

Appraisal in Human-Robot Collaboration

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Abstract

We have investigated the mutual influence of affective and collaboration processes in a cognitive theory to support the interaction between humans and robots or virtual agents. We have developed new algorithms for appraisal processes, as part of a new overall computational model for implementing collaborative robots and agents. We build primarily on the *cognitive appraisal* theory of emotions (Gratch and Marsella 2004) and the *SharedPlans* theory (Grosz and Sidner 1990) of collaboration to investigate the structure, fundamental processes and functions of emotions in a collaboration.

Introduction

Ronald De Sousa in *The Rationality of Emotion* (Sousa 1990) makes a good case for the claim that humans are capable of rationality largely because they are creatures with emotions. The idea of having robots or other intelligent agents living in a human environment has been a persistent dream from science fiction books to artificial intelligence and robotics laboratories. Collaborative robots are becoming the complementary part of the humans' environment to accomplish their industrial and household tasks. In these environments humans are involved in robots' operations and decision making processes. This involvement of the humans influences the efficiency of the robots' interaction and performance, and makes them dependent to the humans' cognitive abilities and mental state.

Our work is part of a larger effort to build robots capable of generating and recognizing humans' emotions to be better collaborators. In this paper, we are reporting on specific problem of appraising events within a collaborative interaction. Our contribution is grounding the general appraisal concepts in the specific context and structure of collaboration. This work is part of the development of our framework based on our *Affective Motivational Collaboration Theory* which is built on the foundations of the *SharedPlans* theory of collaboration (Grosz and Sidner 1990) and the *cognitive appraisal* theory of emotions (Gratch and Marsella 2004).

In the rest of this paper, we are going to briefly introduce the Affective Motivational Collaboration Theory focusing on the collaboration and appraisal mechanisms as well as the mental states. We are also going to provide more details

about the graph representation of the robot's mental state. Finally, we describe our algorithms which we developed to process the value of four crucial appraisal variables as part of the appraisal mechanism in our framework.

Affective Motivational Collaboration Theory

Affective Motivational Collaboration Theory is about the interpretation and prediction of observable behaviors in a dyadic collaborative interaction. The theory focuses on the processes regulated by emotional states. The observable behaviors represent the outcome of reactive and deliberative processes related to the interpretation of the self's relationship to the collaborative environment. Affective Motivational Collaboration Theory aims to explain both rapid emotional reactions to events as well as slower, more deliberative responses. The 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. The theory explains how emotions regulate the underlying processes when these events occur during collaboration. It also elucidates the role of motives as goal-driven emotion-regulated constructs with which an agent can form new intentions to cope with events.

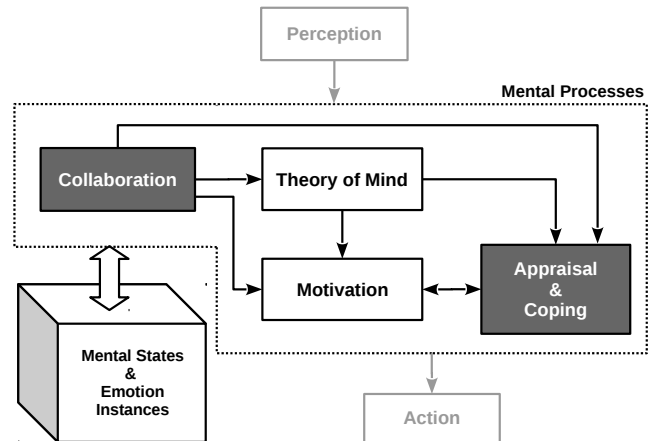


Figure 1: Computational framework based on Affective Motivational Collaboration Theory (arrows indicate primary influences between mechanisms).

Affective Motivational Collaboration Theory explains the functions of emotions in a dyadic collaboration and show how affective mechanisms can coordinate social interactions by enabling one to anticipate other's emotions, beliefs and intentions. Our focus is on the mechanisms depicted as mental processes in Figure 1 along with the mental states. The *Mental States* includes self's (robot's) beliefs, intentions, motives, goals and emotion instances as well as the anticipated Mental States of the other (human). The *Collaboration* mechanism maintains constraints on actions, including task states and the ordering of tasks. The *Collaboration* mechanism also provides processes to update and monitor the shared plan. 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. 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. The *Motivation* mechanism 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. The *Theory of Mind* mechanism is the mechanism that infers a model of the other's anticipated mental state. The self progressively updates this model during the collaboration.

Mental States

The Mental States shown in Figure 1 comprise the knowledge base required for all the mechanisms in the overall model. Mental states are conscious states of the mind providing the content for cognitive processes. 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. The self uses Mental States' attributes whenever there is an arbitration in the internal cognitive processes. We provide more details about the attributes of beliefs and motives in this paper, since they are used in our appraisal algorithms.

