Abstract

For an autonomous system, the ability to justify and explain its decision making is crucial to improve its transparency and trustworthiness. This paper proposes an argumentation-based approach to represent, justify and explain the decision making process of a value driven agent (VDA). By using a newly defined formal language, some implicit knowledge of a VDA is made explicit. The selection of an action in each situation is justified by constructing and comparing arguments supporting different actions. In terms of a constructed argumentation framework and its extensions, the reasons for explaining an action are defined in terms of the arguments for or against the action, by exploiting their defeat relation, as well as their premises and conclusions.

Introduction

In the field of artificial intelligence, to improve the transparency and trustworthiness of autonomous systems, different approaches have been proposed to provide explanations for such systems, see, e.g., (Cocarascu, Čyras, and Toni 2018) [Shih, Choi, and Darwiche 2018] [Madumal et al. 2018]. Working along these lines, we introduce an approach for representing, justifying and explaining the decision making of a value driven agent, or VDA in brief (Anderson, Anderson, and Berenz 2017).

We define a VDA as an autonomous agent that decides its next action using an ethical preference relation over actions, termed a principle, that is abstracted from a set of cases using inductive logic programming (ILP) techniques. For this purpose, each action of a VDA is associated with a set of values representing levels of satisfaction or violation of prima facie duties that that action exhibits. These duties either maximize or minimize ethically relevant features such as honoring commitments, maintaining readiness, harming the patient, etc. A case relates two actions. It is represented as a tuple of the differentials of the corresponding duty satisfaction/violation degrees of the actions being related as well as a determination as to which action is ethically preferable.

Given such a principle, the decision making process of a VDA is as follows: sense the state of the world and abstract it into a set of Boolean perceptions, determine the vectors of duty satisfaction or violation of all actions with respect to this state by a decision tree learned from examples using ID3, and sort the actions in order of ethical preference using the principle such that the first action in the sorted list is the most ethically preferable one.

It is interesting to note that in the VDA there are several kinds of knowledge that can be used for justification and explanation, including the relation between perceptions and actions determined by the decision tree, the ethical consequences of an action represented by a vector of duty satisfaction or violation values of the action, disjuncts in the clause of the principle that are used to order two actions, and the cases from which these disjuncts are abstracted. However, this knowledge has not been explicitly represented and used for justification of actions or providing explanations. In this paper, we will address this problem by exploiting formal argumentation. The structure of this paper is as follows. Section 2 introduces a formalism for representing knowledge of a value driven agent. In Section 3, we present an argumentation-based justification and explanation approach. In section 4, we discuss some further research problems of justifying and explaining more sophisticated autonomous agents. Finally, we conclude the paper in Section 5.

Representing value driven agent

In this section, we first introduce a formal language and then use it to represent the knowledge and the model of a VDA.

The language of a VDA is composed of literals, perceptions, actions and duties.

Definition 1 (Language) Let \( L = (L, P, A, D) \) be a language consisting of a set of literals \( L \), a set of perceptions \( P \subseteq L \), a set of actions \( A \) and a set of duties \( D \), where each literal is a propositional atom or the negation of an atom, and \( L, A \) and \( D \) are pairwise disjoint. For \( l_1, l_2 \in L \), we write \( l_1 = -l_2 \) just in case \( l_1 = -l_2 \) or \( l_2 = -l_1 \).

Example 1 (Language) In \( \{\text{Anderson, Anderson, and Berenz 2019}\} \), there are 10 atoms of perceptions: low battery (lb), medication reminder time (mrt), reminded (r), refused medication (rm), fully charged (fc), no interaction (ni), warned (w), persistent immobility (pi), engaged...
(e), ignored waning (iw); 6 actions: charge, remind, engage, warn, notify and seek task; and 7 duties: maximize honor commitments (MHC), maximize maintain readiness (MMR), minimize harm to patient (mH2P), maximize good to patient (MG2P), minimize non-interaction (mNI), maximize respect autonomy (MRA) and maximize prevent persistent immobility (MPPI).

In (Anderson, Anderson, and Berenz 2019), \( L = P \). The state of the world is represented by a set of perceptions, called a situation in this paper.

**Definition 2 (Situation)** A situation \( S \) is a subset of \( L \), denoting a state of the world. The (infinite) set of situations is denoted as \( SIT \).

