CHAPTER 3
AFFECTIVE MOTIVATIONAL COLLABORATION THEORY

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.

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.

There is also a communicative aspect of emotions. For instance, emotions are often intended to convey information to others [85]. 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 [189]. The interpretation of these relational meanings are handled by the appraisal of events. Appraisal processes give us a way to view emotion as social [259]. 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 [156]. 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.

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. These observable behaviors represent the outcome of processes related to the interpretation of the self's relation-

ship to the collaborative environment. These processes are triggered by the events occurring in the collaboration environment. Therefore, *Affective Motivational Collaboration Theory* explains how emotions regulate the underlying processes in the occurrence of events during collaboration.

Emotion-regulated processes operate based on the self's mental states including the anticipated mental states of the other. These mental states include beliefs, intentions, goals, motives and emotion instances. Each of these mental states possesses multiple attributes impacting the underlying processes of collaboration and ultimately the relation between cognition and behavior of the agent. The nature of these attributes will be discussed in Section 3.5.

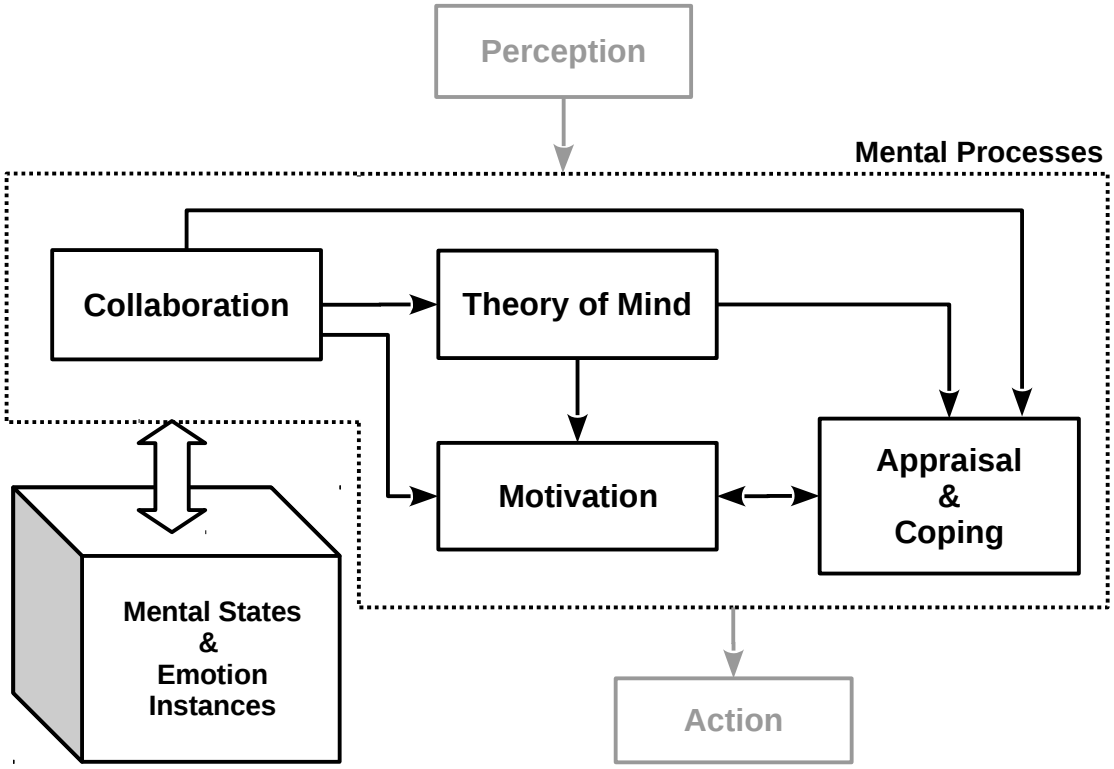

Figure 3.1: Roadmap of *Affective Motivational Collaboration Theory* showing primary influences between processes.

There are several theories discussed in Chapter 2, 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 SharedPlans theory [96]. *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 agents/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 *Appraisal & Coping* mechanism (see Figure 3.1) 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 is connected to a) the Theory of Mind mechanism, to serve as an evaluator whenever the self applies the Appraisal mechanism to the mental states attributed to the human collaborator, b) the Collaboration mechanism, to interpret the progress and changes in the collaboration plan and associated Mental States, and to make changes to the shared plan if required, 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 by forming new intentions based on the appraisal patterns.

The *Motivation* mechanism (Figure 3.1) provides motives to influence the coping process in terms of the collaborative agent's or the human collaborator's needs. The Motivation mechanism uses the Appraisal mechanism to compute attributes (see Section 3.5) 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, the Motivation mechanism applies the beliefs associated with the Appraisal mechanism to generate and compare a new set of motives related to the status of the collaboration. The outcome of the Motivation mechanism is involved in forming a new intention to cope with the current event.

As a result, the self can take an action based on the new intention to sustain the collaboration progress.

The *Theory of Mind* mechanism (Figure 3.1) 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.

The Collaboration mechanism 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.