Belief: *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 or not between the collaborators. The SharedPlans (Grosz and Sidner 1990) 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 motive, 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.

The attributes of a belief are involved in arbitration procedures within different processes in Affective Motivational Collaboration Theory. They impact a range of these processes from, the formation of new beliefs, the evaluation of an external event by the Appraisal mechanism, generation of new motives, updates on collaboration plan, to the activation of coping strategies and ultimately the self's behavior. We use the following six attributes of beliefs in our framework.

- **Strength:** Belief strength is about how strong the self holds salient beliefs about an object, an entity, or an anticipated behavior.
- **Accuracy:** Accuracy of a belief is the relation between that belief and the truth which that belief is about.
- **Frequency:** The frequency of a belief is related to how regularly it appears as the result of an internal or an external event.
- **Recency:** The recency of a belief refers to how temporally close a particular belief is to the current state of collaboration.
- **Saliency:** The saliency of a belief is a cognitive attribute that pertains to how easily the self becomes aware of a belief.
- **Persistence:** It is argued that beliefs form and change due to cognitive and social considerations (Carley 1990). Persistent beliefs are very resistant to these changes.

Motive: *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 appraises the environment), 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). According to Sloman, motives can be compared on various dimensions (Sloman 1987). Motives possess a set of attributes. The Motivation mechanism compares motives based on the quality of these attributes and chooses the one which is the most related to the current state of the collaboration. We have the following five motive attributes in our framework.

- **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.
- **Importance:** The importance of a motive is determined by the corresponding beliefs about the effects of achieving or not achieving the associated goal.
- **Urgency:** The urgency of a motive defines how much time the self has to acknowledge and address that motive before it is too late.

- **Intensity:** The intensity of a motive determines how actively and vigorously that motive can help the self to pursue the goal if adopted; 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.

Intention: *Intentions* are mental constructs directed at future actions. They play an essential role in taking actions according to the collaboration plan as well as behavior selection in the Coping mechanism. 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. Intentions are also involved in selecting intention-related strategies, e.g., planning, seeking instrumental support and procrastination. Intentions possess a set of attributes, i.e., *Temporal Status*, *Direct Experience*, *Certainty*, *Ambivalence*, *Affective-Deliberative Consistency* which moderate the consistency between intention and behavior (Cooke and Sheeran 2004). The details about these attributes are out of this paper’s context.

Goal: *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). The details about goal’s attributes are also out of this paper’s context.

Emotion Instance: *Emotions* in Mental States are emotion instances that are elicited by the Appraisal mechanism, e.g., *Joy*, *Anger*, *Hope*, *Worry*. 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. Each emotion has its own functionality in either 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.

Example Scenario

The example scenario shows a very short part of an interaction between a robot and an astronaut during their collaboration. Their mission is to finish installing a few solar panels together. However, the astronaut encounters with a measurement tool problem:

Astronaut [turn t-1]: Oh no! Finishing the quality check of our installation with this measurement problem is so frustrating. I think we should stop now!

Robot [turn t]: I see. This is frustrating. But, I can help you with the measurement tool and we can finish the task as originally planned.

As shown, the robot in turn t, acknowledges the astronaut’s frustration and appropriately responds to her problem. We will use this example throughout this paper to clarify some of the concepts.

Collaboration

The Collaboration mechanism constructs a hierarchy of goals associated with tasks in the form of a Hierarchical Task Network (see Figure 2), and also manages and maintains 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 (i.e., whether the corresponding goal is achieved). 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 interaction.

The Collaboraiton mechanism receives the data that affects the execution of individual tasks in the collaboration plan. This data is provided via the different elements of Mental States including beliefs, intentions and goals. Collaboration mechanism generates the data that is modified or created during execution of a plan in the form of Mental States which will be used by other processes in our framework. For instance, the Appraisal mechanism uses these Mental States to evaluate the events during collaboration.

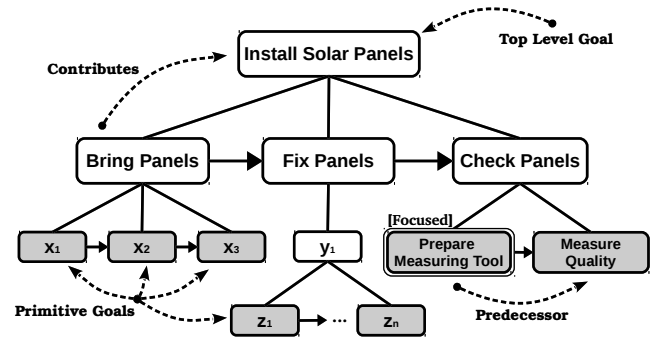


Figure 2: Collaboration structure.