**Example 2 (Situation)** An example of the state of the world: \( S_1 = \{ lb, ¬mr, ¬r, ¬cm, ¬fc, ¬ni, ¬w, ¬pi, ¬e, ¬iw \} \).

In each situation, the duty satisfaction/violation values for each action are determined by a decision tree using the perceptions of the situation as input. A set of vectors of duty satisfaction/violation values of all actions in a situation is called an action matrix.

**Definition 3 (Action matrix of a situation)** A duty satisfaction value is a positive integer, while a duty violation value is negative integer. In addition, if a duty is neither satisfied nor violated by the action, then the value is zero. Given an action \( \alpha \in A \) and a situation \( S \in SIT \), a vector of duty satisfaction/violation values for \( \alpha \), denoted as \( v_S(\alpha) \), is a vector \( v_S(\alpha) = (d_1 : v_{S,\alpha}(d_1), \ldots, d_n : v_{S,\alpha}(d_n)) \) where \( v_{S,\alpha}(d_i) \) is the satisfaction/violation value of \( d_i \in D \). Then, an action matrix of a situation \( S \) is defined as \( M_S = \{ v_S(\alpha) \mid \alpha \in A \} \). The set of action matrices of all situations \( SIT \) is denoted as \( M_{SIT} = \{ M_S \mid S \in SIT \} \).

In this definition, a vector of duty satisfaction/violation values for each action will be used to define the ethical preference over actions, by considering the ethical consequences of actions in a principle.

For brevity, when the order of duties is clear, in a principle the lower bound of the differentials between duties is also written as \( u_i = (u_i(d_1), \ldots, u_i(d_n)) \).

**Example 4 (Principle)** According to (Anderson, Anderson, and Berenz 2019), we have \( \pi = \{ u_1, \ldots, u_10 \} \) where

\[
\begin{align*}
u_1 &= (-1, -4, -4, -2, -4, -4, 2) \\
u_2 &= (-1, -4, -4, -2, 0, 0, 1) \\
u_3 &= (0, -3, 0, -1, 0, 1, 0) \\
u_4 &= (0, -3, 0, 1, 0, 0, 0) \\
u_5 &= (0, -1, 0, 0, 0, 0, 0) \\
u_6 &= (0, -3, 0, -1, 1, -1, 0) \\
u_7 &= (-1, -4, 1, -2, -4, -4, 0) \\
u_8 &= (1, -3, 0, -2, -4, -4, 0) \\
u_9 &= (0, 3, 0, -2, 0, 0, 0) \\
u_{10} &= (-1, -4, 1, -1, -4, -4, -1)
\end{align*}
\]

These 10 elements in \( \pi \) correspond to 10 disjuncts of the principle in (Anderson, Anderson, and Berenz 2019).

Given a principle and two vectors of duty satisfaction/violation values, we may define a notion of ethical preference over actions. Let \( v_S(\alpha_1) = (d_1 : v_{S,\alpha_1}(d_1), \ldots, d_n : v_{S,\alpha_1}(d_n)) \) and \( v_S(\alpha_2) = (d_1 : v_{S,\alpha_2}(d_1), \ldots, d_n : v_{S,\alpha_2}(d_n)) \) be vectors of duty satisfaction/violation values. In the following definition, we use \( v_S(\alpha_1) > v_S(\alpha_2) \) to denote \( (d_1 : v_{S,\alpha_1}(d_1) > v_{S,\alpha_2}(d_1)), \ldots, (d_n : v_{S,\alpha_1}(d_n) > v_{S,\alpha_2}(d_n)) \).

**Definition 5 (Ethical preference over actions)** Given a situation and its corresponding action matrix, actions are sorted by a principle. This principle is discovered by applying inductive logic programming (ILP) techniques to a set of cases. Clauses of the principle specify lower bounds of the differentials between corresponding duties of any two actions that must be met or exceeded to satisfy the clause.

The duties in each vector are MHC, MMR, mH2P, MG2P, mNI, MRA and MPPI in order.
The intuition is that the larger the distance between them, the lesser the relevance between them.

**Definition 6 (Relevance of principle clause)** Let $v_S(\alpha)$ be a vector of duty satisfaction/violation values of $\alpha$ and $u \in \pi$ a clause of $\pi$. The relevance of $u$ to $\alpha$ is defined as the distance between vectors $u$ and $v_S(\alpha)$, written as $d(u, v_S(\alpha))$, such that $d(u, v_S(\alpha)) = \sqrt{(u(d_1) - v_{S,\alpha}(d_1))^2 + \ldots + (u(d_n) - v_{S,\alpha}(d_n))^2}$.