3.1 Example Scenario

We now provide the following scenario in a robotic domain to draw your attention to the collaborative interactions. In the scenario, there is a mission specialist astronaut, who has had a high success rate in accomplishing space missions. She is capable of operating the manipulator system and supporting equipment. She works as a commander in the field during the operation. She is focused, organized, mentally stable, curious and patient. She is trained to collaborate with special-purpose field operation robots.

There is also a robot which is assigned to the mission to provide services to the astronaut. It has been tested in extreme environmental conditions and has a very low failure rate. It is capable of communicating with the astronaut and understanding the astronaut's nonverbal behavior. It has the ability to identify and assess its own emotions and those of the astronaut.

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.

1. ***Astronaut***: Please hold the panel on this structure.

   [*Robot holds the panel and Astronaut begins to work on the panel.*]

   [*Both the Robot and the Astronaut continue their collaboration to achieve their*

shared goal.]

2. ***Astronaut***: At this point you should be careful how you hold the panel. Turn the right side 45 degrees towards me.

3. ***Robot***: Is this what you want?

4. ***Astronaut***: Yes, do not move it.

   [*Astronaut finishes fixing the panel onto the structure and checks the connectors to make sure they are working.*]

5. ***Astronaut***: The connectors on this panel have problems and we might not be able to finish this task.

6. ***Robot***: Don't worry! I can replace the connectors in 4 minutes. We definitely can finish this task after that.

7. ***Astronaut***: Okay, go ahead and fix the connectors.

   [*Robot fixes the issue with the connectors and passes them to the Astronaut. Astronaut connects the wires to the connectors.*]

8. ***Astronaut***: I need you to begin welding this panel and also prepare the measurement tool for me.

9. ***Robot***: Do you want me to prepare the measurement tool first? Then, I can begin welding afterwards.

10. ***Astronaut***: Yes, that's fine!

    [*Astronaut waits for the Robot to weld the panel and prepare the measurement tool for him. Robot finishes the welding task after a long time, then prepares and passes the measurement tool to the Astronaut. But, the measurement tool has an accuracy problem.*]

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

12. ***Robot***: I see. But, I can help you with the measurement and we can finish the task as originally planned.

13. ***Astronaut***: That would be great!

    [*Robot helps the Astronaut to finish the measurement task with its own measurement tool.*]

    [*Then, the Robot goes back to its own internal goal, which is to fetch the second panel to finish the overall task.*]

3.2 General Argument

Affective Motivational Collaboration Theory focuses on emotion-regulated processes involved in collaboration and builds on two well-established theories in this context. The first is Grosz and Sidner's SharedPlans collaboration theory, which is based on the concepts of mutual belief and shared plans [96, 103]. Secondly, we build on the computational model of the appraisal theory of emotions by Marsella and Gratch [92, 90, 162, 163] which explains how emotions arise from an individual's interpretation of its relationship with the environment, and specifies the dimensions of appraisal and the appraisal patterns characteristic of different emotions [224].

Existing collaboration theories (including SharedPlans) consider the nature of a collaboration to be more than a set of individual acts. These theories argue for an essential distinction between a collaboration and a simple interaction or even a coordination in terms of commitments [96, 152]. We believe there is also a need for a computational theory to specify and characterize the underlying cognitive processes of collaborative activities. The study of these cognitive processes helps explain why and how humans collaborate with each other. For instance, SharedPlans theory can describe our scenario in Section 3.1 in terms of fundamental Mental

States, such as mutual beliefs, intentions, and shared plans. However, it does not describe the underlying processes leading to these Mental States. *Affective Motivational Collaboration Theory* extends the SharedPlans theory by describing these processes. Furthermore, emotions, due to their evaluative and regulatory nature, provide fundamental functions (see Section 3.3.6) each of which plays an essential role in maintaining a collaboration's structure and status. In other words, these functions explain the dynamics of a collaboration structure.

Affective Motivational Collaboration Theory specifies the processes involved in the progress of a collaboration and how they impact the collaboration's underlying structure. For example in the exchange below, the Robot in order to respond appropriately to the Astronaut's requests, needs to maintain its relationship with the new situation in the environment. Different emotion functions such as adaptation, goal management and attentional focus are involved in such situations:

8. ***Astronaut***: I need you to begin welding this panel and also prepare the measurement tool for me.

9. ***Robot***: Do you want me to prepare the measurement tool first? Then, I can begin welding afterwards.

What is the nature of the processes involved in a collaboration? For example in the exchange below, the Robot changes its focus of attention to something important to the Astronaut because of its perception of the Astronaut's negative emotion:

5. ***Astronaut***: The connectors on this panel have problems and we might not be able to finish this task.

6. ***Robot***: Don't worry! I can replace the connectors in 4 minutes. We definitely can finish this task after that.

And, how do these processes impact the social characteristics of a collaboration?

For instance, in the exchange below, emotions and the Appraisal mechanism can influence self's awareness during collaboration:

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

12. ***Robot***: I see. But, I can help you with the measurement and we can finish the task as originally planned.