In the followings, we briefly describe the methods which provide detail information about the collaboration structure, and are used in our algorithms to compute the values of appraisal variables.

- The *recognizeGoal()* method returns the unique goal to which the given event directly contributes irrespective of the event type (i.e., action, utterance, or emotional expression). If this method does not recognize a goal in the plan to which the event contributes, we consider the corresponding goal ambiguous in our processes.
- The *topLevelGoalStatus()* method returns the status of the top level goal whether it is *achieved*, *blocked* or *in progress*. In our example, “Install Solar Panels” is the top level goal (see Figure 2).
- The *currGoalStatus()* method returns the current goal status whether it is *achieved*, *blocked*, *unknown* or *in progress*. In our example, “Prepare Measurement Tool” is the current goal.

- The *precondStatus()* method returns the status of the precondition for the given goal whether it is *satisfied*, *unsatisfied* or *unknown*. For instance, the precondition for fixing a panel is whether the panel is appropriately located on its frame.
- The *doesContribute()* method returns whether the given goal contributes to another goal in the higher level of the plan hierarchy. For instance, an abstract (nonprimitive) goal of “Bring Panels” contributes to the higher level goal of “Install Solar Panels” (see Figure 2).
- The *extractContributingGoals()* method returns all the contributing goals of the given goal. For instance, as shown in Figure 2 the “Prepare Measuring Tool” and “Measure Quality” or two goals contributing to the “Check Panels” nonprimitive goal.
- The *extractPredecessors()* method returns the predecessors of the given goal. For instance, as shown in Figure 2, the “Prepare Measuring Tool” goal is the predecessor of another goal called “Measure Quality”.
- The *extractInputs()* method returns all the required inputs for the given goal. For example, the goal “Fix Panels” requires inputs such as the *welding tool* and the *panel*.
- The *isAvailable()* method returns whether the given input is available. For instance, if the *welding tool* is required for the goal “Fix Panels”, is it available now?
- The *isAchieved()* method returns whether the given goal is achieved. In other words, whether all the postconditions of the give goal are *satisfied*.
- The *isFocused()* method returns whether the given goal has the focus now. As shown in Figure 2, the goal “Prepare Measuring Tool” has the focus. The focused goal is the goal that the robot currently pursues to achieve.
- The *getResponsible()* method returns responsible agents of the given goal. In a dyadic collaboration, both of the agents can be partly responsible for a nonprimitive goal, while each agent is responsible for one or more primitive goal. For instance, both the robot and the astronaut are responsible for the nonprimitive goal of “Install Solar Panels”, whereas it is only the astronaut who is responsible for the primitive goal of “Prepare Measuring Tool”.

Appraisal Mechanism

Appraisal of External 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 external 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 current event. It appraises the external event, in terms of appraisal variables using, a) the collaboration structure, b) the social characteristics of collaboration, and c) 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.

The social characteristics of collaboration (see Section are conceptual properties associated with collaboration. These concepts provide deeper understanding of the collaborative interactions in terms of the underlying processes from both the personal and the social perspectives. Furthermore, these concepts determine when each process is used during a collaboration and why. Lastly, the self will progressively generate and update various types of Mental States during collaboration. The occurrence of a new external 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.

Appraisal of Internal Events

The formation of a *new belief* (one that has not already been evaluated by the Appraisal mechanism, such as a belief about a new motive), and the formation of a *new motive*, are the two types of internal events that will be evaluated by the Appraisal mechanism. Thus, the Appraisal mechanism is involved in the formation of a new belief to ultimately create balanced behaviors during the course of a collaboration. The Appraisal mechanism receives the output of the Theory of Mind and Motivation mechanisms as well as the available Mental States (e.g., beliefs about the current emotion instances of the self and the other) and evaluates the environment in terms of the appraisal variables whenever a new belief is generated. As mentioned in Section, a) the collaboration structure, b) the social characteristic of the collaboration, and c) the history of the self’s Mental States, are also crucial in the evaluation of internal events. The outcome of this appraisal process can result in a new belief about emotion instances, e.g. believing to have hope, or it can generate beliefs about different attributes of the Mental States of the self or the other.

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 is generally needed to support the evaluation of the events. The Motivation mechanism sends data to *Appraisal* whenever, for example, a new set of motives is being generated or the motive comparator wants to evaluate different motives for an arbitration procedure.

- **Output:** The output of *Appraisal* can directly and indirectly impact other mechanisms. The Motivation mechanism uses this data to generate, compare and monitor mo-

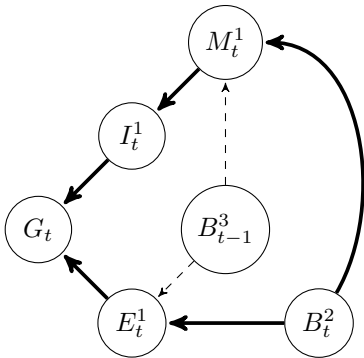
tives based on the current internal appraisal of the agent as well as the appraisal of the environment. This output data also assists the Belief Formation mechanism to create new beliefs about the current emotional state of the agent or the human as well as the corresponding appraisal of individual motives.

