Improving Adaptive Human-Robot Cooperation through Work Agreements

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***Abstract*— Human-robot teams for disaster response need to dynamically adapt their task allocation and coordination to the momentary context, based on adequate trust stances and taking account of the relevant values and norms (such as safety, health, and privacy). This paper presents a *Work Agreement* framework that supports this capability. The research question is: Which minimal set of concepts, relations, and associated formalization can be used to model Work Agreements with adequate expressiveness and flexibility? An ontology has been developed that defines core concepts with their relations ⟨*creditor, debtor, antecedent, consequent, lifespan, acceptance*⟩, encompassing the knowledge to specify, activate, monitor, and reason about work agreements. The framework was implemented and tested as part of the TRADR project. The TRADR system brought forward the desired adaptive team behavior of the concerning robot. The tests led to further refinements of the work agreements framework.**

I. INTRODUCTION

An important added value of using robots in urban search and rescue (USAR) is that they can be deployed in hazardous situations where humans would not be able or allowed to engage (see Fig. 1). For effective ongoing contributions to USAR missions, they should be able to collaborate with their (human) team members, such as their team leader, operator, and rescuers in the field [1]. Such collaboration encompasses four challenges for the development of robot teamwork.

Fig. 1. One of the robots of the TRADR project exploring a hazard area in an urban search and rescue (USAR) evaluation scenario.

First, when working as a team, the team members depend on one another in accomplishing their joint goal. Effective teamwork therefore requires for the team members to *trust* one another to accomplish their part of the task [2]. Second, the team members need to *coordinate* their tasks with one another to ensure their efforts are well-aligned. This coordination presents a challenge for the team members, especially in unstructured and non-routine tasks, such as USAR, as the situation in which the actors perform their tasks is not known upfront. Third, dealing with unfamiliar and unpredictable situations requires for dynamic planning and *task allocation* among the team members. The situation on the spot will determine the tasks and behaviors required by the team members, along with the necessary communication and coordination to mitigate mutual dependencies between the team members. Fourth, the behaviors in the team should comply with the core *values* of the organization and its members, such as safety, health, and privacy [3].

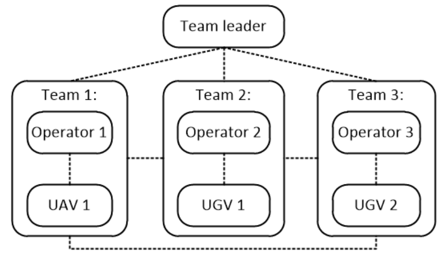

Fig. 2. Within the context of the TRADR project, a USAR team consists of three operators and three robots - one Unmanned Aerial Vehicle (UAV) and two Unmanned Ground Vehicles (UGVs). The operators work closely together with their robot, forming human-operator teams that communicate with one another through the TRADR system, and are managed by the team leader. Dotted lines represent communication possibilities between parties.

Explicit work agreements between human and robotic team members can help tackle these four challenges. Agreeing on which actions should (not) be performed by whom in specific conditions enables team members to compensate for one another's shortcomings and/or provide help in situations where team members are unable to overcome problems independently, which increases overall trust in the team and its members [2]. Work agreements allow for the team members to agree on the coordination of task execution and communication beforehand in a generic manner, addressing the applicable dynamic contextual factors. They guide the behavior of the team members by offering a structure for dynamic task allocation, communication, and progress monitoring within the team. In addition, work agreements can be used to deal with value tensions, such as the trade-off between privacy and safety (see [4]) and can be used to establish a normative system.

To illustrate the use of work agreements, we present the following brief example situated within the context of the TRADR research program: a human-robot team collaborating in a USAR setting (also see Fig. 2 and 3). Imagine, one

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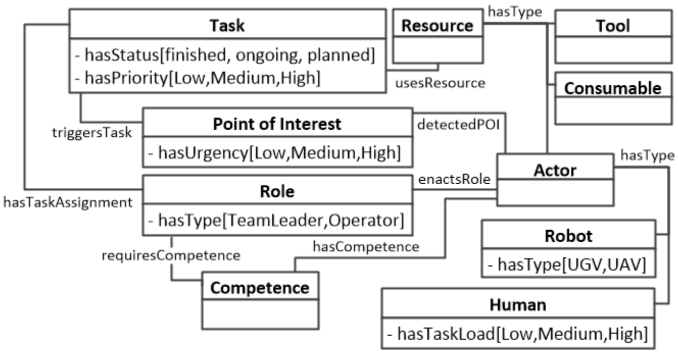

Fig. 3. The domain ontology (only partially displayed here) consists of important concepts used to describe the world, and the relations between them. The ontology can be used by the team members to reason about the appropriateness for them to take on new tasks as they detect new objects in their surroundings, and to communicate with one another about the division and progress of their tasks, and the detection of new points of interest.

of the team members is tasked to explore a hazard area. The assignment and corresponding task allocation are clear; the team leader is aware of the team member's activities. Yet even though the current whereabouts and activities are all known, any potential changes to the task execution remain unspecified. For example, under what circumstances is the robot allowed or obligated to pause its current activities in service of a more pressing task? To tackle such situations beforehand, work agreements can be used, for example, to explicate that if the robot encounters a life-threatening situation for humans, it immediately pauses its current activities, takes on the new task, and notifies the team leader about this.