Finally, *Affective Motivational Collaboration Theory* incorporates motivation as an emotion-regulated and goal-driven mechanism, by which the self can form a new intention based on its own beliefs about self and the other, as well as the result of an Appraisal mechanism. In general, a new motive can be involved in formation of a new intention and the self can take a new action based on the new intention. The Motivation mechanism also connects the outcome of the Appraisal mechanism and the Collaboration mechanism by applying the self's belief structure and appraisal patterns. The result of this process generates a set of competing motives, each of which can influence the formation of self's intention. The self can store its own motives as well as the other's motives along with their corresponding attributes which can impact the Appraisal mechanism. In the following example extracted from the scenario, the Astronaut informs the Robot of a new problem, and the Robot forms a new intention to solve the problem:

5. ***Astronaut***: The connectors on this panel have problems and we might not be able to finish this task.

6. ***Robot***: Don't worry! I can replace the connectors in 4 minutes. We definitely can finish this task after that.

As another example, the Astronaut faces a problem in his own task and informs the Robot of his decision. The Robot forms a new intention to help the Astronaut to overcome his problem and ultimately, make progress in their collaboration:

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

12. ***Robot***: I see. But, I can help you with the measurement and we can finish the task as originally planned.

3.3 Events

The *events* occurring in this collaborative environment include a) *utterances* spoken by the collaborators, b) *primitive actions* executed, deferred, or aborted, and c) observable *emotion instances*. These events are the events that our affective collaborative agent perceives. We will discuss below the operation of individual processes in our theory based on these events. Each of the following six sub-sections describe how an individual mechanism in Figure 3.1 handles the events.

3.3.1 Collaboration Mechanism and Events

The Collaboration mechanism is responsible for maintaining the internal structure of a collaboration, including the focus of attention, constraints on actions, updating the shared plan and, in general, monitoring the collaboration. All of these structures require updating each time the self perceives an external event. For instance, an utterance by the other can impact the self's focus of attention during the collaboration, or the effect of a primitive action can influence the self's view of an impasse on a task. As another example, the perception of the other's emotion instance can cause significant changes in the self's collaboration monitoring.

3.3.2 Appraisal Mechanism and Events

The other's *utterances*, the effect(s) of the collaborators' *primitive actions*, and the other's *emotion instances* (expressed nonverbally) are the three types of events perceived by the self during collaboration. The Appraisal mechanism receives the

output of the Perception and Collaboration mechanisms as well as the requisite Mental States related to the current event. It appraises the event, in terms of appraisal variables using the collaboration structure and the history of the self's related Mental States. The collaboration structure contains information about the collaboration's shared plan and the collaborators' shared goal, the temporal and the hierarchical constraints of the tasks, and the current focus of attention. Moreover, the self progressively generates and updates various types of Mental States (discussed in Section 3.5) during collaboration. The occurrence of a new event causes a change in the self's Mental States. The construct of the new mental state, e.g., beliefs, are semantically connected to the older ones. The Appraisal mechanism uses the history of the Mental States to consistently evaluate a new external event.

3.3.3 Coping with Events

Events do not directly cause the self's Coping mechanism to operate. Instead, it is the formation of Mental States that cause the Coping mechanism to choose an appropriate cognitive response to these events. The cognitive responses (also known as "coping strategies") are considered to act upon the self's relationship to the world and its own Mental States. Events also trigger other processes, which impact the self's Mental States. The changes in Mental States cause the Coping mechanism to provide consistent and appropriate cognitive responses to the world. For instance, suppose the self perceives an utterance and evaluates it in terms of the appraisal variables. The values of these variables and the corresponding emotion instances will cause new beliefs and intentions to be formed, which then cause the Coping mechanism to appropriately choose the self's behavior.

3.3.4 Motivation and Events

The Motivation mechanism acts to regulate the self's Mental States and goal-directed behaviors for internal and social purposes. The Appraisal mechanism eval-

uates the state of self, the environment, or the anticipated mental state of the other. In each of these cases, the outcome of the Appraisal mechanism might indicate the need for internal or behavioral regulation. In such cases, the Motivation mechanism uses the Mental States associated with the state of self, the environment or the other's anticipated Mental States as well as the pattern provided by the Appraisal process to generate motives aligned with private or shared goals. Thus, via the Appraisal mechanism the Motivation mechanism implicitly responds to the events. The attributes of the generated motives (see Section 3.5) will be updated every time a new event occurs. For instance, the Appraisal mechanism may evaluate the outcome of the current task as *unexpected, undesirable, uncontrollable* and *urgent* which is indicative of the failure of a task. Then, the Motivation mechanism provides goal-directed motives, each of which can influence the formation of an intention.

3.3.5 Theory of Mind and Events

Theory of Mind operates when an event occurs and the self wants to infer and interpret the other's mental state. Thus, Theory of Mind helps the self to choose the behavior best matched to the other's anticipated Mental States. The Theory of Mind mechanism infers the mental state of the other, which helps the self to update the user model of the other. The Motivation and the Appraisal mechanisms are also involved in this procedure. For instance, the self can infer the other's mental state through a reverse appraisal procedure. The Motivation mechanism includes another inverse procedure to infer the other's active motives, which can lead to inferring the other's goal, beliefs, motives and intentions.

