1 there are two components, Perception and Action, which are not part of Affective Motivational Collaboration Theory. These components only provide required input and output to our framework which can differ based on the capabilities of a particular sociable robot.

4.1 Affective Motivational Collaboration Theory

Affective Motivational Collaboration Theory (see Fig. 1) is about the interpretation and prediction of the observable behaviors in a dyadic collaborative interaction. The collaboration structure of Affective Motivational Collaboration Theory is based on the SharedPlans theory of collaboration [21,22,24]. Affective Motivational Collaboration Theory focuses on the processes that generate, maintain and update this structure based on mental states. The collaboration structure is important because social robots ultimately need to co-exist with humans, and therefore need to consider humans' mental states as well as their own internal states and operational goals. The processes involved in collaboration are important because they explain how the collaboration structure is formed and dynamically evolved based on the collaborators' interaction.

Affective Motivational Collaboration Theory focuses on the processes regulated by emotional states. It aims to explain both rapid emotional reactions to events as well as slower, more deliberative responses. These observable behaviors represent the outcome of reactive and deliberative processes related to the interpretation of the Robot's relationship to the collaborative environment. These reactive and deliberative processes are triggered by two types of events: *external* events, such as the human's utterances and primitive actions, and *internal* events, comprising changes in the Robot's mental state, such as belief formation and emotional changes. Affective Motivational Collaboration Theory explains how emotions regulate the underlying processes in the occurrence of these events during collaboration.

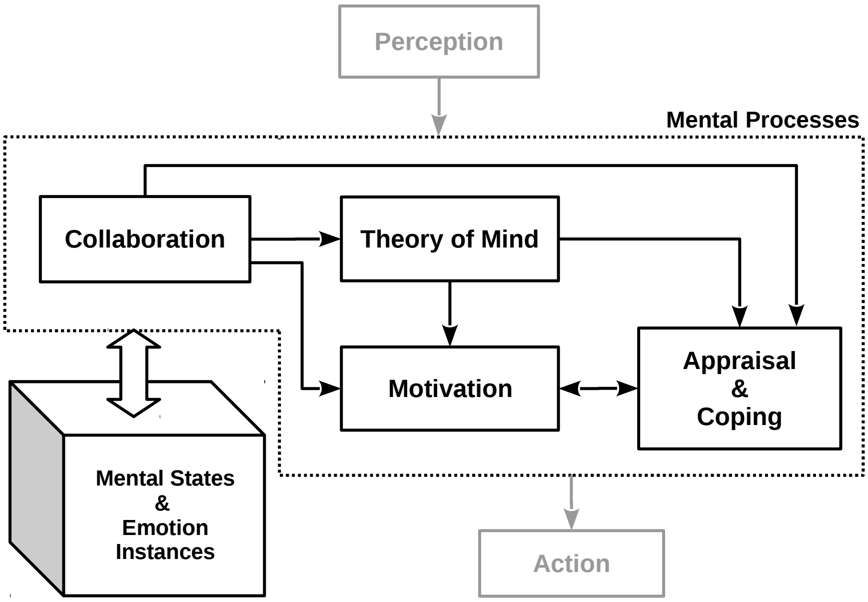

Fig. 1: Computational framework based on *Affective Motivational Collaboration Theory* (arrows indicate primary influences between mechanisms).

Emotion-regulated processes operate based on the Robot's mental state, which also includes the anticipated mental state of the human, generated according to the Robot's model of the human. These mental states include beliefs, intentions, goals, motives and emotion instances. Each of these mental states possess multiple attributes impacting the relation between cognition and behavior or perception.

In summary, Affective Motivational Collaboration Theory consists of five mechanisms[1] all of which store and retrieve data in the Mental States. We will describe all these mental states, each mechanism and their influences on each other briefly below.

4.2 Mental States & Emotion Instances

The Mental States shown in Fig. 1 comprise the knowledge base required for all the mechanisms in the overall framework.

4.2.1 Beliefs

Beliefs are a crucial part of the Mental States. We have two different perspectives on categorization of beliefs. In one perspective, we categorize beliefs based on whether or not they are shared between the collaborators. The SharedPlans [24] theory is the foundation of this categorization in which for any given proposition the Robot may have: a) private beliefs (the Robot believes the human does not know these), b) the

[1] Appraisal and Coping are considered as two distinct mechanisms depicted in one box in Fig. 1

inferred beliefs of the human (the Robot believes the human collaborator has these beliefs), and c) mutual beliefs (the Robot believes both the Robot and the human have these same beliefs and both of them believe that). From another perspective, we categorize beliefs based on who or what they are about. In this categorization, beliefs can be about the Robot, the human, or the environment. Beliefs about the environment can be about internal events, such as outcomes of a new appraisal or a new motive, or external events such as the human's offer, question or request, and general beliefs about the environment in which the Robot is situated. Beliefs can be created and updated by different processes. They also affect how these processes function as time passes.

Beliefs have attributes and they impact different processes of the framework such as the evaluation of an external event by the Appraisal mechanism, and updates to the collaboration plan. We use three belief attributes in the Appraisal mechanism. Belief *strength* is about how strongly the self holds salient beliefs about an object, an entity, or an anticipated behavior. The *saliency* of a belief is a cognitive attribute that pertains to how easily the self becomes aware of a belief. The *persistence* of a belief refers to how resistant the belief is to changes.

4.2.2 Intentions

Intentions are mental constructs directed at future actions. They play an essential role in: a) taking actions according to the collaboration plan, b) coordination of actions with the human collaborator, c) formation of beliefs about the Robot and anticipated beliefs about the human, and d) behavior selection in the Coping mechanism. First, taking actions means that the Robot will intend to take an action for primitive tasks that have gained the focus of attention, possess active motives, and have satisfied preconditions for which required temporal predecessors have been successfully achieved. Second, intentions are involved in action coordinations in which the human's behavior guides the Robot to infer an anticipated behavior of the human. Third, intentions play a role in belief formation, mainly as a result of the permanence and commitment inherent to intentions in subsequent processes, e.g., appraisal of the human's reaction to the current action and self-regulation. Lastly, intentions are involved in selecting intention-related strategies, e.g., planning, seeking instrumental support and procrastination, which is an essential category of the strategies in the Coping mechanism [40]. Intentions possess a set of attributes, e.g. *involvement, certainty, ambivalence* which moderate the consistency between intention and behavior. The issue of consistency between the intentions (in collaboration) and the behaviors (as a result of the Coping mechanism in the appraisal cycle) is important because neither of these two mechanisms alone provides solution for this concern.