The research question we aim to answer in this paper is: *Which minimal set of concepts and relations, and associated formalization can be used to model Work Agreements with adequate expressiveness and flexibility?*

This paper introduces a work agreements framework based on Singh's (1999) commitment model [5]. The framework specifies a structure of interrelated concepts (i.e. an ontology), containing the knowledge required for a robotic team member to reason about work agreements between different team members. The framework was implemented and tested in a field test.

II. WORK AGREEMENTS

Much of the research on human-robot teams aims to optimize the division of tasks between the team members at a single point in time. Yet for effective teamwork, it is not sufficient to look at momentary task allocation; it is crucial to also consider how team trust, cohesion, and coordination develop over time, and how members of well-developed teams dynamically shift between various arrangements of task allocations on the fly (e.g. [6], [7], [2]). Within such well-developed teams, many work agreements have gradually evolved either explicitly or implicitly over time, ensuring smooth collaboration in terms of communication, coordination, and task allocation [8], [9], [10], [11].

Lange and Gutzwiller (2016) [12] identified several design patterns [13], [14] related to command and control of hybrid non-hierarchical teams consisting of humans and autonomous systems. They describe humans and autonomous systems as partners. One of the patterns identified by Lange and Gutzwiller (2016) are work agreements. Work agreements, according to Lange and Gutzwiller, provide human users a means to indicate preferences concerning task allocation and execution. The rationale behind this pattern is twofold: (1) work agreements increase the trust of the human in the autonomous system by making the autonomous system more predictable, and (2) work agreements allow the human to contribute to the behavior of the system.

Work agreements seem especially appropriate for teaming [15], [4], [16], as team situations require coordination, communication, and collaboration [17], [18] in a way that is facilitated by articulating tasks, properly allocating those tasks among the team members, and making sure that the team is aware of how tasks are allocated within the team [19], [20]. An important technical advantage of work agreements is their *reusability* across domains, saving precious development time, while remaining highly specific to governing teamwork-related rules. By separating work agreements from the rest of the code in a dedicated module, work agreements are relatively easy to reuse across applications [21].

Scientific research on the formalization of work agreements (also referred to as "social commitments") comes from the field of normative multi-agent systems, where work agreements are used to support robustness and flexibility of the system as a whole [5]. A work agreement is an explicit agreement made between two actors, specifying that one actor, denoted as *debtor*, owes it to another actor, denoted as *creditor*, to effectuate some *consequent* (e.g., refrain from or see to it that some action is performed or some objective is achieved) if the *antecedent* (e.g., some precondition) is valid [22], [5]. Work agreements, in short, aim to specify permissions, obligations, or prohibitions on agent behaviors. Work agreements hold explicitly between two actors, where one actor commits to adhering to the work agreement to another actor. Therefore, work agreements are sometimes compared to contracts. An example of a work agreement is: "Lawrence is obligated to notify Lisa about his change in intent, if he decides to pause his current task to switch to a more pressing task encountered along the way".

A work agreement is first and foremost a *voluntary* restriction on an actor's autonomy (also see Figure 4), as the actor receiving the *proposed* work agreement is also allowed to reject the work agreement, the *acceptance* of the work agreement, and hence the restriction on its autonomy is completely voluntary. As soon as the debtor has accepted the work agreement, though, the debtor's autonomy is *conditionally* restricted: the debtor must satisfy the work agreement once the *antecedent* becomes valid. If the debtor fails to provide the consequent of an activated agreement before the deadline, this implies that the agreement has been violated. If the debtor succeeds to do so, the work agreement is satisfied [23]. Furthermore, commitments can, in general, be canceled by the actors involved (although this may be subdue to overarching rules); the clauses for revoking them are as important as the conditions for satisfying them.