3.3.6 Functions of Emotions

We have talked about the crucial role of emotions in communicating Mental States, motivating actions, and evaluating and interpreting internal states and the environment. Emotions, generally speaking, provide a set of intra- and interpersonal

functions which regulate internal processes and the self's relationship to the other during the collaboration. Emotions have meanings in a social context which can be interpreted by an observer. The self uses these emotion meanings to trigger appropriate emotion functions with respect to the current social context. Ultimately, the elicited emotion's functions impact the self's Mental States and consequently behaviors. In the rest of this section, we briefly describe how ten different emotion functions are related to the collaboration context. There are other emotion functions, such as learning and memory control, which are outside of the scope of this thesis. We have used some of the concepts behind these emotion functions such as goal management in our framework (see Chapter 4).

Action Selection

Action selection is the function in which emotion instances influence choosing the most appropriate action out of a repertoire of possible actions at a point in time. This function influences the Coping mechanism and results in consistency of the self's actions based on anticipated emotional responses of the other and the satisfaction of the shared goal.

Adaptation

Adaptation is the raison d'être of emotions. It helps the self to properly respond to changing challenges in a dyadic social context by adjusting its behavior. Adaptation is a specialized problem-solving technique implicating the necessity of the self's emotional states for short and long term behavior changes during collaboration.

Social Regulation

Social regulation by emotions is the process which enables the self to communicate internal Mental States through the expression of emotions in a social context. It can assist the self to regulate various social interactions required in the course of

a collaboration, such as conflict resolution and negotiation. Emotional expressions influence the other's behavior by triggering the other's inferential processes and emotional reactions [135].

Sensory Integration

Sensory integration can guide the self through the course of a collaboration by sustaining rich-sensory tasks to demonstrate more effective collaborative behaviors. It benefits the self by anticipating a certain type of inferential process to the other's mental and emotional states. For instance, perceiving fear in the other can lead to an increased focus of attention on the ongoing task, or discerning anger can raise the probability of avoiding current events (generated by the self) by the other.

Alarm

The alarm mechanism is a purely reactive and pattern-driven process [242]. It accounts for persuading the self that an undesired or unsatisfactory condition happened in the past, and since then, has persisted in the self's mental states. The alarm mechanism also provides the self with a rapid reaction to the external or the internal events. The self will be able to interrupt deliberative processes and show quick behavioral reactions. For instance, the self can consider corrective actions when a high probability of anticipated failure occurs during the collaboration.

Motivation

Motivation is a goal-driven emotion function associated with the self's behaviors. There is a motive behind every intentional action created by the Motivation mechanism. This motive is computed based on underlying beliefs relying on the evaluative role of emotions. Therefore, the motive behind any behavior carries an anticipated value of the future consequence for that behavior. It also reveals the belief foundation of a behavior. Consequently, the self can apply this function of emotions to a)

cope with certain types of problems, and b) infer the other's mental state based on each action.

Goal Management

The goal management function identifies the existence or the need for a high priority goal for the self. These goals include both private goals and shared goals. Emotions provide an evaluation mechanism for the self to choose or reprioritize goals at each point in time. This function of emotions can impact the self's behavior with respect to the dynamics of interaction during the course of a collaboration.

Attentional Focus

Emotion instances and the patterns generated by the Appraisal mechanism are directly linked to the attention mechanism of the self. Both positive and negative results of a cognitive evaluation of events can change, maintain, or intensify the self's focus of attention. For instance, negative emotions, e.g., fear or anger, can influence the self's focus of attention by orienting the self towards the events [76]. Positive emotions, e.g., happiness, can broaden or expand the self's focus of attention from details of the events to their general features [78].

Strategic Processing

The occurrence of new events can lead the self to rapid and/or strategic responses. The Coping mechanism contains various strategies associated with different components of the Mental States, e.g., belief or intention-related strategies. The content of the self's Mental States changes as time passes, which creates internal events causing the Coping mechanism to choose an appropriate action. The Appraisal mechanism allows the self to demonstrate a rapid response or strategically prioritize the current internal events generated based on the changes in the Mental States. For instance, is a mild, reactive facial expression an adequate response to the other's current ut-

terance or does the self need to show a stronger behavior? Is it the new belief about the current state of the collaboration, or is it the new intention pursuing the self's private goal that the self needs to cope with? Thus, appraisal patterns and emotion instances impact the self's strategic processing.

Self Model

Emotions can be a representation of how the self interprets the collaboration environment. The self can generate or update beliefs about its self-model when faced with unambiguous events and apply the same self-model when confronted with events possessing more ambiguity and uncertainty. Creating a self-model can also help the self to demonstrate more consistent and coherent behaviors when similar situations occur during the collaboration. This reliability in the self's behavior can help the other to predict the self's responses during collaboration.

3.4 Components of the Architecture

The *Affective Motivational Collaboration Model* consists of seven mechanisms (see Figure 3.1) most of which directly store and fetch the data in the Mental States. The Mental States will keep all the required data about the self (agent), other (human) and the environment (including events). In this section we exaplain each of the mechanisms and the Mental States.

3.4.1 Collaboration

- **Input:** The input to the *Collaboration* mechanism includes all the data that affects the execution of individual tasks in the collaboration plan. This data will be provided via the different elements of Mental States including beliefs, intentions and goals. These Mental States will establish the agent's initial plan and will be updated throughout the collaboration process by the Perception mechanism and other processes.

