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Toward Improving Human-Robot Collaboration with Emotional Awareness

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Abstract ...

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1 Introduction

- The importance of understanding collaboration.
- The importance of understanding underlying processes of the collaboration process.

2 Example Scenario

2.1 The Backstory

The scenario transpires in a NASA's research center. Light, temperature and other environmental factors are simulated based on conditions on the surface of the moon. The mission is to finish installing the required solar panels to provide energy for the operation of NASA's science lab on the moon. Ninety percent of these panels have already been installed. However, the operation is now faced with low batteries which forces everyone to be cautious about consuming energy. The astronaut is inspecting the working conditions in the

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field and planning the installation of the remaining panels in collaboration with the robot. He determines that the sun will cast shadows over the installation structure, leading to potential difficulties. The astronaut asks control base to go through the final checks of the robot and prepare it for the operation.

2.2 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 of their private and/or shared goals occurring 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 blocking 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 its communication skills to overcome these problems and to motivate the astronaut to propose alternative tasks. The following is part of an interaction between the astronaut and the robot during their collaboration on installing solar panels.

2.3 Agreeing on Shared Goal (Emotion-Awareness)

This and the next hypothetical examples show that agreeing on a shared goal requires the Robot to be aware of its collaborator's emotions (here, frustration). In this example, the Astronaut's first turn (A1), shows her verbally conveying her frustration with respect to the disfunctioning measurement tool for checking the quality of the installed panel. In return, the Robot's first turn (A2), as the crucial part of this interaction, shows the Robot perceiving the Astronaut's frustration and acknowledging that verbally.[1] Later on, in Section 4.1, we are going to show how the computational mechanisms, discussed in Section 3.1, are involved in this process. In other words, we are going to discuss how the emotion-driven goal-directed mechanisms can work together and lead the Robot's behavior to acknowledge perceived emotion of the Astronaut properly to avoid termination of the collaboration. Continuing in turn A3, the Astronaut's utterance shows the change of the underlying belief from termination of the collaboration to a belief showing the possibility of seeking instrumental support by asking the Robot whether it is possible 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 does not express a negative emotion (i.e., frustration), and she is asking for instrumental support, the Robot can provide the alternative task

[1] The underlined section of the Robot's utterances (in turn A2) shows the influence of using emotion-driven processes which leads to acknowledgement of the Astronaut's emotion. See the absence of these utterances as the consequence of ignoring the Astronaut's emotions in the same turn in the next example (Section 2.4).

as a potential solution. Here is another advantage of the emotion-awareness in this hypothetical example. Although, the Robot, according to the shared plan (see Sections 5.4 and 3.1), could provide the same alternative task as solution to the Astronaut, instead, it procrastinated providing the potential solution based on the Astronaut's negative emotional state, i.e., frustration. Finally, since agreeing on a shared goal is a collaborative negotiation process, emotion-awareness plays an imperative role in providing a more fair offer to the collaborator during negotiation. As a result, the Astronaut's response in the last turn (A5) shows the acceptance of the Robot's potential solution to continue collaboration and agreeing on the shared goal. In the next example we are going to show what happens to the same hypothetical example when the Robot ignores the Astronaut's emotion and tries to save the collaboration process from failure.

A1. Astronaut: Oh no! Finishing the quality check of our installation with this measurement problem is so frustrating. I think we should stop now!
[*Astronaut is frustrated.*]

A2. Robot: I see. This is frustrating. But, I can help you with the measurement tool and we can finish the task as originally planned.
[*Robot perceives Astronaut's frustration and acknowledges that.*]

A3. Astronaut: Can you fix the measurement tool?
[*Astronaut's emotion is neutral.*]

A4. Robot: The next task is fixing the panel and it needs you to prepare and attach the welding rod to your welding tool. To save our time, I will fetch another measurement tool while you are preparing your welding tool.
[*Robot perceives Astronaut's neutral emotion, and tries to negotiate and provide a fair offer.*]

A5. Astronaut: That would be great!
[*Astronaut is content.*]