4.2.3 Motives

Motives are mental constructs which can initiate, direct and maintain goal-directed behaviors. They are created by the emotion-regulated Motivation mechanism. Motives can cause the formation of a new intention for the robot according to: a) its own emotional states, b) its own private goal, c) the collaboration (shared) goal, and d) other's anticipated beliefs. Motives possess a set of attributes. The Motivation mechanism compares motives based on the quality of these attributes and chooses the one which is the most related to the current state of the collaboration. We also use two motive attributes in Appraisal mechanisms. The *importance* of a motive is determined by the corresponding beliefs about the effects of achieving or not achieving the associated goal. The *urgency* of a motive defines how much time the self has to acknowledge and address that motive before it is too late. These attributes are involved in the comparison of newly generated motives based on the current state of the collaboration. Ultimately, the Robot forms or updates an intention associated with the winning motive in the Mental States.

4.2.4 Goals

Goals help the Robot to create and update the structure of the collaboration plan. Goals direct the formation of intentions to take appropriate corresponding actions during collaboration. Goals also drive the Motivation mechanism to generate required motive(s) in uncertain or ambiguous situations, e.g., to minimize the risk of impasse or to reprioritize goals. Goals have three attributes. The *specificity* of goals has two functions for the Robot. First, it defines the performance standard for evaluating the progress and quality of the collaboration. Second, it serves the Robot to infer the winner of competing motives. The *proximity* of goals distinguishes goals according to how "far" they are from the ongoing task. Proximal (or short-term) goals are achievable more quickly, and result in higher motivation and better self-regulation than more temporally distant (or long-term) goals. Goals can influence the *strength* of beliefs, which is an important attribute for regulating the elicitation of social emotions. The *Difficulty* of goals impacts collaborative events and decisions in the appraisal, reverse appraisal, motive generation and intention formation processes. For instance, overly easy goals do not motivate; neither are humans motivated to attempt what they believe are impossible goals.

4.2.5 Emotion Instances

Emotions in Mental States are emotion instances that are elicited by the Appraisal mechanism. These emotion instances include the Robot's own emotions as well as the anticipated emotions of the human which are created with the help of the processes in the Theory of Mind mechanism, e.g., worry.

4.3 Collaboration Mechanism

The *Collaboration* mechanism (see Fig. 1) constructs a hierarchy of tasks and also manages and maintains the constraints and other required details of the collaboration specified by the plan. These constraints on task states and on the ordering of tasks include the inputs and outputs of individual tasks, the preconditions specifying whether it is appropriate to perform a task (which can be used as an indication of an impasse), and the postconditions specifying whether a just-completed task was successful (or failed). The Collaboration mechanism includes processes to update and monitor the shared plan. It also keeps track of the focus of attention, which specifies the salient objects, properties and relations at each point of the collaboration. These processes depend on the operation of other mechanisms. For instance, the Appraisal mechanism is required to evaluate the current mental state with respect to the current status of the collaboration. Also, the Appraisal and Motivation mechanisms provide interpretation of task failure and the formation of a new mental state (e.g. an intention) respectively.

4.4 Appraisal & Coping Mechanisms

Appraisal is a subjective evaluation mechanism based on individual processes each of which computes the value of the appraisal variables. The Appraisal mechanism is responsible for evaluating changes in the Robot's mental state, the anticipated mental state of the human, and the state of the collaboration environment. Collaboration requires the evaluative function of the Appraisal mechanism for various reasons. The course of a collaboration is based on a full or a partial plan [22, 23] which needs to be updated as time passes and collaborators achieve, fail at or abandon a task assigned to them. The failure of a task should not destroy the entire collaboration. Appraising the environment and the current event helps the Robot to update the collaboration plan in response to changes in the environment and avoid further critical failures during collaboration. Appraisal also helps the Robot to have a better understanding of the human's actions by making inferences based on appraisal variables [40] [60]. Furthermore, in order to collaborate successfully, a collaborator cannot simply use the plan and reach to the shared goal; there should be an adaptation mechanism not only for updating the plan but also the underlying mental state. The output of Appraisal can directly and indirectly impact other mechanisms. For instance, the Motivation mechanism uses this data to generate, compare and monitor motives based on the current internal appraisal of the Robot as well as the appraisal of the environment.

The Coping mechanism is responsible for adopting the appropriate behavior (action) with respect to interpretation of the ongoing internal and external changes. The Coping mechanism provides the Robot with different coping strategies associated with changes in the Robot's mental state with respect to the state of the collaboration. In other words, the Coping mechanism produces cognitive responses based on the appraisal patterns.

4.5 Motivation Mechanism

The *Motivation* mechanism operates whenever the Robot a) requires a new motive to overcome an internal impasse in an ongoing task, or b) wants to provide an external motive to the human when the human faces a problem in a task. In both cases, the Motivation mechanism uses the Appraisal mechanism to compute attributes of the competing motives. The purpose of the Motivation mechanism in Affective Motivational Collaboration Theory is to generate new emotion-driven goal-directed motives considered as "potential" intentions. These motives are generated based on what the Robot believes about the environment including the Robot and the other collaborator and the corresponding appraisals. The Robot uses these motives to reach to a private or shared goal according to new conditions caused by changes in the environment. The Motivation mechanism consists of an arrangement of three distinct processes. First, several motives are generated with respect to the current mental state. Only one of these competing motives is most likely to become a new intention. Therefore, a comparison process decides which motive is more likely to be consistent with the current state based on the values of the motive attributes (e.g., motive importance and motive urgency). Finally, the new motive will be used to form a new intention. As a result, the Robot can take an action based on the new intention to sustain the collaboration progress. Furthermore, the Motivation mechanism can serve the Theory of Mind mechanism by helping the Robot to infer the motive behind the human's current action.