**Example 5 (Relevance of principle clause)** Consider the distance between $v_{S,\text{charge}}$ and $u_5$, $u_8$ and $u_9$ respectively.

- $d(u_5, v_{S,\text{charge}}) = \sqrt{10}$.
- $d(u_8, v_{S,\text{charge}}) = 59$.
- $d(u_9, v_{S,\text{charge}}) = \sqrt{2}$.

**Definition 7 (Ethical preference over actions - cont.)** We say that $\alpha_1$ is ethically preferable (or equal) to $\alpha_2$ with respect to its most relevant clause $u \in \pi$ if and only if $v_S(\alpha_1) \geq v_S(\alpha_2)$ and there exists no $u' \in \pi$ such that $d(u', v_S(\alpha_1)) < d(u, v_S(\alpha_1))$ and $v_S(\alpha_1) \geq v_S(\alpha_2)$.

**Example 6 (Ethical preference over actions - cont.)** Consider the actions charge and remind. For each $u \in \{v_5, u_8, u_9\}$, $v_S(\text{charge}) \geq u$ $v_S(\text{remind})$. Among them, $u_8$ is the most relevant clause to the action charge.

Based on the above notions, a value driven agent (VDA) is formally defined as follows.

**Definition 8 (Value driven agent)** A value driven agent is a tuple $Ag = (L, SIT, M, \pi)$ where $L = (L, P, A, D)$.

In a VDA, given a situation and an action matrix, a set of solutions can be defined as follows.

**Definition 9 (Solution)** Let $Ag = (L, SIT, M, \pi)$ be a value driven agent. Given a situation $S \in SIT$ and an action matrix $M_S \in M$, a solution of $Ag$ with respect to $S$ is $\alpha : v_S(\alpha)$ if and only if there is an ordering $A$ over $\pi$ such that $\alpha$ is the first action in the sorted list. The set of all solutions of $Ag$ with respect to $S$ is denoted as $\text{sol}(Ag, M_S, \pi) = \{ \alpha : v_S(\alpha) | \alpha \in A \text{ such that } \alpha : v_S(\alpha) \text{ is a solution of } Ag \text{ w.r.t. } S \}$.

According to Definition 9, we directly have the following proposition.

**Proposition 1 (The number of solutions)** Given $Ag = (L, SIT, M, \pi)$, a situation $S \in SIT$ and an action matrix $M_S \in M$, there are $k$ solutions of $Ag$ if and only if there are $k$ different orderings of $A$ with respect to $\pi$ such that there are $k$ different actions in the head of the sorted lists.

Now, let us make explicit other knowledge that is implicit in a VDA, i.e., the relation between a situation and an action with its duty satisfaction/violation values. This relation is implied by the decision tree. In this paper, it is represented as a defeasible rule, called an action rule.

**Definition 10 (Action rule)** Let $Ag = (L, SIT, M, \pi)$ be a VDA, where $L = (L, P, A, D)$. An action rule of $Ag$ under a situation $S \in SIT$ is $R : p_1, \ldots, p_n \Rightarrow \alpha : v_S(\alpha)$, where $R$ is a label of the rule, $p_i \in S$ is a perception, $\alpha \in A$ is an action, $v_S(\alpha)$ is a vector of the duty satisfaction/violation values of $\alpha$ in the situation $S$.

An action rule $R : p_1, \ldots, p_n \Rightarrow \alpha : v_S(\alpha)$ can be read as if $p_1, \ldots, p_n$ hold, then performing action $\alpha$ will presumably bring the ethical consequence $v_S(\alpha)$. The set of all action rules of $Ag$ under situation $S$ is denoted as $\text{RUL}_S(\text{Ag})$. Action rules can be automatically and dynamically generated and updated according to the data from a VDA.

For convenience, $p_1, \ldots, p_n$ in $R : p_1, \ldots, p_n \Rightarrow \alpha : v_S(\alpha)$ is also written as $p_1 \land \ldots \land p_n$.