- **Function:** *Appraisal* is a subjective evaluation mechanism based on individual processes each of which computes the value of the appraisal variables used in my 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 task assigned to them. The failure of a task 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. 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.

Mental Graph

A graph illustration of mental state and a clear short and descriptive walkthrough example.

The *FINDPATH* function uses the Dijkstra algorithm to find the shortest path.



Appraisal Processes

All of the algorithms in this section use a mental graph which is a directed acyclic graph constructed based on the

mental states of the robot at each turn during the collaboration (see Section). They also use the content of the most recent event at each turn which includes the recognized goal associated with the event and the belief about the event. The goals can be associated with any type of event including action, utterance, or emotional expression.

We found four appraisal variables, i.e., *Relevance* (Algorithm 1), *Desirability* (Algorithm 2), *Expectedness* (Algorithm 3), and *Controllability* (Algorithm 4) to be the most important variables in a collaboration context. There are other appraisal variables introduced in psychological (Scherer, Schorr, and Johnstone 2001) and computational literature (Gratch and Marsella 2004); we do not provide algorithms for them in this paper. We believe most of these variables can be straightforwardly added to our appraisal mechanism later, e.g., *Perspective* (i.e., the view point from which an event is judged).

Relevance

Relevance as an appraisal variable measures the significance of an event for the robot. An event can be evaluated to be relevant if it has a positive utility or it can causally impact a state with a positive utility (Marsella and Gratch 2009). Relevance is an important appraisal variable since the other appraisal dimensions are only derived for the relevant events.

Algorithm 1 determines the relevance of the given event with respect to the shared goal. An event is *irrelevant* if there is no connection between the event and the current shared goal. If there is a connection, the relevance of the event will depend on the significance of the event with respect to the current collaboration status. The significance of an event is determined based on the utility of the event as it is also presented in (Gratch and Marsella 2004; Marsella and Gratch 2009). We believe although the utility of the event represents the significance of the event, the other collaborator's expressed emotion also plays a role by influencing the significance of the utility through a threshold. As a result, evaluating the relevance of the events can cause a collaborative robot to effectively respond only to the events which can positively impact the status of the shared goal without dedicating all other resources to every single event. The relevance process also benefits the information that the collaboration structure contains, e.g., shared goal.

The algorithm starts by taking the belief about the current event (b_{ε_t}) and the shared goal (g_t) associated with the current mental graph. After perceiving an event, it is the belief about that event which represents the event in robot's mental state. Continuing in line 3, the g_t represents the shared goal (in the mental graph) at time (turn) t within the shared plan. Then, we find the shortest path (\mathcal{P}) between the corresponding nodes of b_{ε_t} and g_t in the mental graph. As we mentioned earlier, if there is no path between the belief about the current event and the active shared goal, the algorithm finds the event *irrelevant* to the current shared goal, and terminates.

However, if there is a path between b_{ε_t} and g_t , we need a way to determine whether the event is relevant to the current collaboration status. Therefore, first, we compute the utility of the event (\mathcal{U}) such that ($0 \leq \mathcal{U} \leq 1$) based on the values

of the attributes associated with the belief about that event (b_{ε_t}), as well as the attributes of the motive within the path \mathcal{P} . Yet, the significance of an event in a collaborative environment not only is based on the utility of the event, but it is also influenced by the emotional state of the other collaborator. In other words, the relevance of a belief about an event is influenced by the perceived emotion of the human collaborator. The human's emotion influences the decision about the utility of the event in form of a threshold value (τ_t). For instance, a positive expressed emotion of the human reduces the threshold value which consequently makes the robot find an event relevant with even a slightly positive utility.

We compute this threshold value (τ_t) using a Fuzzy Logic system on a three-dimensional space of the somatic markers associated with the other's expressed emotion as they are described in (Breazeal 2002). In this space every emotion can be mapped to a vector of three values, i.e., *Arousal*, *Valence* and *Stance*. The details about this process is out of this paper's context. Finally, we make our decision about the relevance of an event with respect to the human's emotional state. Consequently, an event can be considered *irrelevant* even though there is a path between b_{ε_t} and g_t .