4.6 Theory of Mind Mechanism

The *Theory of Mind* mechanism is the mechanism for inferring a model of the human's anticipated mental state. The Robot uses the Theory of Mind mechanism to infer and attribute beliefs, intentions, motives and goals to its collaborator based on the user model it creates and maintains during collaboration. The Robot progressively updates this model during the collaboration. The refinement of this model helps the Robot to anticipate the human's mental state more accurately, which ultimately impacts the quality of the collaboration and the achievement of the shared goal. Furthermore, the Robot can make inferences about the motive (or intention) behind the human's actions using the Motivation mechanism. This inference helps the Robot to update its own beliefs about the human's mental state. In the reverse appraisal process [13], the Robot also applies the Appraisal mechanism together with updated beliefs about the human's Mental States to infer the human's current mental state based on the human's emotional expression. Finally, the Collaboration mechanism provides the collaboration structure, including status of the shared plan with respect to the shared goal and the mutual beliefs to the Theory of Mind mechanism. Consequently, any change to the Robot's model of the human will update the Robot's mental state.

4.7 Perception & Action

Perception is outside of our theory and is responsible for producing the sensory information used by the mechanisms in our framework; it is only a source of data to the computational framework (see Fig. 1). Thus, our computational framework starts with high-level semantic representation of events (including utterances). The output of the Perception component provides a unified perception representation across all of the mechanisms.

The Action component in Fig. 1, which is also outside of our theory, functions whenever the Robot needs to show a proper behavior according to the result of the internal processes of the collaboration procedure; it is only a sink of data in our computational framework. The only input to the Action component is provided by the Coping mechanism. This input will cause the Action component to execute an appropriate behavior of the Robot. This input to Action has the same level of abstraction as the output of the Perception mechanism, i.e., it includes the Robot's utterances, primitive actions and emotional expressions.

5 Appraisal in Collaboration

In this section, we focus on a small part of a larger framework based on our Affective Motivational Collaboration Theory. We describe the methods which retrieve information about the collaboration structure, and are used to compute the values of appraisal variables. Then, we introduce our algorithms implemented to compute the value of four appraisal variables depicted in Fig. 2.

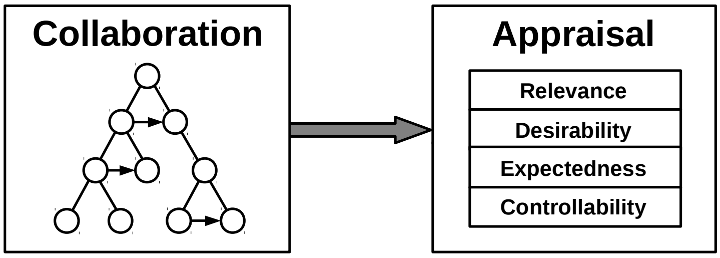

Fig. 2: Using Collaboration structure in Appraisal (mechanisms in our framework).

5.1 Collaboration

The Collaboration mechanism constructs a hierarchy of goals associated with tasks in the form of a hierarchical task network (see Fig. 3), and also manages and maintains the constraints and other required details of the collaboration including the inputs and outputs of individual tasks, the *preconditions* (specifying whether it is appropriate to perform a task), and the *postconditions* (specifying whether a just-completed task was successful). Collaboration also keeps track of the focus of attention, which determines the salient objects, properties and relations at each point, and shifts the focus of attention during the interaction.

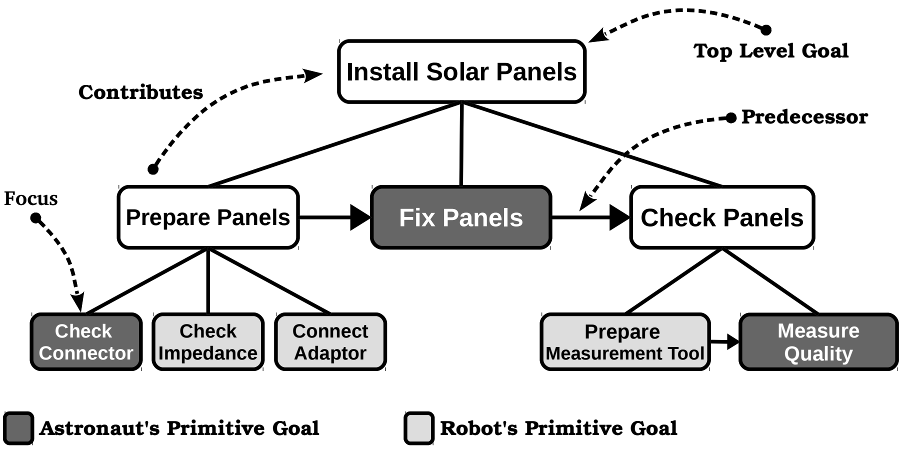

Fig. 3: Collaboration structure (shared plan).

Here, we briefly describe the methods which retrieve information about the collaboration structure, and are used in our algorithms to compute the values of appraisal variables. In these methods, ε_t is the event corresponding to time *t*, and g_t is a given goal at time *t*.

- *recognizeGoal(ε_t)* returns the unique goal to which the given event (action, utterance, or emotional expression) directly contributes; it is only one goal since the robot can only do one primitive action at a time in our collaboration model, i.e, in the goal tree, a given primitive action can only directly contribute to one parent goal. The method returns *ambiguous* if it does not recognize a goal in the plan[1].
- *getGoalStatus(g_t)* returns whether g_t's status is ACHIEVED, FAILED, BLOCKED, INAPPLICABLE, PENDING, or IN PROGRESS. In our example, "Check Connector" is the current (focused) goal and it is PENDING, and the "Prepare Panels" and "Install Solar Panels" are IN PROGRESS. The focused goal is the goal that the robot currently pursues.
- *getTopLevelGoal(g_t)* returns g_t's top level goal.
- *precondStatus(g_t)* returns the status of the precondition for the given goal whether it is SATISFIED, UNSATISFIED or UNKNOWN. For instance, the precondition for fixing a panel is whether the panel is appropriately located on its frame.
- *isLive(g_t)* returns *true* if all the predecessors of g_t are ACHIEVED and all the preconditions are SATISFIED, i.e., PENDING or IN PROGRESS goals; otherwise returns *false*.
- *isFocusShift(g_t)* returns *true* if the given goal is not the previous focus (top of the stack); otherwise returns *false*.
- *isNecessaryFocusShift(g_t)* returns *true* if the status of the previous focus was ACHIEVED; otherwise returns *false* [32].
- *isPath(g_1, g_2)* returns *true* if there is a path between g_1 and g_2 in a plan tree structure; otherwise returns *false*.
- *getContributingGoals(g_t)* returns g_t's children.
- *getPredecessors(g_t)* returns g_t's predecessors.
- *getInputs(g_t)* returns all required inputs for g_t. For example, the goal "Fix Panels" requires inputs such as *welding tool* and *panel*.
- *isAvailable(g_t)* returns whether the given input is available. For instance, whether the *welding tool* is available for the goal "Fix Panels".
- *isFocused(g_t)* returns whether the focus is on g_t.
- *getResponsible(g_t)* returns responsible agent(s) for g_t. In a dyadic collaboration, both of the agents (jointly) can be partly responsible for a nonprimitive goal, while each (self or other) is responsible for one or more primitive goals. For instance, both the Robot and the Astronaut are responsible for the nonprimitive goal of "Install Solar Panels", whereas it is only the Robot who is responsible for the primitive goal of "Prepare Measurement Tool".