- **Output:** The output of *Collaboration* includes all the data that is modified or created during execution of a plan in the form of Mental States. These Mental States will be used by the internal processes in the Theory of Mind mechanism. Additionally, the Appraisal mechanism will use these Mental States to evaluate the events during collaboration. These Mental States also will be used by other processes, e.g. goal management, for the purpose of maintaining the collaboration.

- **Function:** The *Collaboration* mechanism will construct a hierarchy of tasks and also manage and maintain the constraints and other required details of the collaboration specified by the plan. These details include 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 (which can be used as an indication of an impasse or failure). *Collaboration* also keeps track of the focus of attention, which determines the salient objects, properties and relations at each point of the collaboration. Moreover, *Collaboration* has the ability to shift the focus of attention during the collaboration. All the other mechanisms in the overall *Affective Motivational Collaboration Model* are influenced by changes in the collaboration plan. The *Collaboration* mechanism in general performs various logical deductions required by other processes in our computational model. It is designed to ameliorate the shortcomings of the existing Collaboration theories by providing required inferences such as dynamic planning based on the recent changes in the collaboration environment and the internal changes in the agent's Mental States. For instance, in our scenario (see Section 3.1), when the Astronaut interrupts the Robot asking for a new and urgent task, the Robot needs to alter the collaboration plan to continue. *Collaboration* also supports essential monitoring processes during the collaboration such as event monitoring.

3.4.2 Appraisal

- **Input:** The most significant part of *Appraisal's* input data is based on the activity of the Collaboration mechanism. This data includes all the required Mental States associated with the Collaboration mechanism. For instance, the beliefs and their Strengths will be used by algorithms inside of *Appraisal* to compute the value of the appraisal variables. *Appraisal* also receives data from the Theory of Mind mechanism. This data helps the agent use *Appraisal* for inferring the human's intentions and motives based on a reverse appraisal procedure. The input data from the Perception mechanism is generally needed to support the evaluation of the events. The *Appraisal* mechanism also uses the information about the motives in the underlying processes.

- **Output:** The output of *Appraisal* can directly and indirectly impact other mechanisms. The Motivation mechanism uses this data to generate and maintain motives based on the current appraisal of the environment.

- **Function:** *Appraisal* is a subjective evaluation mechanism based on individual processes each of which computes the value of the appraisal variables used in our computational model. The Collaboration mechanism needs the evaluative assistance of the *Appraisal* mechanism for various reasons. The course of a collaboration is based on a full or a partial plan which needs to be updated as time passes and collaborators achieve, fail at or abandon a goal assigned to them. The failure to achieve a goal should not destroy the entire collaboration. Appraising the environment and the current events helps the agent to update the collaboration plan and avoid further critical failures during collaboration. *Appraisal* also helps the agent to have a better understanding of the human's behavior by making inferences based on appraisal variables. 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 States. For instance, there are beliefs about the appraisal of the self and the other that augment the model of what collaborators have done, and what and how they are planning to achieve the current shared goal based on their emotional states. This process will be discussed in more detail under the Motivation mechanism (see Section 3.4.4). Additionally, the beliefs formed based on the appraisals can impact other mechanisms such as the Theory of Mind, Motivation and Coping, essentially including the whole computational model.

3.4.3 Coping

- **Input:** The *Coping* mechanism operates based on the data stored in different aspects of the Mental States. This data includes changes in the agent's beliefs as well as the agent's intentions (whether they are created or altered during the collaboration), and the private or shared goals.

- **Output:** The output of the *Coping* mechanism is the data specifying the intention for a behavior which the agent needs to perform based on the current state of the collaboration.

- **Function:** The *Coping* mechanism is responsible for interpreting ongoing changes in the Mental States and adopting the appropriate behavior with respect to these changes. This component includes rules categorized into four coping strategies which are *Belief-related, Intention-related, Attention-related* and *Desires-related* strategies [162]. These rules will apply to the attributes and structures of the Mental States to cope with the internal changes as well as the demands of the environment. For example, the *Coping* mechanism will utilize certain beliefs about the self to regulate the agent's internal states, while using mutual beliefs to maintain progress in the existing collaboration. As another example, motives' attributes can guide the *Coping* mechanism by voting for a particular behavior.

3.4.4 Motivation

- **Input:** The most essential part of the input to *Motivation* is the Mental States, and more specifically the private and shared goals associated with the collaboration. *Motivation* also uses data from two other mechanisms, namely, Theory of Mind and Appraisal. Input from Theory of Mind is used by *Motivation* whenever new motives need to be generated or compared according to the shared goal. Input from Appraisal is used whenever the motive attributes are involved in the internal processes of the *Motivation*.

- **Output:** The output of *Motivation* includes the data required to form new intentions to reach the private or the shared goals. The motives which are the output of the *Motivation* mechanism are also used by the Coping mechanism to choose appropriate behavior according to the goals of the collaboration plan.

- **Function:** The *Motivation* mechanism works closely with the Appraisal mechanism. The purpose of this component is to generate new motives which will be added to the Mental States. These motives are generated based on what the agent believes about the environment including self and the other collaborator and the corresponding appraisals. The agent uses these motives to achieve a private or shared goal according to new conditions, to interact better with a human who needs social interactions, or to evaluate the success of task performances. The *Motivation* mechanism consists of several processes. These processes generate several motives with respect to the agent's current Mental States. Then, these motives will be used to make a decision to form an intention in the Coping mechanism.