2.4 Agreeing on Shared Goal (Emotion-Ignorance)

This example shows the same process of agreeing on a shared goal as previous one except that it diverges from reaching to an agreement, despite the fact that it begins with the same utterance (B1) as it appears in previous example (A1). As mentioned earlier in Section 2.3, the emotion-awareness is beneficial in collaboration by channeling the collaboration process towards the shared goal in the right direction. Without the emotion-awareness a collaborative Robot will try to maintain the status of the shared goal and prevent it from failure without considering its collaborator's negative emotion which can be a direct result of a type of task failure during collaboration. First, the emotion-ignorant Robot does not acknowledge the Astronaut's frustration (i.e., B2 in compare to A2 in Section 2.3), since it does not perceive that emotion. Then, while negotiating the shared goal the Robot fails to offer a potential solution based on the Astronaut's emotional state, resulting in the failure of the negotiation during collaboration.

In this example, the Robot is not capable of perceiving the Astronaut's emotion, thus it does not apply the Astronaut's emotion (i.e., frustration) as an influential factor in its computational mechanisms (see Section 3.1). Hence, in the Robot's first response to the Astronaut's utterances (B2), first it does not acknowledge the Astronaut' emotion, and second, it immidiately conveys two available alternative actions according to the existing shared plan (see Section 5.4) and asks the Astronaut to select between these two actions. [1] As it appears in the Astronaut's response, the Robot's immidiate proposal does not make any progress in collaboration. As a result, the Astronaut just repeats himself about the task status (B3) while still expresses 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 (B4). The Robot's utterance creates an ambiguious assumption for the Astronaut on 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 it also nullifies the Astronaut's assumption about fixing the disfunctional measurement tool and proposes the potentioal solution of replacing the broken tool and seeing whether the Astronaut agrees on that (B6). In B7, the Astronaut modifies its assumption and announces the shortage of time as justification of expressing her anger. At this point, the Robot's response becomes more crucial since its wrong way of interaction and emotion-ignorance behavior shift the Astronaut's emotional and mental states into a noncollaborative status. Consequently, again, the Robot wants to revive the collaboration process, therefore it provides more information about the repercussions of terminating the collaboration process and wants to see whether the Astronaut can pursue another task (B8). [2] Finally, the incorrect interaction of the Robot caused by its emotion-ignorance behaviors which was developed since the Robot's very first response, leads to an unsuccessful termination of their collaboration (B9).

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

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[1] Notice that the Robot's acknowledgement of the Astronaut's emotion is missing in B2 because of ignoring the Astronaut's emotion – see the Robot's same turn (A2) in Section 2.3. Also, notice (for the same reason) that the underlined uttrance in B2, reveals that the Robot requires the Astronaut's confirmation for the next step.

[2] Notice the underlined section of the Robot's turn B8 indicates its dissociated reasoning about the problem from the Astronaut's mental state.

[*Astronaut is frustrated.*]

B2. Robot: I can help you with the measurement tool, or we can terminate this task. What do you want me to do?
[*Robot does not perceive Astronaut's frustration.*]

B3. Astronaut: As I said the measurement tool does not work properly. We can not continue!
[*Astronaut is frustrated.*]

B4. Robot: Okay. Do you want me to fix this problem or terminate the task?
[*Robot does not perceive Astronaut's frustration.*]

B5. Astronaut: Can you fix my measurement tool?
[*Astronaut is frustrated, even more.*]

B6. Robot: I cannot fix your measurement tool, but I can fetch another one for you if you want?
[*Despite Astronaut's strong frustration, Robot tries to negotiate.*]

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

B8. Robot: Okay. You want me to terminate this task. Terminating this task can influence the quality of installing this solar panel which can cause the mission to fail. Or, do you want us to work on another task? This can help us to install the panel using your welding tool, but I do not know whether the quality of our installation will be acceptable.
[*Not only the Robot does not perceive Astronaut's anger, but also continues to negotiate the next step based on the shared plan to select proper action.*]