[1] Ambiguity introduces some extra complexities which are beyond scope of this paper.

5.2 Appraisal Processes

We consider four appraisal variables to be the most important appraisal variables in a collaboration context, i.e., *Relevance* (since other appraisals are only computed for relevant events), *Desirability* (since it discriminates facilitating and inhibitory events towards the collaboration progress), *Expectedness* (since it underlies a collaborative robot's attention), and *Controllability* (since it is associated with the agent's coping ability) [62]. There are other appraisal variables introduced in psychological [60] and computational literature [18]. We believe most of these variables can be straightforwardly added to our appraisal mechanism later. All of the algorithms in this section use mental states of the robot (discussed in Section 4.2) which are formed based on the collaboration structure. These algorithms use the corresponding recognized goal of the most recent event at each turn.

5.2.1 Relevance

Relevance is an important appraisal variable since the other appraisal variables are meaningful only for relevant events. Relevance as an appraisal variable measures the significance of an event for the self. An event can be evaluated to be relevant if it has a non-zero utility [40]. However, the utility of an event is also influenced by the other collaborator's emotional expressions as the reflection of the other collaborator's mental state with respect to the status of the collaborative environment. Other appraisal models only consider the utility of an event based on the self's goal and plan.

Algorithm 1 determines the relevance of the given event with respect to the current mental state. The relevance of the event depends on the significance of the event with respect to the collaboration status, which is determined based on the utility of the event as presented in [18,40]. Our algorithm for computing the relevance of an event during collaboration involves other factors that other appraisal models do not consider. For instance, the human's perceived emotion, recurrence of a belief, or occurrence of a belief about an unrelated goal by the human play important roles by influencing the utility of an event during collaboration. As a result, evaluating the relevance of events can cause a collaborative robot to respond effectively which can positively impact the status of the shared goal, without dedicating all its resources to every event.

After perceiving an event, the belief about that event represents the event in the robot's mental state. *recognizeGoal* returns the goal to which the current event contributes, unless it is *ambiguous*; g_t represents the shared goal at time (turn) t within the shared plan. We compute the utility ($-1 \leq \mathcal{U} \leq 1$) of the event using the values of the attributes associated with the existing beliefs, and the attributes of the motive associated with the recognized goal (see details below). We use three belief attributes (see Section 4.2) to compute the belief-related part of the utility:

- *Strength*: The extent to which the preconditions (α), postconditions (β), predecessors (λ), and contributing goals (μ) of a goal are known (SATISFIED or UNSATISFIED) makes beliefs about the goal stronger. An UNKNOWN pre and postcondition status of a goal and its predecessors and contributing goals forms weaker beliefs. For instance, if one knows all predecessors of a pursued goal (e.g., "Check Panels") are SATISFIED (i.e., "Fix Panels" and "Prepare Panels"), failure of the pursued goal will elicit one's

Algorithm 1 (Relevance)

function IsEventRelevant(Event ε_t)

$g_t \leftarrow$ *recognizeGoal*(ε_t)

$\mathcal{U} \leftarrow$ getEventUtility(g_t)
$\tau_t \leftarrow$ getEmotionalThreshold(g_t)

if $(\tau_t \leq |\mathcal{U}|)$ **then**
    return RELEVANT
else
    return IRRELEVANT

negative emotion (due to the strong beliefs related to the goal); whereas not knowing the status of the goal-related factors (e.g., whether the Astronaut could find the tool to fix a panel) causes one to form weaker beliefs about the goal.

- *Saliency (S)*: Beliefs related to the focused goal are more salient than beliefs related to any other goal in the plan; according to Fig. 3, if one of the collaborators is preparing a solar panel, beliefs related to all of the other *live* (PENDING or IN PROGRESS) goals (e.g. "Connect Adaptor") will be less salient than beliefs related to the focused goal, i.e., "Check Connector". Beliefs' saliency decreases according to their corresponding *live* goal's distance from the focused goal in the shared plan. *Non-live* goals will not be salient.
- *Persistence (P)*: The recurrence of a belief over time (turns) increases the persistence of the belief. Beliefs occurring only once have the lowest value of persistence. For instance, if the Astronaut keeps saying that she can not find the measurement tool to check the connector, Robot could pursue a new goal outside of the shared plan to acknowledge Astronaut's concern.

We also use two motive attributes discussed in Section 4.2 to compute the motive related part of the utility ($\mathcal{U}$):

- *Urgency* (γ): There are two factors impacting the urgency of a motive: a) whether the goal directing the given motive is the predecessor of another goal for which the other collaborator is responsible, and b) whether achieving the goal directing the given motive can mitigate the other collaborator's negative valenced emotion. For instance, if the Robot has a private goal to fetch another panel while the Astronaut is waiting for the Robot to connect the adaptor, connecting the adaptor will be more urgent than Robot's private goal.
- *Importance* (η): A motive is important if failure of the directing goal causes an impasse in the shared plan (i.e., no further goal is available to achieve), or achievement of the directing goal removes an existing impasse. For example, if the Robot cannot find the adaptor (an impasse to connect the adaptor), and the Astronaut provides another adaptor (external motive), the new motive becomes important to remove the impasse in the shared plan.

We provide the utility function ($\mathcal{U}$) in Equation 1. This function uses: saliency (*S*) and persistence (*P*) of the belief related to the recognized goal, the recognized goal's status (υ), and the aggregation of belief and motive attributes (Ψ) according to Equation 2.

$$\mathcal{U}(\varepsilon_t) = \begin{cases} \upsilon P \cdot S^{\Psi} & \Psi > 0 \\ 0 & \Psi = 0 \end{cases} \tag{1}$$

Intuitively, we use υ to generate positive and negative utility values. The υ's value becomes +1 if the status of the corresponding goal is ACHIEVED, PENDING, or IN PROGRESS, and υ's value becomes -1 if the status of the corresponding goal is FAILED, BLOCKED, or INAPPLICABLE. The *P* influences the value of utility only as a coefficient since recurrent beliefs are not formed frequently during collaboration. The Ψ value indicates the magnitude of the influence of beliefs and motives using their attributes. Hence, the Ψ value impacts the saliency value of beliefs exponentially, helping to differentiate between beliefs.