Algorithm 1 (Relevance)

```

1: function ISEVENTRELEVANT(MentalGraph  $\mathcal{G}_t$ , Event  $\varepsilon_t$ )

2:    $b_{\varepsilon_t} \leftarrow \text{GETBELIEF}(\varepsilon_t)$ 
3:    $g_t \leftarrow \text{currGoal}(\mathcal{G}_t)$ 

4:    $\mathcal{P} \leftarrow \text{FINDPATH}(b_{\varepsilon_t}, g_t)$ 

5:   if ( $\mathcal{P} = \emptyset$ ) then
6:     return IRRELEVANT
7:   else
8:      $\mathcal{U} \leftarrow \text{GETEVENTUTILITY}(b_{\varepsilon_t}, g_t)$ 
9:      $\tau_t \leftarrow \text{GETEMOTIONALTHRESHOLD}(\mathcal{G}_t)$ 
10:    if ( $\mathcal{U} \geq \tau_t$ ) then
11:      return RELEVANT
12:    else
13:      return IRRELEVANT

```

Desirability

Desirability characterizes the value of an event to the robot in terms of whether the event facilitates or thwarts the collaboration goal. Desirability captures the valence of an event with respect to the robot's preferences (Gratch and Marsella 2004). In a collaborative robot preferences are biased towards those events facilitating progress in the collaboration. An event is desirable if it somehow facilitates the state of the shared goal, or if it inhibits the state of a goal that is inconsistent with respect to the shared goal.

Desirability plays an important role in the overall architecture; it makes the processes involved in the other mechanisms (e.g., Motivation or Theory of Mind) and consequently the robot's mental state congruent with the collaboration status which is the robot's desire. Therefore, it causes the robot to dismiss events causing inconsistencies in the

Algorithm 2 (Desirability)

```

1: function ISEVENTDESIRABLE(MentalGraph  $\mathcal{G}_t$ , Event  $\varepsilon_t$ )

2:   if ( $\text{topLevelGoalStatus}() = \text{ACHIEVED}$ ) then
3:     return HIGHEST-DESIRABLE
4:   else if ( $\text{topLevelGoalStatus}() = \text{BLOCKED}$ ) then
5:     return HIGHEST-UNDESIRABLE
6:   else if ( $\text{topLevelGoalStatus}() = \text{INPROGRESS}$ ) then

7:     if ( $\text{currGoalStatus}() = \text{ACHIEVED}$ ) then
8:       return HIGH-DESIRABLE
9:     else if ( $\text{currGoalStatus}() = \text{BLOCKED}$ ) then
10:      return HIGH-UNDESIRABLE
11:    else if ( $\text{currGoalStatus}() = \text{INPROGRESS}$ ) then
12:      return MEDIUM-DESIRABLE
13:    else if ( $\text{currGoalStatus}() = \text{UNKNOWN}$ ) then

14:       $g_{\varepsilon_t} \leftarrow \text{recognizeGoal}(\varepsilon_t)$ 

15:      if ( $g_{\varepsilon_t} = \text{AMBIGUOUS}$ ) then
16:        return HIGH-UNDESIRABLE

17:      if ( $\text{precondStatus}(g_{\varepsilon_t}) = \text{SATISFIED}$ ) then
18:        return LOW-DESIRABLE
19:      else if ( $\text{precondStatus}(g_{\varepsilon_t}) = \text{UNSATISFIED}$ ) then
20:        return LOW-UNDESIRABLE
21:      else if ( $\text{precondStatus}(g_{\varepsilon_t}) = \text{UNKNOWN}$ ) then

22:         $g_t \leftarrow \text{currGoal}(\mathcal{G}_t)$ 

23:        if ( $\text{doesContribute}(g_{\varepsilon_t}, g_t)$ ) then
24:          return NEUTRAL
25:        else if ( $\neg \text{doesContribute}(g_{\varepsilon_t}, g_t)$ ) then
26:          return MEDIUM-UNDESIRABLE

```

robot's collaborative behavior. Moreover, desirability is also crucial from the collaboration's point of view. A collaborative robot needs to know whether its own and the other collaborator's actions, utterances, and emotional expressions are desirable in terms of their consistence with the status of the current shared goal. In other words, the collaboration mechanism uses the appraisal process of desirability to coordinate what the self or the other does, says, and expresses during collaboration. Reciprocally, the appraisal mechanism and in this case the desirability process use the collaboration structure to obtain their required information.

Algorithm 2 provides a process in which the desirability of an event is computed with regard to the status of the shared goal; i.e., it operates based on whether and how the event changes the status of the current shared goal. It receives the current mental graph, \mathcal{G}_t , and the current event, ε_t , from input, and decides whether and how the event is desirable or undesirable. First, the algorithm checks the status of the collaboration's top level goal (lines 2 to 6), and if the top level goal is still in progress, it continues by checking the status of the current shared goal (lines 7 to 13). If any of the top level and current shared goals are achieved in these two steps, the robot interprets the event as a desirable one. However, if any of these goals are blocked, the event will be considered undesirable by the robot.