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

2.5 Delegation of a Task (Emotion-Awareness)

This and the next hypothetical examples as a completely different collaborative behaviors show how delegation of a task critically depends on understanding how worried the other collaborator is and the necessity of having sufficient time, which play together. This example shows when the Robot is aware of the Astronaut's worriedness, it can use its own motivation mechanism drived by emotions to come up with a way to alleviate that. Its methods are to exactly postpone any questions until such time as they are critical (effects are appeared in C2, C4). At the beginning of this example (C1), Astronaut is worried because of the lack of time in achieving the shared goal (finishing to install solar panels) for the overall task. She proposes the Robot to 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., worriedness) and using the same cognitive mechanisms (see Section 3.1) acknowledges the Astronuat's emotion just as it did in first example in Section 2.3. [1] As mentioned earlier, we are going to show step-by-step (see Sections 4.1 and 4.3) how different emotion-driven goal-directed mechanisms get invloved in each turn of the collaboration process to appropriately respond to the Astronaut based on the *Affective Motivational Collaboration Theory* (see Section 3.1). Continuing in this example, after acknowledging the Astronaut's emotion, the Robot infers that it needs to postpone asking questions about the missing parts of the shared plan (see Section 5.4) since installing a panel is a collaborative task and some of the primitive tasks need to be done by the Astronaut. Then, the Astronaut perceives the Robot's response as a proper acceptance of the task delegation and tries to communicate the status of her own, even though she is still worried about finishing the overall task (C3). Now, the Robot without asking the actual questions, declares the possibility of asking some follow-up questions whenever the Astronaut's answers are required to make progress in executing some primitive tasks while installing the second panel (C4). Here, the Robot not only prevents overwhelming the Astronaut with several questions related to executing the next steps in the future, but its utterance implicitly reveals its knowledge of tasks' requirements to the Astronaut. As a result, the Robot's appraoch on acceptance of the delegated task mitigates the Astronaut's negative emotion (i.e., worriedness) which makes her to respond possitively to the Robot's proposal. The next example explains the same hypothetical task delegation scenario except it shows the negative impact of missing the Astronaut's emotion on task delegation process.

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.
[*Astronaut is worried.*]

C2. Robot: Okay. Don't worry. I can handle that.
[*Robot perceives Astronaut's worriedness and acknowledges that. Also, it doesn't ask the Astronaut (because of perceiving worriedness) if it is okay to leave the current task which was helping the Astronaut to install the first panel.*]

[*Robot perceives the Astronaut's request as on open planning (as oppose to specific executive) task delegation.*]

C3. Astronaut: I will try to fix it asap.
[*Astronaut's is still worried.*]

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

[1] The underlined utterance in the Robot's turn C2, shows the Robot's awareness of the Astronaut's emotion.

[*Robot perceives Astronaut's worriedness.*]

[*Robot checks a) dependencies of the task (a sub-task might need to be done by both parties), b) preconditions, c) required resources, d) possible future conflicts.*]

[*Robot needs to ask several questions to remove uncertainties, but because of the Astronaut's emotion, Robot decided to postpone questions about the details to when the Astronaut's answers are necessary to make progress. Robot modifies its utterance in a proper way.*]

C5. Astronaut: That's fine. Just let me know.
[*Astronaut is neutral.*]

2.6 Delegation of a Task (Emotion-Ignorance)

This last hypothetical example is also about task delegation (similar to the example in Section 2.5) and it shows how ignoring the collaborator's emotions in task delegation procedure can impact the progress of a collaboration. In this example, the emotion-ignorant Robot is doing planning in its most efficient manner (efficient because time is short): asking a lot of questions (see utterances in D2, D4, D6, D8, D10) 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.

As it is shown, the very first utterance of the Astronaut (D1) is the same as the first utterance in previous example (C1). The Astronaut is worried and expresses her worry. However, the Robot is not capable of perceiving and consequently acknowledging the Astronaut's emotion. As a result, the Robot responds to the Astronaut while the Astronaut's proposed task changes the Robot's focus of attention to a new task, and now, the Robot tries to determine a proper solution for an action selection problem. The reason that the Robot perceives the Astronaut's proposal as an 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 nonprimitive task (i.e., installing the second panel). Therefore, the Robot immediately tries to confirm leaving the current unfinished task (D2). Notice the absence of acknowledging the Astronaut's emotion by the Robot in this turn (compare C2 in Section 2.5 and D2 here). This vacancy of the emotional awareness is the beginning of the failure of the task delegaton process. As we can see, the Robot's response does not mitigate the Astronaut's worriedness about the future of the collaboration. [1] Next, the Astronaut tries to help the Robot to select the proper action by responsing possitively about the Robot leaving the current task (D3). Now, the Robot shifts its focus of attention