In equation 2, the subscript *k* refers to the *known* goal-related factors (SATISFIED or UNSATISFIED); whereas the subscript *all* includes both *known* and *unknown* goal-related factors. In this equation, both urgency (γ) and importance (η) attributes of motives can impact the outcome of the goal-related belief attributes' ratio, and ultimately the Ψ value.

$$\Psi = \frac{\alpha_k + \beta_k + \lambda_k + \mu_k}{\alpha_{all} + \beta_{all} + \lambda_{all} + \mu_{all}} + \eta + \gamma \tag{2}$$

$$\begin{aligned} \eta, \gamma &\in \mathbb{N}, & \eta, \gamma &\geq 0 \\ \alpha_k, \beta_k, \lambda_k, \mu_k &\in \mathbb{N}, & \alpha_k, \beta_k, \lambda_k, \mu_k &\geq 0 \\ \alpha_{all}, \lambda_{all}, \mu_{all} &\in \mathbb{N}, & \alpha_{all}, \lambda_{all}, \mu_{all} &\geq 0 \\ \beta_{all} &\in \mathbb{N}, & \beta_{all} &\geq 1 \end{aligned}$$

The significance of an event in a collaborative environment is based on the utility of the event and the human's perceived emotion. The human's perceived emotion influences the relevance of the event in the form of a threshold value τ_t. In Equation 3, we use the valence of the perceived emotion ($\mathcal{V}_{e_h}$) to compute τ_t.

$$\tau_t = \begin{cases} 1 - \mathcal{V}_{e_h} & \mathcal{V}_{e_h} > 0 \\ |\mathcal{V}_{e_h}| & \mathcal{V}_{e_h} \leq 0 \end{cases} \tag{3}$$

$$\mathcal{V}_{e_h} \in \mathbb{R}, \qquad -1 \leq \mathcal{V}_{e_h} \leq 1$$

Hence, perceiving human's positive emotion (e.g., happiness) reduces the threshold value which makes the robot find an event RELEVANT with even a slightly positive utility. Similarly, an event can be considered IRRELEVANT even though the utility has a relatively positive value, because of perceiving the human's negative emotion.

5.2.2 Desirability

Desirability characterizes the value of an event to the robot in terms of whether the event facilitates or thwarts the collaboration goal. Desirability captures the valence of an event with respect to the robot's preferences [18]. In a collaborative robot, preferences are biased towards those events facilitating progress in the collaboration. Desirability plays an important role in the overall architecture; it makes the processes involved in the other mechanisms (e.g., Motivation and Theory of Mind) and consequently the robot's mental state, congruent with the collaboration status which is a collaborative robot's desire. Therefore, it causes the robot to dismiss events causing inconsistencies in the robot's collaborative behavior. Moreover, desirability is also crucial from the collaboration's point of view.

Algorithm 2 (Desirability)

function IsEventDesirable(Event ε_t)

  $g_t \leftarrow$ *recognizeGoal*(ε_t)
  $g_{top} \leftarrow$ *getTopLevelGoal*(g_t)

  if (*getGoalStatus*(g_{top}) = ACHIEVED) **then**
    return MOST-DESIRABLE
  else if (*getGoalStatus*(g_{top}) = FAILED) **then**
    return MOST-UNDESIRABLE
  else if (*getGoalStatus*(g_{top}) = BLOCKED) **or**
  (*getGoalStatus*(g_{top}) = INAPPLICABLE) **then**
    return UNDESIRABLE
  else if (*getGoalStatus*(g_{top}) = PENDING) **or**
  (*getGoalStatus*(g_{top}) = INPROGRESS) **then**

    if (*getGoalStatus*(g_t) = ACHIEVED) **then**
      return DESIRABLE
    else if (*getGoalStatus*(g_t) = FAILED) **then**
      return MOST-UNDESIRABLE
    else if (*getGoalStatus*(g_t) = BLOCKED) **or**
    (*getGoalStatus*(g_t) = INAPPLICABLE) **then**
      return UNDESIRABLE
    else if (*getGoalStatus*(g_t) = PENDING) **or**
    (*getGoalStatus*(g_t) = INPROGRESS) **then**
      return NEUTRAL

Algorithm 2 provides a process in which the desirability of an event is computed with regard to the status of the shared goal; i.e., it operates based on whether and how the event changes the status of the current shared goal. It distinguishes between the top level goal and the current goal because the top level goal's change of status attains a higher positive or negative value of desirability. For instance, failure of the top level goal (e.g., installing solar panel) is more undesirable than failure of a primitive goal (e.g., measuring the quality of the installed panel).

A top level goal' status must be ACHIEVED (i.e., SATISFIED postcondition) to consider the event MOST-DESIRABLE. When the goal's status is FAILED (i.e., UNSATISFIED postcondition) or BLOCKED, the associated event has the MOST-UNDESIRABLE or UNDESIRABLE values respectively. A goal is BLOCKED if any of the required goals or goals recursively through the parent goal are not ACHIEVED. An INAPPLICABLE goal is also considered as UNDESIRABLE. A goal is INAPPLICABLE if any of its predecessors are not ACHIEVED, and/or its preconditions are not SATISFIED. For PENDING and INPROGRESS top level goals, the status of the current goal associated with the top level goal determines the status of the event ε_t. Only a non-primitive goal can have INPROGRESS status, if it has been started but is not yet completed. A goal can be PENDING if it is live, or if it is a non-primitive goal that has not been started yet. ACHIEVED current goals mark an event (ε_t) as DESIRABLE, while FAILED or BLOCKED current goals render the event associated with them as MOST-UNDESIRABLE and UNDESIRABLE respectively. PENDING or INPROGRESS current goals mark their associated events as NEUTRAL.

5.2.3 Expectedness

Expectedness is the extent to which the truth value of a state could have been predicted from causal interpretation of an event. In the collaboration context the expectedness of an event evaluates the congruency of the event with respect to the existing knowledge about the shared goal. Thus, expectedness underlies a collaborative robot's attention. The collaboration mechanism uses expectedness to maintain the robot's attention and subsequently its mental state with respect to the shared goal. Reciprocally, the appraisal mechanism uses the underlying information of the collaboration structure to evaluate the expectedness of an event [63].