**Example 7 (Action rule)** Continuing Example 3

Given $S_I$, there are six defeasible rules, where $LB = \text{lb} \land \neg \text{mrt} \land \neg \text{r} \land \neg \text{rm} \land \neg \text{fc} \land \neg \text{mi} \land \neg \text{w} \land \neg \text{pm} \land \neg \text{e} \land \neg \text{w}$. $\text{R}_1 : LB \Rightarrow \text{charge} : v_{S,\text{charge}}$. $\text{R}_2 : LB \Rightarrow \text{remind} : v_{S,\text{remind}}$. $\text{R}_3 : LB \Rightarrow \text{engage} : v_{S,\text{engage}}$. $\text{R}_4 : LB \Rightarrow \text{warn} : v_{S,\text{warn}}$. $\text{R}_5 : LB \Rightarrow \text{notify} : v_{S,\text{notify}}$. $\text{R}_6 : LB \Rightarrow \text{seekTask} : v_{S,\text{seekTask}}$.

Note that in this example, it is possible for an action to not satisfy any duties and there might be no effect on the conclusion of decision making if one removes those rules associated with them. However, theoretically, we have not ruled out the possibility that no action satisfies any duty in some situations, where the most preferable action would then be the one that violated duties the least. So, we remove nothing, keeping all rules constructed in terms of Definition 10.

In summarizing this section, we may conclude that the formal model of a VDA and the set of action rules properly capture the underlying knowledge of the VDA. In next section, we will introduce an argumentation-based approach for the justification and explanation of the decision-making a VDA.

**Argumentation-based justification and explanation**

Argumentation in artificial intelligence is a formalism for representing and reasoning with inconsistent and incomplete information (Dung 1995). It also provides various ways for explaining why a claim or a decision is made, in terms of justification, dialogue, and dispute trees (Cyrs, Satoh, and Toni 2016), etc. In this section, we show how to justify and explain decision making of a VDA by using argumentation.

In terms of structured argumentation (e.g., ASPIC+ (Modgil and Prakken 2014)), there are three basic notions including arguments, relations between arguments and argumentation semantics. We will define them in the setting of this paper. First, an argument is a set of reasons supporting a claim or an action. In what follows, for a given argument, the function $\text{concl}$ returns its conclusion, and $\text{sub}$ returns all its sub-arguments.

**Definition 11 (Argument)** Let $Ag = (L, SIT, M, \pi)$ be a value driven agent, where $L = (L, P, A, D)$. Argument $X$ in a situation $S$ is

- $p$ if $p \in S$ with $\text{concl}(X) = p$ and $\text{sub}(X) = \{p\}$.
\( X_1, \ldots, X_n \Rightarrow \alpha : v_S(\alpha) \) such that there exists \( \text{concl}(X_1), \ldots, \text{concl}(X_n) \Rightarrow \alpha : v_S(\alpha) \in \text{RULE}(Ag) \) for some \( S \in \text{SIT} \).

The set of arguments of \( Ag \) in a situation \( S \) is denoted as \( \text{Arg}(Ag, S) \).

Second, the relations between arguments include sub-argument relation, attack relation and defeat relation. We say that argument \( Y \) is a subargument of \( X \) if and only if \( Y \in \text{sub}(X) \). For the attack relation, we have the following definition.

**Definition 12 (Attack relation between action arguments)**

An action argument \( X_1 \) attacks another action argument \( X_2 \) in a situation \( S \) if and only if \( \text{concl}(X_1) = \alpha_1 : v_S(\alpha_1) \) and \( \text{concl}(X_2) = \alpha_2 : v_S(\alpha_2) \) for some actions \( \alpha_1 \) and \( \alpha_2 \), and \( \alpha_1 \neq \alpha_2 \).

When one argument \( X \) attacks another argument \( Y \), if the priority of \( X \) is at least as high as that of \( Y \), then we say that \( X \) defeats \( Y \). The notion of priority over action arguments is as follows.

**Definition 13 (Priority over action arguments)**

Given a principle \( \pi \), an action argument \( X_1 \) is at least as preferred as another action argument \( X_2 \) in a situation \( S \in \text{SIT} \) with respect to some \( u \in \pi \), denoted as \( X_1 \preceq_u X_2 \), if and only if \( \text{concl}(X_1) = \alpha_1 : v_S(\alpha_1) \) and \( \text{concl}(X_2) = \alpha_2 : v_S(\alpha_2) \) for some actions \( \alpha_1 \) and \( \alpha_2 \), and \( v_S(\alpha_1) \geq u \) for some actions \( \alpha_1 \) and \( \alpha_2 \), such that \( u \) is the most relevant clause with respect to \( \alpha_1 \).