[1] The underlined section in D2 shows the Robot's need for confirmation of leaving an unfinished task.

to the new task and uses the Collaboration mechanism (see Section 3.1) to obtain required information such as task dependencies, existing preconditions and required resources as well as the existance of a plan. Subsequently, the absence of the required information and dependencies to the Astronaut's actions causes the Robot to ask a question about whether the Astronaut will be able to help in some parts of the task (D4). Although, the Robot's interactive behavior is crucial in many collaborative contexts, here it implies that the Astronaut's worriedness caused by the lack of time is ignored by the Robot. This ignorance of the Astronaut's emotional state influences her mental states and consequently her behavior. Thus, she succinctly responds to the Robot's question (D5). The Robot asks another question about the required inputs for the task which are dependent to the Astronaut without considering her worriedness (D6). At this point, since the Astronaut believes that the Robot's questions are unneccessary, she becomes frustrated and impatiently answers the Robot's question (D7). However, once again, not only the Robot misses the Astronaut's emotion, but it also uses a collaboration function (i.e., Reflection - see Section 3.1) to prevent failure of a task in the future based on reflection of the same task in similar situation in the past (D8). [1] Then, the Astronaut does not recall the event referenced by the Robot and since she is frustrated, she does not even try to remove the ambiguity of the existing issue (D9). Therefore, the Robot tries to see whether the Astronaut wants the Robot to clarify the issue for her by providing her some examples (D10). [2] At last, the Astronaut terminates the collaboration task because of the lack of time (D11).

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.
[*Astronaut is worried.*]

D2. Robot: Okay. I can handle that. Is it okay if I leave the current task though?
[*Robot does not perceive Astronaut's worriedness.*]

[*Robot perceives the Astronaut's request as on open planning (as oppose to specific executive) task delegation.*]

D3. Astronaut: Yes, that's fine. I can finish it by my own.
[*Astronaut is still worried.*]

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?
[*Robot does not perceive Astronaut's worriedness.*]

[*Robot checks a) dependencies of the task (a sub-task might need to be done by both parties), b) preconditions, c) required resources, d) possible future conflicts.*]

[1] Notice that the undelined section in D8 is the result of the Robot's inference about the possibility of a future problem.

[2] The underlined utterance in D10 indicates another situation in which the Robot misses the Astronaut's emotion.

[*Robot needs to ask several questions to remove uncertainties, so it does, since it misses the Astronaut's negative emotion.*]

D5. Astronaut: Yes, I will.
[*Astronaut is more worried about finishing the first panel.*]

D6. Robot: We also need your welding tool and supplies as well as the measuring tool to install the second panel.
[*Robot does not perceive Astronaut's worriedness. So, it continues to ask question.*]

D7. Astronaut: Just let me know whenever you need something!
[*Astronaut becomes frustrated, since he thinks the Robot's questions are killing time.*]

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. Last time this issue terminated our mission.
[*Not only the Robot does not perceive Astronaut's frustration, but also asks about some possible future problems based on reflection of the same tasks in the past.*]

D9. Astronaut: Robot, I really don't understand what you are talking about!
[*Astronaut becomes more frustrated.*]

D10. Robot: Do you want me to provide some examples?
[*Robot does not perceive Astronaut's strong frustration. So, it doesn't stop asking questions.*]

D11. Astronaut: We don't have time for this anymore!
[*Astronaut becomes angry.*]

3 Computational Framework

As we mentioned in Section 2, all provided examples in Sections 2.3 to 2.6 will be discussed in more detail using a computational theory which we call it the *Affective Motivational Collaboration Theory*. There are several mechanisms involved in our computational framework applying different concepts of the *Affective Motivational Collaboration Theory* to provide an emotion-regulated collaborative behavior for a robot. In this section, we are going to breifly describe all these mechanisms without elaborating the constructing processes involved in each mechanism since it is not in the scope of this paper. We also explain different types of associated mental states in our computational framework based on the *Affective Motivational Collaboration Theory*.