Algorithm 3 (Expectedness)

function ISEVENTEXPECTED(Event ε_t)

    $g_t \leftarrow$ *recognizeGoal*(ε_t)
    $g_{top} \leftarrow$ *getTopLevelGoal*(g_t)

    if $($*isLive*$(g_t))$ **then**
        if $(\neg$*isFocusShift*(g_t) **or**
          isNeccessaryFocusShift$(g_t))$ **then**
            return MOST-EXPECTED
        else
            return EXPECTED
    else
        if $($*isPath*$(g_t, g_{top}))$ **then**
            return UNEXPECTED
        else
            return MOST-UNEXPECTED

In Algorithm 3 we provide the process of computing the expectedness based on the shared plan and status of the shared goal. The key point in this algorithm is the status of the current shared goal (g_t), which is associated with the event ε_t and its relationship with the top level goal ($g_{_{top}}$).

The intuition captured here is that one expects the current goal to be finished before undertaking another activity, but the goals that can be the next focus of attention are also to be expected. Therefore, if the goal is live, the algorithm checks whether the goal has not changed, or whether the interpretation of the last event results in a necessary focus shift. Shifting the focus to a new goal is necessary when the former goal is achieved and a new goal is required. Consequently the new event is the MOST-EXPECTED one. However, even if the focus shift is not necessary, the new event can be considered as EXPECTED, since the corresponding goal is already live. For goals that have not yet been started (that is, are not live), the algorithm must determine how unexpected it would be to pursue one now; if the goal is at least in the plan, i.e., on the path to the top level goal, it is just UNEXPECTED while any others are MOST-UNEXPECTED.

5.2.4 Controllability

Controllability is the extent to which an event can be influenced; it is associated with a robot's ability to cope with an event [18]. Thus, a robot can determine whether an event's outcome can be altered by actions under either of the collaborators' control. In other words, controllability is a measure of a robot's ability to maintain or change a particular state as a consequence of an event.

Algorithm 4 (Controllability)

function ISEVENTCONTROLLABLE(Event ε_t)
    $g_t \leftarrow$ *recognizeGoal*(ε_t)

    $\mathcal{M} \leftarrow$ GETAGENCYRATIO(g_t)
    $\mathcal{R} \leftarrow$ GETAUTONOMYRATIO(g_t)

    $\mathcal{P} \leftarrow$ GETSUCCPREDECESSORSRATIO(g_t)
    $\mathcal{I} \leftarrow$ GETAVAILABLEINPUTS(g_t)

    $\mathcal{V}_{e_h} \leftarrow$ GETEMOTIONVALENCE(g_t)
    $\omega \leftarrow$ GETWEIGHTS(g_t)

    $\mathcal{X} \leftarrow \frac{\omega_0 \cdot \mathcal{M} + \omega_1 \cdot \mathcal{R} + \omega_2 \cdot \mathcal{P} + \omega_3 \cdot \mathcal{I}}{\omega_0 + \omega_1 + \omega_2 + \omega_3} + \mathcal{V}_{e_h}$

    if $(\mathcal{X} > 0)$ **then**
        return CONTROLLABLE
    else
        return UNCONTROLLABLE

Controllability is important for the overall architecture. For instance, the robot can choose to ask or negotiate about a collaborative task which is not controllable, or form a new motive to establish an alternative goal for the current uncontrollable event. In general, other mechanisms in the architecture use the controllability output in their decision making processes; meanwhile controllability uses information from the collaboration structure, e.g., predecessors of a goal.

An important determinant of one's emotional response is the sense of control over occurring events. This sense of subjective control is based on one's reasoning about self's power. For instance, the robustness of one's plan for executing actions can increase one's sense of power and subsequently the sense of control. In the collaboration context, we have translated the sense of control into a combination of four different factors including a) *agency* and b) *autonomy* of the robot, as well as the ratios of c) *successful predecessors*, and d) the *available inputs* of a given goal (i.e., g_t) in the shared plan.

In Algorithm 4, we partially compute the controllability of an event based on the above four factors. We use weighted averaging of these factors to determine their impact on the controllability of an event (line 9). The value of all these weights are set to *1.0* for the purpose of simplicity at this stage (**GETWEIGHTS**). We will adjust these weights after further investigating the influence of these factors, and implementing other mechanisms in the overall architecture. We believe that the human's perceived emotion also impacts the controllability of an event (**GETEMOTIONVALENCE**). The $(-1.0 \leq \mathcal{V}_{e_h} \leq 1.0)$ is the valence value of the human's perceived emotion. Positive emotions, e.g., happiness, possess positive values, and negative emotions, e.g., anger, have negative values. The magnitude of this value can change with respect to the intensity of the perceived emotion. Thus, a positive controllability value indicates that an event is CONTROLLABLE; otherwise UNCONTROLLABLE.

GETAGENCYRATIO: *Agency* is the capacity of an individual to act independently in a given environment. In a collaborative environment collaborators are sometimes required to act independently of each other. Hence, they need to have some internal motives that are formed based on their own mental states rather than motives that are reinforced by the other. These internal motives will lead the collaborators to acquire new intentions when required. If the robot's mental state possesses only an internal motive supporting the recognized goal, we consider a maximum agency value denoted as $\mathcal{M}$ in Algorithm 4 (i.e., $\mathcal{M} = 1.0$); otherwise we consider the minimum agency value (i.e., $\mathcal{M} = 0.0$). Note that the process of forming new internal motives is beyond scope of this paper.

GETAUTONOMYRATIO: *Autonomy* is the ability to make decisions without the influence of others, and implies acting on one's own and being responsible for that. In a collaborative environment, tasks are delegated to the collaborators based on their capabilities. Therefore, each collaborator is responsible for the delegated task and the corresponding goal. In Algorithm 4, $\mathcal{R}$ denotes the value of autonomy with regard to the goal g_t. This value $(0.0 \leq \mathcal{R} \leq 1.0)$ is the ratio of the number of goals contributing to g_t for which the robot is responsible over the total number of contributing goals, if the goal associated with the current event is a nonprimitive goal. However, if the associated goal of the current event corresponds to a primitive goal the value of

$\mathcal{M}$ would be 0.0 or 1.0. In general, higher autonomy leads to a more positive value of controllability.