According to Definition [13] since \( v_S(\alpha_1) \geq u \) and \( v_S(\alpha_2) \geq u \) implies \( v_S(\alpha_1) \geq v_S(\alpha_3) \), we have the following proposition.

**Proposition 2 (Transitivity of priority relation)**

Priority relation over action arguments is transitive.

**Definition 14 (Defeat relation between action arguments)**

Given a principle \( \pi \), an action argument \( X_1 \) defeats argument \( X_2 \) in a situation \( S \in \text{SIT} \) with respect to \( u \in \pi \), denoted as \( X_1 \Rightarrow_u X_2 \), if and only if \( X_1 \Rightarrow_u X_2 \), and \( X_1 \subset u \). The set of defeats between arguments of \( Ag \) in a situation \( S \in \text{SIT} \) is denoted as \( \text{Def}(Ag, S) \).

When combining a set of arguments and the defeat relation, we get an abstract argumentation framework (or briefly, AAF), a notion originally proposed in [Dung 1995].

**Definition 15 (AAF of a VDA in a situation)**

An AAF of a value driven agent \( Ag \) in a situation \( S \) is \( F_{Ag, S} = (\text{Arg}(Ag, S), \text{Def}(Ag, S)) \).

**Example 8 (AAF of a VDA in a situation)**

Continuing Example 4, we have the following 16 arguments (visualized in Fig. 7):

\[
\begin{align*}
X_1 & : \text{lb} \\
X_2 & : \text{mt} \\
X_3 & : \text{r} \\
X_4 & : \text{rm} \\
X_5 & : \text{fc} \\
X_6 & : \text{ni} \\
X_7 & : \text{w} \\
X_8 & : \text{pi} \\
X_9 & : \text{e} \\
X_{10} & : \text{iw} \\
X_{11} & : X_1, \ldots, X_{10} \Rightarrow \text{charge} : v_S(\text{charge}) \\
X_{12} & : X_1, \ldots, X_{10} \Rightarrow \text{remind} : v_S(\text{remind}) \\
X_{13} & : X_1, \ldots, X_{10} \Rightarrow \text{engage} : v_S(\text{engage}) \\
X_{14} & : X_1, \ldots, X_{10} \Rightarrow \text{warn} : v_S(\text{warn}) \\
X_{15} & : X_1, \ldots, X_{10} \Rightarrow \text{notify} : v_S(\text{notify}) \\
X_{16} & : X_1, \ldots, X_{10} \Rightarrow \text{seekTask} : v_S(\text{seekTask}) \\
\end{align*}
\]

**Note.** For instance, that \( X_{11} \) and \( X_{12} \) attack each other. Moreover, since \( v_{S_1}(\text{charge}) - v_{S_1}(\text{remind}) = (1, 4, 0, 0, 0, 0, 0) \geq u \) where \( u \in \{u_5, u_8, u_9\} \) and \( u_9 \) is the most relevant clause with respect to charge, we have \( X_{11} \succ u_9 X_{12} \) and therefore \( X_{11} \) defeats \( X_{12} \). Similarly, we may identify the defeat relation between defeated arguments is omitted.

Third, given an AAF, the notion of argumentation semantics can be used to evaluate the status of arguments. There are a number of argumentation semantics capturing different intuitions and constraints for evaluating the status of arguments in an AAF, including complete, preferred, grounded and stable, etc. First, a complete extension is defined in terms of the notions of conflict-freeness and defense. Given an AAF \( (A, \mathcal{R}) \), we say that a subset \( E \subseteq A \) is conflict-free if and only if there exist no \( X_1, X_2 \in E \) such that \( X_1 \text{ defeats } X_2 \). An AAF is admissible if and only if for every argument \( Y \in A \) if \( Y \text{ defeats } X \) then there exists \( Z \in E \) such that \( Z \text{ defeats } Y \). Set \( E \) is admissible if and only if it is conflict-free and defends each argument in \( E \). Then, we say that \( E \) is a complete extension if and only if \( E \) is admissible and each argument in \( A \) is defended by \( E \) in \( E \); \( E \) is a preferred extension if and only if \( E \) is a maximal complete extension with respect to set-inclusion; \( E \) is the grounded extension if and only if \( E \) is a minimal complete extension with respect to set-inclusion; \( E \) is a stable extension if and only if \( E \) is a maximal complete extension with respect to set-inclusion.