The algorithm continues in the case of an unknown status of the current shared goal, and checks whether the precondition(s) of the associated goal with the current event, g_{ε_t} , are satisfied (lines 17 to 21). The robot prefers the satisfied preconditions and interprets the event as desirable while unsatisfied preconditions are undesirable for the robot. For instance, a satisfied precondition of a future goal is still desirable for the robot to some extent. Note that the robot also checks the ambiguity of the associated goal with the current event (line 15). An ambiguous goal is a goal which is not recognized in the robot's plan, and it is undesirable for the robot. After all, if the preconditions of the associated goal with the current event are unknown, the robot checks whether this goal, g_{ε_t} , contributes to the current shared goal, g_t (lines 22 to 25). As a result a contributing goal will obtain a neutral desirability in comparison with a noncontributing goal which will be undesirable for the robot.

Expectedness

Expectedness is the extent to which the truth value of a state could have been predicted from causal interpretation of an event (Marsella and Gratch 2009). In the collaboration context the expectedness of an event measures the congruency of the event with respect to the existing knowledge about the shared goal. Therefore, expected events are those of which beliefs about them are congruent to the status of the collaboration since their associated goals are expected with respect to the shared plan.

Expectedness underlies a collaborative robot's attention by evaluating the congruence of events with respect to the structure of an existing shared plan. Congruent beliefs in a robot's mental state will lead to more consistent and effective outcomes of the processes in the overall architecture. Therefore, a collaborative robot uses expectedness to

maintain its own mental state towards the shared goal. The robot will also be able to respond to unexpected but relevant events. As a result, the collaboration mechanism uses expectedness to maintain the robot's attention and subsequently its mental state with respect to the shared goal. In parallel, the appraisal mechanism uses the underlying information of the collaboration structure to evaluate the expectedness of an event.

Algorithm 3 (Expectedness)

```

1: function ISEVENTEXPECTED(MentalGraph  $\mathcal{G}_t$ , Event  $\varepsilon_t$ )
2:    $g_t \leftarrow \text{currGoal}(\mathcal{G}_t)$ 
3:    $g_{\varepsilon_t} \leftarrow \text{recognizeGoal}(\varepsilon_t)$ 
4:   if ( $g_{\varepsilon_t} = \text{AMBIGUOUS}$ ) then
5:     return UNEXPECTED
6:   if ( $g_t = g_{\varepsilon_t}$ ) then
7:     return EXPECTED
8:   else
9:     if ( $\neg \text{isAchieved}(g_t)$ ) then
10:      return UNEXPECTED
11:    else
12:      if ( $\neg \text{isAchieved}(g_t.\text{parent})$ ) then
13:        if ( $\text{doesContribute}(g_{\varepsilon_t}, g_t.\text{parent})$ ) then
14:          return EXPECTED
15:        else
16:          return UNEXPECTED
17:      else
18:        if ( $\text{doesContribute}(g_{\varepsilon_t}, g_t)$ ) then
19:          return EXPECTED
20:        else
21:          if ( $\text{isFocused}(g_{\varepsilon_t})$ ) then
22:            return EXPECTED
23:          else
24:            return UNEXPECTED

```

In algorithm 3 we provide the process of the expectedness based on the shared plan and status of the shared goal. The key point in this algorithm is the status of the current shared goal (g_t) and its relationship with the goal associated with the current event (g_{ε_t}). The algorithm receives the current mental graph, \mathcal{G}_t , and the current event, ε_t , from input, and decides whether the current event is expected.

First, we need to extract the goal in the current mental graph and the recognized goal associated with the current event. Similar to the desirability algorithm (Algorithm 2), we check whether the g_{ε_t} is ambiguous. In the case of ambiguity in g_{ε_t} , we consider the current event unexpected since an effective collaboration requires perceivable and unambiguous goals associated with the events. We continue by the comparison of the current shared goal and the recognized goal associated with the current event with respect to the shared plan. If these two goals are not the same, it is possible that the current shared goal is already achieved. The event will be unexpected (line 10) if the current shared goal is not achieved and the current event does not refer to the same

goal. However, if the current goal is achieved, it is important to see whether its parent is also achieved (line 12). This step is important because the event can be expected if the new goal contributes to the parent of the recently achieved goal. Therefore, if the parent goal in the hierarchical plan is not achieved, the contribution of the associated goal to the current event can help us to decide whether the event is expected (lines 12 to 16). However, if the parent goal is already achieved, the new goal can contribute (as a child) to the recently achieved shared goal, i.e., g_t , which is also expected (line 19). On the contrary, if the new goal does not contribute to g_t , it might be a goal in another branch in the shared plan which has received focus and should be achieved. In such a case, again, the event will be expected; otherwise we consider the event unexpected (lines 21 to 24).