3.4.5 Theory of Mind

- **Input:** *Theory of Mind* receives its input from the Mental States as well as the Collaboration and Perception mechanisms. This mechanism uses the current Mental States to infer the human's Mental States (which are simpler than the Mental States associated with self). The Collaboration mechanism provides the structure of the collaboration plan, including the constraints which can be used in the internal inference processes of *Theory of Mind*, such as reverse appraisal. The Perception mechanism also helps *Theory of Mind* with the input data from the sensory system.

- **Output:** The output of *Theory of Mind* will be stored in the Mental States. The Motivation mechanism can use this output to generate new motives according to the current state of the collaboration.

- **Function:** The agent uses the *Theory of Mind* mechanism to infer and attribute beliefs, intentions, motives and goals to its collaborator. The agent can also infer the Mental States of the human based on the reverse appraisals of the human's behavior. Another internal process of the *Theory of Mind* is inferring the human's motives on the basis of his behavior.

3.4.6 Perception

We consider the *Perception* mechanism only as a source of data to our computational model (see Figure 3.1). Thus, our computational model starts with high-level semantic representation of events (including utterances), i.e., Natural Language Processing is out of the scope of this work.

- **Output:** We will support the human side of the dialogues using predefined utterances for verbal communication with the agent. These utterances will be a part of the output data of the *Perception* mechanism. The output of the *Perception* mechanism will be given to the Collaboration, Theory of Mind and

Appraisal mechanisms. We will provide a unified perception representation across all of these mechanisms.

- **Function:** The *Perception* mechanism is responsible for producing the sensory information used by other processes in our model.

3.4.7 Action

We consider the *Action* mechanism only as a sink of data in our computational model (see Figure 3.1).

- **Input:** The input to the *Action* mechanism is provided by the Coping mechanism. This data will cause the *Action* mechanism to execute an appropriate behavior of the agent. This data has the same level of abstraction as the output of the Perception mechanism, i.e., it includes agent's utterances, primitive actions and emotional expressions.

- **Function:** The *Action* mechanism functions whenever the agent needs to show a proper behavior according to the result of the internal processes of the collaboration procedure.

3.4.8 Mental States

The Mental States shown in Figure 3.1 comprise the knowledge base required for all the mechanisms in the overall model.

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 they are shared between the collaborators. The SharedPlans [103] 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, we 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.

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, 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 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; these strategies are an essential category of the strategies in the Coping mechanism. Intentions possess a set of attributes, e.g. *Involvement, Certainty, Ambivalence* (see Section 3.5.4), 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 a solution for this concern.

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) the other's anticipated beliefs (how an action helps the other). Motives also possess a set of attributes, e.g., *Insistence* or *Failure Disruptiveness* (see Section 3.5.3). These attributes are involved in the 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.

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.

Emotions in Mental States are emotion instances that are elicited by the Appraisal mechanism (see Section 3.5.5 for list of emotion types used in this model).

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.

3.5 Attributes of Mental States

Mental states are conscious states of the mind providing the content for cognitive processes. As we discussed *Affective Motivational Collaboration Theory* operates with the following Mental States: beliefs, intentions, motives, goals and emotion instances. These Mental States possess attributes, each of which provides a discriminating and unique interpretation of the related cognitive entities. These Mental States' attributes are used in different cognitive processes such as the Appraisal mechanism and the Motivation mechanism. We provide more details about these attributes in this section.

3.5.1 Attributes of Beliefs

The attributes of a belief are involved within different processes in *Affective Motivational Collaboration Theory*. They impact the evaluation of an event by the Appraisal mechanism, generation of new motives, updates on the collaboration plan, activation of coping strategies and ultimately the self's behavior. The following six attributes of beliefs are most related to *Affective Motivational Collaboration Theory*.

- ***Strength:*** Belief strength is about how strong the self holds salient beliefs about an object, an entity, or an anticipated behavior. It can be measured through scales, for instance, how probable or likely that belief is, or just whether it is true or false. The strength of a belief can impact the self's appraisal processes, e.g. relevance (see Relevance algorithm in Chapter 4). A belief may be strong, but not necessarily accurate, and vice versa.

- ***Saliency:*** The saliency of a belief is a cognitive attribute that pertains to how easily the self becomes aware of a belief. This property of a belief has a prominent influence on the self's attention during collaboration. It directs the self's focus of attention to the most pertinent spatio-temporal salient event (see Relevance algorithm in Chapter 4).

- ***Persistence:*** It is argued that beliefs form and change due to cognitive and social considerations [42]. Persistent beliefs are very resistant to these changes. However, even persistent beliefs can change. Persistence of goal-related belief(s) influences the appraisal of the relevancy of an event (see Relevance algorithm in Chapter 4).