It has been verified that each AAF has a unique (possibly empty) set of grounded extension, while many AAFs may have multiple sets of extensions, which may be used to capture the intuition that there can be multiple solutions in some decision-making scenarios. When an AAF is acyclic, it has only one extension under all semantics. Then, we say that an argument of an AAF is skeptically justified under a given semantics if it is in every extension of the AAF, and credulously justified if it is in at least one but not all extensions of the AAF. For convenience, we use \( \sigma \) to denote an argumentation semantics, which can be complete, grounded, stable or preferred. For more information about argumentation semantics, please refer to [Baroni, Caminada, and Giacomin 2011].

**Example 9 (Argumentation semantics)**

Consider the AAF in Figure 7. It is acyclic and has only one extension under any argumentation semantics \( \sigma \), i.e.,
In this example, all arguments in \( E \) are skeptically justified.

Given a set of justified arguments, we may define the set of justified conclusions as follows.

**Definition 16 (Justified conclusion)** Let \((A, R)\) be an AAF, and \( X \subseteq A \) be a skeptically (credulously) justified argument under an argumentation semantics \( \sigma \). A skeptically (credulously) justified conclusion is written as \( \text{concl}(X) \). We say that \( \text{concl}(X) \) is a skeptically (credulously) justified action if and only if \( X \) is an action argument.

**Example 10 (Justified conclusions)** According to Example 9, all elements in \( S_{E} \cup \{ \text{charge} : v_{S_{E}}(\text{charge}) \} \) are justified conclusions, in which \( \text{charge} : v_{S_{E}}(\text{charge}) \) or charge is a justified action.

Now, let us verify that the representation by using argumentation-based approach is sound and complete under stable semantics.

**Proposition 3 (Soundness and completeness of representation)**

Let \( Ag = (L, SIT, M, \pi) \) be a VDA, where \( L = (L, P, A, D) \). Let \( \alpha \in A \) be an action. Given a situation \( S \) in SIT and an action matrix \( M_{S} \in M \), it holds that \( \alpha : v_{S}(\alpha) \) is a solution of \( Ag \) with respect to \( S \), and if only if \( \alpha : v_{S}(\alpha) \) is a justified action in \( F_{Ag,S} = (\text{Arg}(Ag,S), \text{Def}(Ag,S)) \) under stable semantics.

**Proof 1** On the one hand, if \( \alpha : v_{S}(\alpha) \) is a solution of \( Ag \) with respect to \( S \), then there exists an ordering over \( A \), such that \( \alpha \) is the first action of the sorted list. It follows that for each \( \beta \in A \setminus \{ \alpha \} \), either \( v_{S}(\alpha) > v_{S}(\beta) \) or \( \alpha \) and \( \beta \) are not comparable. According to Definition 17, there exist \( X, Y \in \text{Arg}(Ag,S) \) such that \( \alpha : v_{S}(\alpha) = \text{concl}(X) \) and \( \beta : v_{S}(\beta) = \text{concl}(Y) \). It follows that \( X \) defeats \( Y \), or \( X \) and \( Y \) defeat each other. In either case, any argument defeating \( X \) is defeated by \( X \). It follows that \( \{X\} \cup S \) is a stable extension. So, \( \alpha : v_{S}(\alpha) = \text{concl}(X) \) is a justified action in \( F_{Ag,S} \) under stable semantics. On the other hand, if \( \alpha : v_{S}(\alpha) \) is a justified action in \( F_{Ag,S} = (\text{Arg}(Ag,S), \text{Def}(Ag,S)) \) under stable semantics, then there exists \( X \in \text{Arg}(Ag,S) \) such that \( \text{concl}(X) = \alpha : v_{S}(\alpha) \). Since in situation \( S \), any two different action arguments attack each other, no two action arguments can be in the same extension. So, \( \{X\} \cup S \) is a stable extension of \( F_{Ag,S} \). According to the definition of a stable extension, \( X \) defeats each action argument in \( \text{Arg}(Ag,S) \setminus \{X\} \). In other words, for every action argument \( Y \in \text{Arg}(Ag,S) \setminus \{X\} \) such that \( \text{concl}(Y) = \beta : v_{S}(\beta) \), \( v_{S}(\alpha) \geq u \) \( v_{S}(\beta) \) for some \( u \in S \). So, one may construct an ordering of actions such that \( \alpha \) is the first action in the sorted list. Therefore, \( \alpha : v_{S}(\alpha) \) is a solution of \( Ag \) with respect to \( S \).