3.1 Affective Motivational Collaboration Theory

Affective Motivational Collaboration Theory is about the interpretation and prediction of the observable behaviors in a dyadic collaborative interaction.

The 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 self's relationship to the collaborative environment. These reactive and deliberative processes are triggered by two types of events: *external* events, such as the other's *utterances* and *primitive actions*, and *internal* events, comprising changes in the self's mental states, 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.

Emotion-regulated processes operate based on the self's mental states including the anticipated mental states of the other, generated according to the self's model of the other. These mental states include beliefs, intentions, goals, motives and emotion instances. Each of these mental states possesses multiple attributes impacting the relation between cognition and behavior or perception.

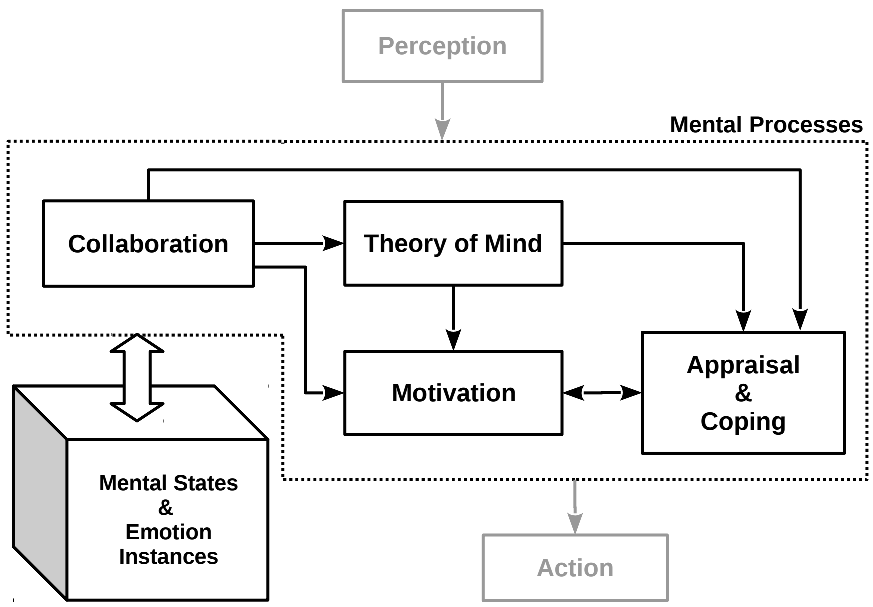

Fig. 1 Roadmap of *Affective Motivational Collaboration Theory* showing primary influences between processes.

There are several theories which describe the underlying structure of a collaboration based on mental states of the collaborators. The collaboration structure of *Affective Motivational Collaboration Theory* is based on the Shared-Plans theory [9]. *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.

3.2 Underlying Mechanisms

The *Affective Motivational Collaboration Model* consists of seven mechanisms (see Fig. 1) most of which directly store and fetch the data in the Mental States.

3.2.1 Collaboration Mechanism

The *Collaboration* mechanism (see Fig. 1) maintains constraints on actions. These constraints include constraints on task states and on the ordering of tasks. The Collaboration mechanism also provides processes to update and monitor the shared plan. These processes depend on the Appraisal mechanism to evaluate the current Mental States with respect to the current status of the collaboration. The self also shifts its focus of attention according to the outcome of the Appraisal mechanism. Moreover, the Collaboration mechanism can help the self to identify the failure of a task. The Appraisal and Motivation mechanisms provide interpretation of task failure and the formation of new Mental States (e.g. intentions) respectively. Ultimately, the Coping mechanism allows the self to perform behavior appropriate to the current state of the collaboration.

3.2.2 Appraisal & Coping Mechanism

The *Appraisal & Coping* mechanism (see Fig. 1) consists of the two processes of Appraisal and Coping. The Appraisal mechanism is responsible for evaluating changes in the self's Mental States, the anticipated Mental States of the other, and the state of the collaboration environment. Consequently, the Appraisal mechanism (Fig. 1) is connected to a) the Theory of Mind mechanism, to serve as an evaluator whenever the self applies the Appraisal mechanism in reverse appraisal [8], b) the Collaboration mechanism, to interpret the progress and changes in the collaboration plan and associated Mental States, c) the Motivation mechanism, to generate and assess the self's new goal-driven motives whenever a new motive or intention is required, e.g., following the failure of a task, and d) the Perception mechanism, to interpret the external events from the collaboration environment. The Coping mechanism provides the self with different coping strategies associated with changes in the self's mental states with respect to the state of the collaboration. In other words, the Coping mechanism produces cognitive responses based on the appraisal patterns.