GETSUCCPREDECESSORSRATIO: The structure of a shared plan contains the order of the required *predecessors* of a goal. Predecessors of a goal, g_t, are goals that the collaborators should achieve before trying to achieve goal g_t. We use the ratio of successfully achieved predecessors of the recognized goal over the total number of predecessors of the same goal. If all of the predecessors of the given goal are achieved, then $\mathcal{P} = 1.0$ which is the maximum value for $\mathcal{P}$. On the contrary, failure of all of the predecessors will lead to $\mathcal{P} = 0.0$. Therefore, a higher $\mathcal{P}$ value positively impacts the value of controllability for the current event.

GETAVAILABLEINPUTS: Finally, *inputs* of a task are the required elements that the collaborators use to achieve the specified goal of the task. These inputs are also part of the structure of a shared plan. We compute the ratio of the available required inputs over the total required inputs of the goal associated with the current event. This value (denoted as $\mathcal{I}$ in Algorithm 4) will be bound between 0.0 and 1.0. Similar to the other factors in the controllability process, the closer the value of $\mathcal{I}$ gets to 1.0, the more positive impact it has on the overall controllability value of the event.

In summary, the output of these four appraisal processes serves as critical input for the other mechanisms of the Affective Motivational Collaboration Framework, shown in Fig. 1. By providing adequate interpretation of events in the collaborative environment, the appraisal mechanism enables the robot to carry out proper collaborative behaviors.

6 Evaluation

We conducted a user study to test our hypothesis that humans and our algorithms will provide similar answers to questions related to different factors used to compute four appraisal variables: relevance, desirability, expectedness, and controllability. We conducted a between-subject user study using an online crowdsourcing website – CrowdFlower[1]. We had a questionnaire for each appraisal variable. There were 12 questions (including 2 test questions) in the controllability and expectedness questionnaires, 14 questions (including 2 test questions) in the desirability questionnaire, and 22 questions (including 3 test questions) in the relevance questionnaire. Each subject group originally had 40 subjects. We limited the subject pools to those with the highest confidence level on the crowdsourcing website in the United States, Britain, and Australia. Test questions were included to check the sanity of the answers. We eliminated subjects providing wrong answers to our sanity questions, and subjects with answering times less than 2 minutes. The final number of accepted subjects in each group is provided in Table 1.

To minimize the background knowledge necessary for our test subjects, we used a simple domestic example of preparing a peanut butter and jelly sandwich, and a hard boiled egg sandwich for a hiking trip. We provided textual and graphical instructions for both questionnaires; Fig. 4 shows the corresponding task model. The instructions presented a sequence of hypothetical collaborative tasks to be carried out by the test

[1] http://www.crowdflower.com

Table 1: Evaluation Results

appraisal variables	# of subjects	mean	stdev	p-value
Relevance	29	0.713	0.107	<0.001
Desirability	35	0.778	0.150	<0.001
Expectedness	33	0.785	0.120	<0.001
Controllability	33	0.743	0.158	<0.001

subject and an imaginary friend, Mary, in order to accomplish their goal of preparing two sandwiches. We also provided a simple definition and an example of each appraisal variable. The collaboration structure and the instructions were the same for both questionnaires. The questions introduced specific situations related to the shared plan, which included blocked tasks and failure or achievement of a shared goal. Each question provided three answers which were counterbalanced in the questionnaire. We provided an option like C in all questions (see Fig. 5), because we did not want to force subjects to choose between two options when they did not have a good reason. There were two questions designed based on each factor that we use in our algorithms (see Section 5.2). The questions were randomly placed in the questionnaire. Fig. 5 shows an example question from the relevance questionnaire which was designed to test whether human subjects perceive saliency as a factor in relevance. The input for our algorithms was the task model depicted in Fig. 4.

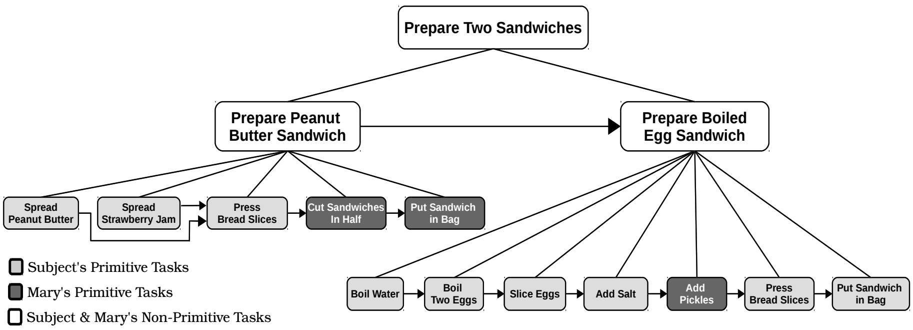

Fig. 4: Collaboration Task Model for the Evaluation.

Average results and standard deviation of the fractions of subjects' answers agreeing with our algorithms output for both questionnaires are presented in Table 1. Each question had 3 answers. Therefore, a random distribution would result in 33% agreement with our algorithms' output. However, the average ratio indicating similarity between human subjects decisions and the output of our algorithms is significantly higher than 33%. The total number of subjects' answers similar to the *relevance* algorithm (n=29) averaged 71.3% (s=10.7%), the *desirability* algorithm (n=35) averaged 77.8% (s=15.0%), the *expectedness* algorithm (n=33) averaged 78.5% (s=12.0%), and the *controllability* algorithm (n=33) averaged 74.3% (s=15.8%). It is worth noting that the human subjects agreed 100% on some questions, while on some other questions there was a much lower level of agreement. Our results indicate that people largely performed as our hypothesis predicted. The p-values obtained based on a one-tailed z-test (see Table 1) show the probability of human subjects' answers being generated from a random set. The very small p-values indicate that the data set is not random; in fact, the high percentage of similarity confirms our hypothesis and shows that the algorithms can help us to model appraisal in a collaboration.

> Imagine you have pressed the two slices of bread (one covered with strawberry jam and one covered with peanut butter) together and passed it to Mary. Which of the following two actions is **more expected**?
>
> A. Mary puts the given sandwich into a zip lock bag after cutting it in half.
>
> B. Mary puts some pickles on another slice of bread.
>
> C. Equally expected.

Fig. 5: Example Expectedness Question.