Based on arguments, defeat relation between arguments, and a set of justified conclusions, the explanation of choosing an action includes the following perspectives: state of the world (the premise of the accepted action argument), satisfied duty (in the conclusion of the accepted action argument), overturned actions and underlying reasons (the conclusions of defeated arguments, differentials of duty satisfaction/violation in the clause of a principle associated with each defeat). We use the following example to illustrate an explanation, while the formal definition is omitted.

**Example 11 (Explanation)** According to Examples 8 and 7, the explanation of the justified action charge : \( v_{S_{E}}(\text{charge}) \) is as follows.

Action charge is selected, because:

1. Supporting argument \( X_{11} \) is justified, with
   - perception battery low (lb) in the premise
   - action charge in the conclusion
   - maximal duty satisfaction MMR = 2 in \( v_{S_{E}}(\text{charge}) \)
2. All conflicting arguments are rejected, with action charge more ethically preferable than
   - remind in \( X_{12} \) that is defeated by \( X_{11} \) w.r.t. \( u_{9} \)
   - engage in \( X_{13} \) that is defeated by \( X_{11} \) w.r.t. \( u_{9} \)
   - warn in \( X_{14} \) that is defeated by \( X_{11} \) w.r.t. \( u_{5} \)
   - notify in \( X_{15} \) that is defeated by \( X_{11} \) w.r.t. \( u_{5} \)
   - seekTask in \( X_{16} \) that is defeated by \( X_{11} \) w.r.t. \( u_{9} \)

**Discussion: Justification and explanation in more sophisticated autonomous agents**

In the previous two sections, we have introduced an argumentation-based formalism for representation, justification and explanation in a VDA. In the current version of VDA (Anderson, Anderson, and Berenz 2019), we have not taken into consideration some more complicated scenarios. For instance, a VDA may not only have practical reasoning concerning which action should be selected, but also have epistemic reasoning about the state of the world. In this new scenario, besides a set perceptions, we may add epistemic rules, which could be strict or defeasible, to represent the knowledge of the world.

**Definition 17 (Epistemic rule)** Let \( Ag = (L, SIT, M, \pi) \) be a value driven agent, where \( L = (L, P, A, D) \). An epistemic rule of \( Ag \) is either a strict rule \( R : p_{1}, \ldots, p_{n} \rightarrow p \) or a defeasible rule \( R : p_{1}, \ldots, p_{n} \rightarrow p, \) where \( p_{1}, p \in L \) are literals.

**Example 12 (Epistemic rule)** Assume that the message concerning whether the battery is low is obtained by observation. In this sense, the elements in \( S_{E} \) are not all facts. Instead, they can be assumptions. For instance, now we consider \( lb \in S_{E} \) as an assumption, denoting that the battery is presumably low by observation. Now, we assume that signal of the battery is found abnormal (.ab). In this case, we may infer that the battery is probably not low. We use a defeasible rule to represent this piece of knowledge: \( R_{7} : ab \Rightarrow \neg lb \).

Due to incomplete and uncertain information, there may be several possible situations. According to Example 12, there are two possible situations \( S_{17} \) and \( S_{18} = (S_{17} \setminus \{lb\}) \cup \{ab, \neg lb\} \). To justify which situation holds, one may construct an AAF at the epistemic level, visualized in the left part of Figure 2 in which two additional arguments are as follows. We assume that \( R_{18} \) is superior to the assumption \( lb \).

\[
X_{17} : ab \\
X_{18} : X_{17} \Rightarrow \neg lb
\]
By using the AAF in left part of Figure 2, we may justify that $S'_1$ holds. Under this situation, the action matrix is as follows.

$$v_{S_1}(\text{charge}) = (0, 1, 0, -1, 0, 0, 0).$$

$$v_{S_1}(\text{remind}) = (-1, -1, 0, 1, 0, 0, 0).$$

$$v_{S_1}(\text{engage}) = (0, -1, 0, -1, 0, 0, 0).$$

$$v_{S_1}(\text{warn}) = (0, 0, 0, -1, 0, -1, 0).$$

$$v_{S_1}(\text{notify}) = (0, 0, 0, -1, 0, -2, 0).$$

$$v_{S_1}(\text{seekTask}) = (0, -1, 0, 1, 0, 0, 0).$$

Similar to the previous examples, an AAF for practical reasoning under situation $S'_1$ is visualized in the right part of Figure 2. Similarly, defeat relation between defeated arguments is omitted.