Controllability

Controllability is the extent to which an event can be influenced, and it is associated with a robot's ability to cope with an appraised event (Gratch and Marsella 2004). Thus, a robot can determine whether the outcome of an event can be altered by some actions under either of the collaborators' control. In other words, controllability is a measure of a robot's ability to maintain or change a particular state as a consequence of an event.

Controllability is also important for the overall architecture. For instance, the robot can choose to ask or negotiate about a collaborative task which is not controllable; it can cause the robot to interpret or predict the other's emotional state (e.g., anger if the task is blocked, i.e., uncontrollable for the other), or form a new motive to establish an alternative goal for the current uncontrollable event. In general, other mechanisms in the architecture use the appraisal process of controllability in their decision making processes; meanwhile controllability uses the information from the collaboration structure, e.g., successful predecessors of a goal.

Algorithm 4 (Controllability)

```

1: function ISEVENTCONTROLLABLE(Event  $\varepsilon_t$ )

2:    $\alpha \leftarrow \text{GETAGENCYRATIO}(\varepsilon_t)$ 
3:    $\beta \leftarrow \text{GETAUTONOMYRATIO}(\varepsilon_t)$ 

4:    $\lambda \leftarrow \text{GETSUCPREDECESSORSRATIO}(\varepsilon_t)$ 
5:    $\mu \leftarrow \text{GETAVAILABLEINPUT}(\varepsilon_t)$ 

6:    $\mathcal{U} \leftarrow \frac{\omega_0 \cdot \alpha + \omega_1 \cdot \beta + \omega_2 \cdot \lambda + \omega_3 \cdot \mu}{\omega_0 + \omega_1 + \omega_2 + \omega_3}$ 

7:    $\tau_t \leftarrow \text{GETEMOTIONALTHRESHOLD}()$ 

8:   if ( $\mathcal{U} \geq \tau_t$ ) then
9:     return CONTROLLABLE
10:  else
11:    return UNCONTROLLABLE

```

An important determinant of one's emotional response is the sense of control over the events occurring. This sense of subjective control is based on one's reasoning about self's

power. For instance, the robustness of one's plan for executing actions can increase sense of power and subsequently the sense of control. In the collaboration context, we have translated the sense of control into a combination of four different factors including a) *agency* and b) *autonomy* of the robot, as well as the ratios of c) *successful predecessors*, and d) the *available inputs* of a given goal (i.e., g_{ε_t}) in the shared plan.

In Algorithm 4, we compute the controllability of an event based on these four factors (lines 2 to 5). Algorithms 4a to 4d are used to illustrate the underlying processes of all these factors. We use weighted averaging over these four factors to compute the utility of an event in terms of controllability of the event. However, the value of all these weights are set to 1.0 for the purpose of simplicity at this stage of the project. We will adjust these weights after further investigating the influence of these factors, and implementing other mechanisms in the overall architecture. After computing the value of the utility, we compare this value to an emotional threshold similar to what we discussed in Algorithm 1. This comparison leads to our decision about the controllability of an event (lines 8 to 11).

Algorithm 4a (Get Agency Ratio)

```

1: function GETAGENCYRATIO(Event  $\varepsilon_t$ )

2:    $b_{\varepsilon_t} \leftarrow \text{GETBELIEF}(\varepsilon_t)$ 
3:    $g_{\varepsilon_t} \leftarrow \text{recognizeGoal}(\varepsilon_t)$ 

4:   if ( $g_{\varepsilon_t} = \text{AMBIGUOUS}$ ) then
5:     return 0.0

6:    $\mathcal{P} \leftarrow \text{FINDPATH}(b_{\varepsilon_t}, g_{\varepsilon_t})$ 

7:   if ( $\mathcal{P} \neq \emptyset$ ) then
8:
9:      $\mathcal{M}_{g_t} \leftarrow \text{currMotive}(\mathcal{P})$ 

10:    if ( $\mathcal{M}_{g_t} \neq \emptyset$ ) then
11:      if ( $\mathcal{M}_{g_t} \cdot \text{type} = \text{INTERNAL}$ ) then
12:        return 1.0
13:      else
14:        return 0.0
15:    else
16:      return 0.0
17:  else
18:    return 0.0

```

Agency is the capacity of an individual to act independently in any given environment. In a collaborative environment sometimes collaborators are required to act independently of each other. Hence, they need to have some internal motives that are formed based on their own mental state rather than being reinforced by the other. These internal motives will lead the collaborators to acquire new intentions towards new goals whenever it is required. In Algorithm 4a, if there is a path between the belief about the current event and the recognized goal associated with that event, we extract the motive within the acquired path. We consider maximum

agency value denoted as α in Algorithm 4 (i.e., $\alpha = 1.0$) if the robot's mental state possesses an internal motive towards the recognized goal; otherwise we consider the minimum agency value (i.e., $\alpha = 0.0$) for no motives or external motives only. Note that the process of forming new internal motives is out of this paper's context.