Each question was designed based on different factors that we use in our algorithms (see Section 5.2). Here, we present four example questions from the expectedness, controllability, desirability, and relevance questionnaires, and describe how each question relates to a specific factor within the corresponding algorithm. The input for our algorithms was the task model depicted in Fig. 4.

Fig. 5 shows the example question from the expectedness questionnaire. In this example, with respect to Algorithm 3 (line 6), option A is more expected because the task related to this option provides the next available task in the focus stack (see the task model in Fig. 4). Although the task in option B is part of the existing task model, it is considered as unexpected by our algorithm, since it is not live in the plan. We provided option C to determine whether the human subjects will similarly differentiate between these two options. This question was presented to the human subjects to determine whether their decision for the expectedness of this event is similar to the output of the expectedness algorithm. For this question, the human decision was 97% similar to the algorithm's output. Average results for the expectedness questionnaire are presented in Table 1.

> Imagine you want to make a peanut butter sandwich. Which of the following two actions is **more controllable**?
>
> A. You can spread the peanut butter on one slice of bread and you need Mary to spread strawberry jam on the second slice of bread.
>
> B. You can spread the peanut butter on one slice of bread and strawberry jam on the second slice of bread.
>
> C. Equally controllable.

Fig. 6: Example Controllability Question.

Fig. 6 shows an example question from the controllability questionnaire. The algorithm's output is option B, and is determined by Algorithm 4 (line 3), similarly to the expectedness example above. In this example, option B is more controllable than option A, because the self over total ratio of the responsibility of the predecessors of the given task (see *Autonomy* in Section 5.2.4) is higher than the ratio in option A; i.e., self is responsible to spread peanut butter on one slice of bread and strawberry jam on another slice of bread. In this question, the humans decision was 90% in agreement with the algorithm's output.

Fig. 7 shows an example question from the desirability questionnaire. The output based on the Algorithm 2 (line 14) is option C, since in both option A and option B, the focus goal has been achieved successfully. Therefore, in this example, both options A and B are desirable. The humans' decision was 77% in agreement with the algorithm's output in this question.

Which of the following two actions is **more desirable**?

A. Imagine you pressed two slices of bread together with peanut butter and strawberry jam on them, and passed them to Mary. Mary cuts the peanut butter sandwich in half and puts them in the zip lock bag.

B. Imagine you want to make the egg sandwich. You have sliced the eggs, put them on one slice of bread, salted them, and waiting for Mary to put some pickles on your eggs. Mary puts some pickles on your eggs.

C. Equally desirable.

Fig. 7: Example Desirability Question.

In the example shown in Fig. 8, with respect to Algorithm 1, option A is relevant because of Mary's perceived negative emotion (see Equation 1). Although option B is relevant (since it achieves the next goal in the shared plan), 83% of subjects consider it as less relevant than option A; we believe this is due to the effect of Mary's perceived negative emotion which also generates a higher utility value in our relevance algorithm. Another question also tested belief saliency. However, the options provided only related to the shared plan (i.e., no human emotions in the options). In this case 87% of subjects chose the option that accomplished the next goal in the shared plan. Interestingly, when confronted with a negative emotion from their collaborator, human subjects deviated from the shared plan and found their collaborator's emotion more relevant than the original plan. It is noteworthy that in both the absence and the presence of emotions the human subjects chose the more salient option with respect to our definition of saliency, which was not referenced or provided in the questionnaire.

Imagine you have made the peanut butter sandwich and passed it to Mary to cut it in half. Which of the following two actions is **more relevant**?

A. Mary starts crying since she cut her finger with a knife.

B. You begin to boil the water to boil the eggs for your second sandwich.

C. Equally relevant.

Fig. 8: Example Relevance Question.

Furthermore, as we mentioned earlier, there were two questions related to each factor in our algorithms. Because each question was asking about a specific factor, we were able to perform a sensitivity analysis, similar to the saliency example presented above. We observed similar results for other factors for all four variables.

7 Conclusion and Future Work

There is a correspondence between what a collaboration needs and the social functions of emotions. In this paper, we presented a theory explaining the processes underlying collaboration using social emotions. We provided four hypothetical examples in two pairs, each dealing with an important collaborative behavior. The first pair was about agreeing on a shared goal; the second pair was about delegation of a new task. Each pair of examples contrasted a successful collaboration, due to the Robot's awareness of the Astronaut's emotion, with a failure in collaboration, due to the Robot's ignorance of the Astronaut's emotions. These examples illustrated the importance of emotional awareness to attain successful collaborative behavior.

We then introduced the main components of Affective Motivational Collaboration Theory, our computational framework which integrates emotion-regulated mechanisms, such as appraisal and coping, with collaboration processes, such as planning, in a single unified framework. This framework will let us explain the collaborative processes in computational detail.

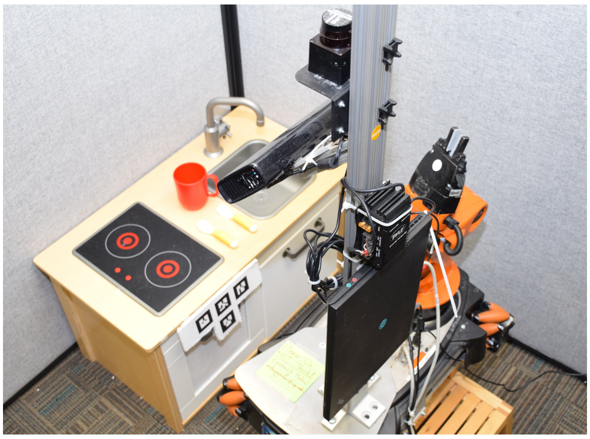

Fig. 9: Setting of the robot in a mock kitchen environment.

As shown in this paper, there are factors involved in appraisal processes that are not accounted for in existing appraisal models. These factors, including the influence of the human collaborator's emotions must be addressed to provide proper collaborative behavior in a robot. The SharedPlans theory and other computational collaboration theories (e.g., Joint Intentions) emphasize the importance of commitment in collaboration. According to these theories collaborators are required to commit to their shared plan or intentions to successfully collaborate and achieve a shared goal. This commitment requires them to appraise their environment based on the shared plan structure, as well as other information that is induced by the collaboration process, such as the recurrence of a belief by the other collaborator and the human collaborator's perceived emotion. In our next step, we want to test our appraisal algorithms and their reciprocal influence on goal management [64] during collaboration. This study will be conducted between a KUKA youbot (see Fig. 9) and human subjects on a different task model.

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