- ***Recency:*** The recency of a belief refers to how temporally close a particular belief is to the current state of collaboration. The recency attribute of the self's belief can bias (recency effect) the evaluation processes of the cognitive mechanism during collaboration. It can create a tendency to weight recent events more than earlier ones whenever it is required according to self's Mental States (see satisfaction drive in Chapter 4). The recency of a belief can ultimately impact adopting an appropriate Coping mechanism.

- ***Accuracy:*** Accuracy of a belief is the relation between that belief and the truth which that belief is about. The accuracy of a belief can be measured by looking at how closely that belief can relate to the truth. The accuracy of a belief as a gradational property can be used in evaluative processes of the self, i.e., Appraisal. It can also impact the self's other goal-driven processes and triggering of an emotion function.

- ***Frequency:*** The frequency of a belief is related to how regularly it appears as the result of the occurence of an event. The frequency of beliefs can impact attributes of the self's other Mental States. For instance, beliefs forming or maintaining intentions with direct experiences (see Section 3.5.4) are more

likely to occur frequently.

3.5.2 Attributes of Goals

The attributes of a goal impact the processes in *Affective Motivational Collaboration Theory*, especially the processes involved in Motivation and Appraisal mechanisms. The attributes of a goal are important because the Motivation and the Appraisal mechanisms in this theory are goal-driven and attribution of the goals according to the self's standards provides coherency of the processes and their outcomes. We discuss the three most relevant goal attributes in this section.

- ***Proximity:*** Goals can be distinguished by how far they project into the future during the collaboration. Proximal (short-term) goals result in more related motives and subsequently better self and social-regulation than temporally distant goals. Proximal goals can impact the self's behaviors by influencing the goal management process (see Section 4.4 in Chapter 4). As a result, the self can determine and maintain the collaboration progress towards the shared goal more accurately while operating based on proximal goals.

- ***Specificity:*** Goals incorporating specific performance standards are more likely to enhance the self's self-evaluation than general goals. Specific goals raise the self-evaluation performance because they provide a more accurate baseline for the mechanisms, e.g., Appraisal or Collaboration (see Section 4.4 in Chapter 4), or any arbitration process that the self needs for self-evaluation during collaboration. Consequently, by increasing the self-evaluation performance, the self can improve the level of satisfaction within the collaboration. As an example, holding an object A in a particular position with respect to an object B for a certain amount of time and welding them with a material C is a more specific goal than a general goal of installing an object on another one.

- ***Difficulty:*** Goals that are moderately difficult have the most impact on the self and social regulation processes of the self. Conversely, overly easy or impossible goals usually do not motivate an individual to achieve the goal. Difficult goals increase the probability of a motive's *failure disruptiveness*, and overly easy goals decrease the *importance* of the related motive; in both cases the goals have less chance to be pursued. The existence of a partial shared plan, dependency on the other to perform a task, the failure of the same or similar task in the past all increase the difficulty level of a goal. See Section 4.4 in Chapter 4 for the influence of difficulty of a goal on the goal management process.

3.5.3 Attributes of Motives

According to Sloman, motives can be compared on various dimensions [241]. This comparison is based on motive attributes. In *Affective Motivational Collaboration Theory* motives are formed based on the self's existing Mental States under the influence of the Appraisal mechanism. The existence of different Mental States, and the results of self appraisal as well as the reverse appraisal of the other can cause a variety of motives to be formed. The Motivation mechanism needs a set of attributes to compare newly generated motives and choose the one which is most related to the current state of the collaboration. We have chosen the following five motive attributes as most related to the collaboration context.

- ***Importance:*** The importance of a motive is determined by the corresponding beliefs about the effects of achieving or not achieving the associated goal (see Section 4.3.1 in Chapter 4). It is a function of belief attributes (e.g. saliency) and the current goal. For instance, if a motive is supported by a belief about the current goal with relatively high attribute values, that motive will become important for the self.

- ***Urgency:*** The urgency of a motive defines how much time the self has to

acknowledge and address that motive before it is too late. The urgency of a motive is a function of beliefs about the other's mental and emotional states (see Section 4.3.1 in Chapter 4). For instance, the self responds to an urgent motive due to the existence of an important anticipated outcome for the other, and limited time to accomplish the corresponding tasks, even if those tasks are not important for the self.

- ***Insistence:*** The insistence of a motive defines the "interrupt priority level" of the motive, and how much that motive can attract the self's focus of attention. This dimension of motive is associated with what the Appraisal mechanism considers as *relevance* and *desirability* when evaluating an event. Beliefs about successive subgoals and the other's anticipated Mental States influence the insistence attribute of a motive. Insistent motives have higher priority and are able to interrupt self's ongoing tasks.

- ***Intensity:*** The intensity of a motive determines how actively and vigorously that motive can help the self to pursue the goal if adopted. Motives with higher intensity will motivate the self to apply certain types of coping processes for an obstructed goal to avoid termination of the collaboration. Motives with higher intensity cause the self to find alternative solutions for the problem rather than abandoning the goal and ultimately the collaboration.

- ***Failure Disruptiveness:*** The failure disruptiveness attribute of a motive determines how disruptive failure is to achieving the corresponding goal. In other words, it gives the self a measure of the pleasantness of achieving a related goal. This attribute directs the self's behavior toward positive and negative outcomes during collaboration.