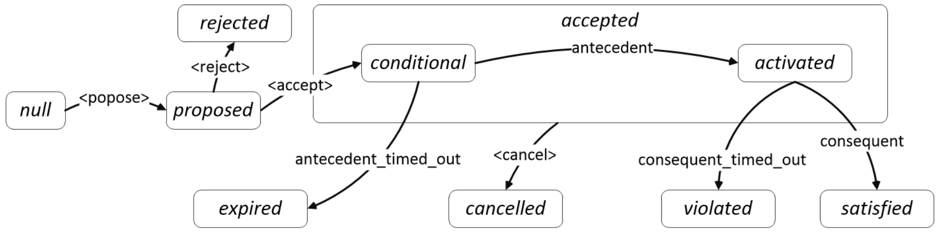

Fig. 4. The lifecycle of a Work Agreement as affected by the dynamics between the actors and events taking place in the environment.

A similar approach to work agreements are *policies*: 'enforceable, well-specified constraints on the performance of a machine-executable action by a subject in a given situation", and come in two flavors: authorization policies, stating what is permitted, and obligation policies, stating what is obligatory a given situation [21]. Mioch et al. (2017), successfully used policies to specify when an automated driving system should provide the user with personalized supportive information, and when to hand over control; both policies were linked to the user's mental state [24]. Like work agreements, policies govern the behavior of the agents, more specifically, particular roles within the team, as policies do not hold between two actors, but instead are generally applicable to a set of actors. Therefore, policies are sometimes compared to laws. An example of a policy is: "Team members are obligated to notify their team leader about a change in intent if they decide to switch tasks after encountering a more pressing task".

The foundation of both policies and work agreements are normative rules in the form of deontic logic [25]. Deontic logic is used to reason about obligations, permissions, and prohibitions. An example of a norm is: $\forall a \in Actors$: $Forbidden(do\ action\ x)$. Deontic logic still forms the core of work agreements and policies, as it enables reasoning and verification [26].

III. WORK AGREEMENT FRAMEWORK

A work agreement is an explicit agreement between two actors (robotic or human), who have both accepted to the agreement. Work agreements can be adapted; depending on the kind of change, the adaptation may need to be reapproved by both actors. Different team members may agree on different kinds of work agreements; they can be personal. Work agreements may also depend on the experience of the team, and on the trust and knowledge shared between the team members. Work agreements should therefore be easily added and changed by different team members in real time, i.e. during task execution.

Following Singh [5], we identify the following key concepts that need to be specified when detailing a work agreement WA (see Fig. 5): *Creditor*: The creditor is the actor to which the debtor is owed the commitment to the work agreement. *Debtor*: The debtor is the actor that is committed to the execution of the work agreement. *Antecedent*: The antecedent describes the conditions that need to be valid to *activate* a work agreement. An *activated* work agreement implies that the consequent should be executed or added as a goal by the debtor. *Consequent*: The consequent is the proposition that the debtor would be committed to execute once the antecedent is valid, e.g. a task or a goal state. A work agreement can have an optional lifespan, before or after which the work agreement is not applicable. If there is no lifespan, the work agreement is generally applicable. Lastly, the work agreement also describes for each of the actors involved whether they accepted the work agreement or not. This leads to the following formalization:

$WA\langle creditor, debtor, antecedent, consequent, L, E\rangle$
$Debtor$:= a non-empty set of actors $\{a_1, a_2, \ldots, a_n\} \in A$
$Creditor$:= a non-empty set of actors $\{b_1, b_2, \ldots, b_n\} \in A$
$Debtor \cap Creditor = \emptyset$
$Antecedent$:= $p \in P$
$Consequent$:= `NORM` ($x \in \{K \cup P\}$), where `NORM`($k \in K$) implies that the actor is either obliged, permitted, or forbidden to perform task k, and `NORM`($p \in P$) implies that the actor is either obliged, permitted, or forbidden to see to it that predicate p is true
L, the $Lifespan$:= `BeAf` ($t \in T$) or `BeAf` ($p \in P$),
E, a set of predicates describing for each actor involved whether they have accepted the work agreement or not: $\forall x \in \{debtor, creditor\}, e_x := true \vee false$,
`BeAf` := `[BEFORE | AFTER]`
`NORM` := `[IS | IS NOT]` `[OBLIGATED | PERMITTED]`
A := Set of actors
K := Set of tasks
P := Set of predicates
T := $\langle hh : mm : ss\rangle$

A. Ontology

Ontologies offer explicit, structured, and semantically rich representations of declarative knowledge. The domain ontology (see Fig. 3) consists of important concepts ('classes'), and relations between them, to describe the world. Ontologies distinguish upper level knowledge ('classes'), and lower level knowledge ('individuals') (cf. [24], [27]). For example, individuals of the class 'Task' include: 'navigate to location (X,Y)', 'take a picture of object p', and 'pick up object Q'.