3.2.3 Motivation Mechanism

The *Motivation* mechanism (see Fig. 1) operates whenever the self a) requires a new motive to overcome an internal impasse in an ongoing task, or b) wants to provide an external motive to the other when the other faces a problem in a task. In both cases, the Motivation mechanism uses the Appraisal mechanism to compute attributes of the competing motives. Also, the Motivation mechanism can serve the Theory of Mind mechanism by helping the self to infer the motive behind the other's current action. Moreover, if there is an impasse in accomplishing a collaborative task, the self requires a new intention to take a new action no matter whether the self or the other is responsible for the task. In this case, the Motivation mechanism applies the beliefs associated with the blocked task as well as the Appraisal mechanism to generate and compare a new set of motives related to the status of the collaboration. Only one of these competing motives is most likely to become a new intention. The Motivation mechanism forms a new belief and ultimately a new intention based on the winning motive. As a result, the self can take an action based on the new intention to sustain the collaboration progress.

3.2.4 Theory of Mind Mechanism

The *Theory of Mind* mechanism (see Fig. 1) is the mechanism of inferring a model of the other's anticipated Mental States. The self will progressively update this model during the collaboration. The refinement of this model helps the self to anticipate the other's mental state more accurately, which ultimately impacts the quality of the collaboration and the achievement of the shared goal. Furthermore, the self can make inferences about the motive (or intention) behind the other's actions using the Motivation mechanism. This inference helps the self to update its own beliefs about the other's mental state. In the reverse appraisal process, the self also applies the Appraisal mechanism together with updated beliefs about the other's Mental States to make inferences about the other's current mental state based on the other'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 self's model of the other will update the self's mental state.

3.3 Mental States & Emotion Instances

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

3.3.1 Beliefs

Beliefs are a crucial part of the Mental States. I have two different perspectives on categorization of beliefs. In one perspective, I categorize beliefs based on whether they are shared or not between the collaborators. The SharedPlans [13] theory is the foundation of this categorization in which for any given proposition the agent may have: a) private beliefs (the agent believes the human does not know these), b) the inferred beliefs of the human (the agent believes the human collaborator has these beliefs), and c) mutual beliefs (the agent believes both the self and the human have these same beliefs and both of them believe that). From another perspective, I categorize beliefs based on who or what they are about. In this categorization, beliefs can be about the self, the other, or they can be about the environment. Beliefs about the environment can be about internal events, such as outcomes of a new appraisal or a new motivate, or external events such as the human's offer, question or request, and general beliefs about the environment in which the agent is situated. Beliefs can be created and updated by different processes. They also affect how these processes function as time passes.

3.3.2 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 human collaborator, c) formation of beliefs about self and anticipated beliefs about the other, and d) behavior selection in the Coping mechanism. First, taking actions means that the agent will intend to take an action for primitive tasks that have gained the focus of attention, possess active motives, 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 agent 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. And lastly, intentions are involved in selecting intention-related strategies, e.g., planning, seeking instrumental support and procrastination, which these strategies are an essential category of the strategies in the Coping mechanism. 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.

3.3.3 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 agent according to: a) its own emotional states (how the agent feels about something), b) its own private goal (how an action helps the agent to make progress),

c) the collaboration goal (how an action helps to achieve the shared goal), and d) other's anticipated beliefs (how an action helps the other). Motives also possess a set of attributes, e.g., *Insistence* or *Failure Disruptiveness*. These attributes are involved in comparison of newly generated motives based on the current state of the collaboration. Ultimately, the agent forms or updates a belief about the winning motive in the Mental States.