Autonomy is the ability to make decisions without the influence of others. Autonomy implies acting on one's own and being responsible for that. In a collaborative environment, tasks are delegated to the collaborators based on their capabilities. Therefore, each collaborator is responsible for the delegated task and the corresponding goal. In Algorithm 4, β denotes the value of autonomy with regard to the event (ε_t). This value is the ratio of the number of the contributing goals to g_{ε_t} for which the robot is responsible over the total number of contributing goals to g_{ε_t} (see Algorithm 4b). If the goal associated with the current event corresponds to a nonprimitive task, the algorithm checks the responsible agent for each primitive task contributing to the nonprimitive one and returns a value of which ($0 \leq \beta \leq 1$). However, if the associated goal of the current event corresponds to a primitive task the value of β would be 0 or 1. In general, higher autonomy leads to a more positive value of controllability.

Algorithm 4b (Get Autonomy Ratio)

```

1: function GETAUTONOMYRATIO(Event  $\varepsilon_t$ )

2:    $g_{\varepsilon_t} \leftarrow recognizeGoal(\varepsilon_t)$ 

3:   if ( $g_{\varepsilon_t} = \text{AMBIGUOUS}$ ) then
4:     return 0.0

5:    $\Phi_g \leftarrow extractContributingGoals(g_{\varepsilon_t})$ 

6:   for all  $\phi_g^i \in \Phi_g$  do
7:     if ( $getResponsible(\phi_g^i) = \text{SELF}$ ) then
8:        $count_{self} \leftarrow count_{self} + 1$ 

9:   return  $count_{self} / \Phi_g.total()$ 

```

The structure of a shared plan accommodates the order of the required predecessors of a goal. Predecessors of a goal, g , are other goals that the collaborators should achieve before trying to achieve goal g . In Algorithm 4c, we use the ratio of successfully achieved predecessors of the recognized goal (g_{ε_t}) associated with the current event over the total number of predecessors of the same goal. This ratio (denoted as λ in Algorithm 4) is another factor used to compute the controllability of an event. If all of the predecessors of the given goal are already achieved, then $\lambda = 1$ which is the maximum value for λ . On the contrary, failure of all of the predecessors will lead to $\lambda = 0$. Therefore, higher λ value positively impacts the value of controllability for the current event.

Inputs of a task are the required elements that the collaborators use to achieve the specified goal of the task. These inputs are also part of the structure of a shared plan. In Al-

Algorithm 4c (Get Succeeded Predecessors Ratio)

```

1: function GETSUCPREDECESSORSRATIO(Event  $\varepsilon_t$ )

2:    $g_{\varepsilon_t} \leftarrow recognizeGoal(\varepsilon_t)$ 

3:   if ( $g_{\varepsilon_t} = \text{AMBIGUOUS}$ ) then
4:     return 0.0

5:    $\Theta_g \leftarrow extractPredecessors(g_{\varepsilon_t})$ 

6:   for all  $\theta_g^i \in \Theta_g$  do
7:     if ( $isAchieved(\theta_g^i)$ ) then
8:        $count_{achieved} \leftarrow count_{achieved} + 1$ 

9:   return  $count_{achieved} / \Theta_g.total()$ 

```

gorithm 4d, we extract the required inputs of the associated goal with the current event, and check whether all the required inputs are available for the goal g_{ε_t} . The outcome will be the ratio of the available required inputs over the total required inputs of the goal associated with the current event. This value (denoted as μ in Algorithm 4) will be bound to 0 and 1. Similar to the other factors in the controllability process, the closer the value of μ gets to 1, the more positive impact it has on the overall controllability value of the event.

Algorithm 4d (Get Available Input Ratio)

```

1: function GETAVAILABLEINPUTRATIO(Event  $\varepsilon_t$ )

2:    $g_{\varepsilon_t} \leftarrow recognizeGoal(\varepsilon_t)$ 

3:   if ( $g_{\varepsilon_t} = \text{AMBIGUOUS}$ ) then
4:     return 0.0

5:    $\mathcal{X}_g \leftarrow extractInputs(g_{\varepsilon_t})$ 

6:   for all  $\chi_g^i \in \mathcal{X}_g$  do
7:     if ( $IsAvailable(\chi_g^i)$ ) then
8:        $count_{available} \leftarrow count_{available} + 1$ 

9:   return  $count_{available} / \mathcal{X}_g.total()$ 

```

Related Work

Conclusion & Future Work

Discussion about the application of the appraisal process in different mechanisms in our computational theory including Motivation mechanism.

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