Figure 2: AAFs for epistemic and practical reasoning

In this updated scenario, the justified action is $\text{seekTask}$ that is supported by the justified argument $X'_{16}$. Now, let us present an updated explanation for the new justified action.

Example 13 (Updated explanation) The explanation of the justified action $\text{seekTask}$ is as follows.

Action $\text{seekTask}$ is selected, because:

1. Argument $X_{18}$ supporting situation $S'_1$ is justified, with $\neg \text{lb}$ in the conclusion of $X_{18}$.

2. Supporting argument $X'_{16}$ is justified, with battery not low ($\neg \text{lb}$) in the premise, action $\text{seekTask}$ in the conclusion, and maximal utility satisfaction $\text{MG2P} = 1$ in the conclusion.

3. All conflicting action arguments are rejected, with action $\text{seekTask}$ more ethically preferable than
   - $\text{charge}$ in $X'_{11}$ that is defeated by $X'_{16}$ w.r.t. $u_4$
   - $\text{remind}$ in $X'_{12}$ that is defeated by $X'_{16}$ w.r.t. $u_5$
   - $\text{engage}$ in $X'_{13}$ that is defeated by $X'_{16}$ w.r.t. $u_5$
   - $\text{warn}$ in $X'_{14}$ that is defeated by $X'_{16}$ w.r.t. $u_5$
   - $\text{notify}$ in $X'_{15}$ that is defeated by $X'_{16}$ w.r.t. $u_5$

From the above examples, we may observe that for more sophisticated autonomous agents, there may be more than one type of reasoning, and different components of a system may be entangled. One example in this direction is the BOID architecture introduced in (Broersen et al. 2001). Furthermore, in a multi-agent system, reasoning about actions of one agent is dependent both on the individual values of the agent concerned and on what others choose to do (Atkinson and Bench-Capon 2018).

Conclusions

In this paper, we have proposed an argumentation-based approach for representation, justification and explanation of a VDA. The contributions are three-fold. First, we provide a formalism to represent a VDA, making explicit some implicit knowledge. This lays a foundation for the justification and explanation of reasoning and decision making in a VDA. Second, we adapt existing structured and abstract argumentation theories to the setting of a decision making in a VDA, such that the priority relation and defeat relation over arguments are linked to the ethical consequences of actions that are reflected by clauses of a principle, and the justification and explanation of an action can be defined accordingly. Third, unlike existing argumentation systems where formal rules are designed in advance, in our approach, rules are generated and updated at run time by automatically translating a situation and an action matrix to a set of rules, while the priority relation between rules is also dynamically evaluated in terms of a principle. Thanks to the graphic nature of an AAF, when the system becomes more complex, there exist efficient approaches to handle the dynamics of the system, e.g., (Liao, Jin, and Koons 2011; Liao 2014).

Concerning future work, first, we have not identified nor formally represented the relation between a principle and a set of cases from which the principle is learned. Doing so is likely to provide further information that explains why an action is chosen in a given situation. Second, in the existing version of VDA (Anderson, Anderson, and Berenz 2019), neither epistemic reasoning nor multi-agent interaction (Broersen et al. 2001; Atkinson and Bench-Capon 2018; Chopra et al. 2018) has been considered. The addition of such extensions to the VDA will serve to extend its capabilities.

The work reported in this paper shares some similarity with the symbolic approach introduced in (Shih, Choi, and Darwiche 2018), in the sense that some implicit functions of the system is made explicit by using a symbolic representation. However, rather than translating the function between a set of features and a classification, we translate several types of implicit knowledge of a VDA by a logical formalism. Other related works are those based on argumentation, e.g., (Cocarascu, Cyras, and Toni 2018), in which an AAF is constructed in terms of highest ranked features. To the best of our knowledge, no work in existing literature exploits argumentation to address similar research problems in the present paper.

Clearly, formal justification and explanation of the behavior of autonomous systems enhances the transparency of such systems. Further, we contend that autonomous systems that can argue formally for their actions are more likely to engender trust in their users than systems without such a capability. That principle-based systems such as the one detailed in this paper and others (e.g., (Vanderelst and Winfield 2018; Sarathy, Scheutz, and Malle 2017)) seem to lend themselves readily to explanatory mechanisms adds further support for their adoption as a formalism to ensure the ethical behavior of autonomous systems.
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