3.3.4 Goals

Goals help the agent to create and update its collaboration plan according to the current private and shared goal content and structure, i.e., the *Specificity, Proximity* and *Difficulty* of the goal. 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. The *Specificity* of goals has two functions for the agent. First, it defines the performance standard for evaluating the progress and quality of the collaboration. Second, it serves the agent 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 people motivated to attempt what they believe are impossible goals.

3.3.5 Emotions

Emotions in Mental States are emotion instances that are elicited by the Appraisal mechanism. The agent also keeps beliefs about these emotion instances in the Mental States. The Belief Formation mechanism creates or updates these beliefs about emotions. These emotion instances include the agent's own emotions as well as the anticipated emotions of the other which are created with the help of the processes in the Theory of Mind mechanism.

4 Walk Through Computational Examples

In this section, we are going to discuss how the individual computational mechanisms (see Section 3.2) are involved in generating the Robot's collaborative behaviors discussed in each example in Section 2. The following four walk through examples are in the same order as the four examples in Section 2. Notice that in emotional ignorance examples, we use the same mechanisms as in the emotional awareness examples. These examples can demonstrate the applicability of the *Affective Motivational Collaboration Theory* in modelling and understanding of the emotion-regulated underlying processes of a collaboration procedure.

4.1 Agreeing on Shared Goal (Emotion-Awareness)

4.2 Agreeing on Shared Goal (Emotion-Ignorance)

4.3 Delegation of a Task (Emotion-Awareness)

4.4 Delegation of a Task (Emotion-Ignorance)

5 Related Work

5.1 Emotions in Social Context

5.2 Social Functions of Emotions

5.3 Affect and Motives

5.4 Collaboration Theories

The prominent collaboration theories are mostly based on plans and joint intentions [6,13,14], and they were derived from the BDI paradigm developed by Bratman [2] which is fundamentally reliant on folk psychology [19]. The two theories, Joint Intentions [6] and SharedPlans [13], have been extensively used to examine and describe teamwork and collaboration.

The SharedPlans theory is based on the theories of Bratman and Pollack [4,17,18], who outline a mental-state view of plans in which having a plan is not just knowing how to do an action, but also having the intention to do the actions entailed. Bratman's views of intention goes back to the philosophical views of Anscombe [1] and Castañeda [5] about intention. Also, as Grosz and Sidner mention in [13] the natural segmentation of discourse reflects intentional behaviors in each segment. These intentions are designated as Discourse Segment Purposes (DSPs) which are the basic reasons for engaging in different segments of discourse. DSPs are a natural extension of Gricean intentions at the utterance level [16].

Cohen and Levesque also mention that in Joint Intentions theory their view of intention is primarily future-directed [7] which makes their view similar to Bratman's theory of intention [3], contra Searle [20].

The SharedPlans model of collaborative action, presented by Grosz and Sidner [11–13], aims to provide the theoretical foundations needed for building collaborative robots/agents [10]. SharedPlans is a general theory of collaborative planning that requires no notion of joint intentions, accommodates multi-level action decomposition hierarchies and allows the process of expanding and elaborating partial plans into full plans. SharedPlans theory explains how a group of agents can incrementally form and execute a shared plan that then guides and coordinates their activity towards the accomplishment of a shared goal. SharedPlans is rooted in the observation that collaborative plans are not simply a collection of individual plans, but rather a tight interleaving of mutual beliefs and intentions of different team members. In [12] Grosz and Kraus use first-order logic to present the formalization of SharedPlans.

Grosz and Sidner in [13] present a model of plans to account for how agents with partial knowledge collaborate in the construction of a domain plan. They are interested in the type of plans that underlie discourse in which the agents are collaborating in order to achieve a shared goal. They propose that agents are building a shared plan in which participants have a collection of beliefs and intentions about the actions in the plan. Agents have a library of how to do their actions, i.e. recipes. These recipes might be partially specified as to how an action is executed, or contributes to a goal. Then, each agent communicates their beliefs and intentions by making utterances about what actions they can contribute to the shared plan. This communication leads to the construction of a shared plan, and ultimately termination of the collaboration with each agent mutually believing that there exists one agent who is going to execute an action in the plan, and the fact that that agent has intention to perform the action, and that each action in the plan contributes to the goal [13,15].

6 Conclusion and Future Work

- Talking about other examples that I have.

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