3.5.4 Attributes of Intentions

The attributes of an intention influence several processes in *Affective Motivational Collaboration Theory*. They can be involved in mechanisms such as Appraisal and Coping. One of the most important uses of intention attributes is to moderate the intention-behavior relations [59]. Ultimately, the self can show more consistent behavior with respect to its own preceding behaviors and current state of the collaboration. We decided to include the following five intention attributes extracted from the psychology literature in *Affective Motivational Collaboration Theory*.

- ***Temporal Status:*** The temporal status of an intention can be defined as the extent to which an intention remains consistent over time. The self needs to maintain the stability of its intentions as time passes until the task is performed. Temporally stable intentions helps the other to accurately predict the self's behavior. The anticipated cognitive load of perceiving the self's task by the other impacts the temporal stability of the self's intention. In other words, the temporal stability of an intention moderates the intention-behavior relation of the self during collaboration.

- ***Direct Experience:*** The direct experience of an intention refers to whether the self previously has performed a task based on a similar intention. The self can refer to the corresponding Mental States of the intention directly experienced in the past before taking a new action. The Mental States associated with the prior experience of an intention can influence the appraisal of a new event requiring the self to perform the same task. For instance, the existence of a direct experience of an intention can impact the degree of the *expectedness* and *controllability* of an event during the collaboration which ultimately guides the Coping mechanism to produce an appropriate behavior.

- ***Certainty:*** The certainty of an intention is determined by the quality of the underlying motive and the beliefs associated with that motive. The more

strong, accurate, frequent, recent, salient and *persistent* a set of pertinent beliefs of the self are, the more chance the related motive has to be selected. Since the certainty of an intention depends on the associated motive, the nature of the pursued goal also implicitly impacts the certainty of that intention. A goal with a higher *specificity* (see Section 3.5.2) value influences the certainty of the affiliated intention. The certainty of an intention is an important moderator of the self's intention-behavior consistency.

- ***Ambivalence:*** The Mental States of the self might contain contradictory intentions towards the pursuit of the same goal, which makes those intentions ambivalent. For instance, the self might already have an intention to perform a task according to the shared plan, while the Appraisal and the Motivation mechanisms dynamically cause formation of a new opposing intention. Furthermore, ambivalent intentions can occur because of the contrast between the self's private goal and the shared goal during the collaboration. The ambivalence attribute of an intention is inversely related to the intention-behavior consistency of the self.

- ***Affective-Deliberative Consistency:*** The self's intentions possess an affective and a deliberative component. The affective component refers to the emotion instance and in general the affective evaluation of the self's intention towards its own behavior. However, the deliberate component refers to the self's actual intention which is formed either based on the existing shared plan or under the influence of a new motive generated by the Motivation mechanism. For instance, as an example of affective-deliberative inconsistency, the self can appraise an event as an *urgent* and *uncontrollable* one (which leads the self's emotion towards anger), despite the fact that pursuing the goal related to this intention is required for the satisfaction of the shared plan. In general, mutually consistent affective and deliberate components of an intention positively impacts the consistency of the self's intention and behavior.

3.5.5 Emotion Instances

Each emotion has its own functionality in either an intrapersonal or interpersonal level. These emotions not only regulate the self's internal processes, but also assist the self to anticipate the other's Mental States. In this section, we provide the description of some of the emotions that can be elicited during collaboration, and are involved in our scenario (see Section 3.1). In this theory, to avoid the controversial issue of whether virtual agents or robots can feel emotions, we are going to use the convention of having emotions by the agent or the robot. The agent can also possess beliefs about an emotion instance which is similar to having beliefs about any other proposition.

- ***Joy:*** Joy is the state of an individual's well-being and is associated with the sense of successful achievement of a goal. Joy reveals one's sense of pleasure which implies an impending gain for the individual.

- ***Anger:*** Anger can be elicited by an unfair obstacle, hindering the individual's goal attainment and it is usually triggered by some external event (e.g., threat) which provokes a behavioral reaction. Anger functions to set boundaries or escape from dangerous situations, and implies an urgent desire for justice.

- ***Hope:*** Hope is the result of an optimistic evaluation of an event by an individual having expectations of positive and desirable future outcomes related to that event. It is usually a poignant assimilation of the present discontent and the future content implying an imagined or anticipated successful future goal state.

- ***Guilt:*** Guilt is based on self-condemnation in response to a negative outcome of one's self performance evaluation. It is caused by the violation of others' beliefs about the self, and others' standards and bearing significant responsibility for that violation. The occurrence of guilt usually implies the desire to atone in social context.

- ***Pride:*** Pride is a product of the satisfied sense of one's own actions or decision outcomes. It implies the self-approval of the evaluation oucomes of one's own actions. Pride is associated with the achievement motivation (see Section 2.5.2) wherein succeeding at a particular goal motivates the corresponding action.

- ***Shame:*** Shame is produced when one evaluates one's own actions or behaviors and attributes failure to oneself. The individual focuses on specific features of the self which led to failure. Shame implies the existence of remorse.

- ***Worry:*** Worry is one's emotional attempt to avoid anticipated potential threats or unidentified undesirable events. The individual's concern can be about a real or an imagined issue. Worry implies a fear of a future failure about which one should make a decision or take an action at present.