The formalization of the work agreements was expressed in a separate domain-independent ontology, as shown in Fig. 5. When instantiating the work agreements framework for a particular application, the domain ontology is added to the work agreements ontology to express the domain-specific concepts needed for the creation of domain specific work

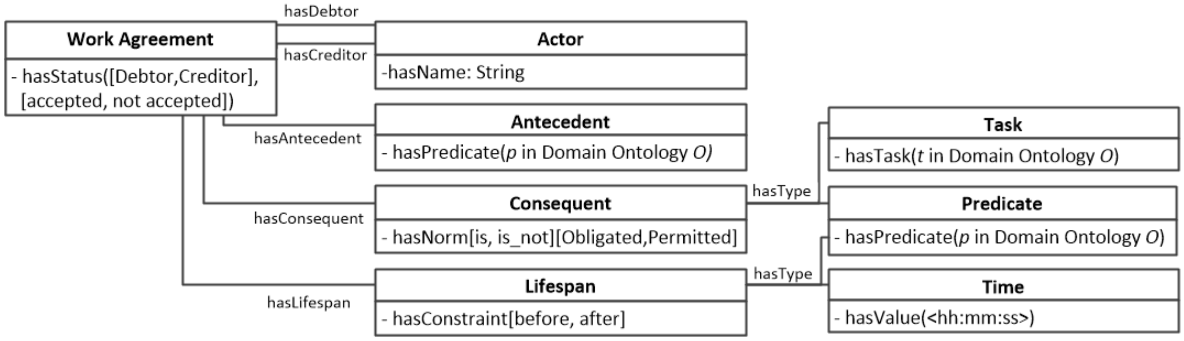

Fig. 5. The ontology representing the main concepts and relations needed to express work agreements. The predicates and tasks are to be expressed in line with the Domain Ontology (also see Fig. 3).

agreements. Together, the work agreements ontology and the domain ontology enable each actor to reason about the status of work agreements following the work agreements lifecycle. In addition, they facilitate the real-time adaptation of work agreements by team members.

IV. Implementation and Verification

To verify our work agreement framework, we implemented it in the TRADR robots used during the TRADR Joint Exercise (TJEx) and TRADR Evaluation (TEval) studies performed as part of the EU-FP7 TRADR project [28]. The TRADR ("Long-Term Human-Robot Teaming for Disaster Response") project investigated the use of robotics in an urban search and rescue setting [1]. Both TJex and TEval were conducted in the Netherlands at practice sites consisting of a maze of pipes, containers, barrels, and barriers, where participants executed various fictional disaster response scenarios to test the system. Participants were members of the Rotterdam Fire Departments (the TRADR end-users). The studies tested the full extent of the TRADR system's capabilities, including the creation of maps enabling autonomous UGV navigation, multi-robot patrolling, and searching for Points of Interest (POIs), such as victims, fire, smoke, and chemical leakage.

A. *TJEx 2017*

During the TRADR Joint Exercise (TJEx), the concept of work agreements was first introduced and verified in a large scenario-based evaluation of the TRADR system, that took place at a training site of the Rotterdam fire brigade in Rozenburg, The Netherlands. Examples of the work agreements implemented in the robots were:

- if a robot has added a new photo of an object, it should notify the team leader
- if a robot-operator team has stopped performing a task, it should notify the team leader
- if a robot has detected a new POI, it should notify the team leader and its operator

All work agreements were implemented in a hard-coded manner: they were not adaptable by the team members. Our framework was sufficiently expressive to create a wide variation of work agreements, sufficiently formal to support reasoning of the robots, and sufficiently robust to ensure appropriate autonomy restrictions - the robots behaved in line with the work agreements. Unfortunately, however, the number of work agreements resulted in a flood of notifications for the operators and team leader, and there was no way for them to prioritize the notifications. As a result, participants stopped paying attention to them after a few runs.

In addition to the technical runs, interviews were held with four fire fighters, one of whom was a member of the voluntary fire department (not a professional fire fighter). Apart from the runs they participated in during TJex, the fire fighters had no experience working with (semi-) autonomous robots, nor with the TRADR system. The interviews started with an imaginary case where the autonomy of the robots would be far more advanced compared to what they had experienced during TJex; the researchers drafted a future in which UGVs would be capable of performing advanced missions autonomously. The researchers then continued to explain the concept of human-robot teaming and the use of work agreements to regulate task division, communication, and coordination among the team members. Subsequently, the researchers initiated a discussion among the participants asking them what kind of work agreements they would like to make with their robotic team members.

The firefighters indicated that if the robot would perform tasks autonomously, it should provide continuous updates, e.g. about newly discovered POIs. Participants expected the robot to be able to distinguish relevant from irrelevant information, such as a wall full of barrels with chemical substances versus a leaking container. They would prefer not to be responsible for deciding on the relevance of information, as they would see no reason to send the robot in if they already knew upfront what it might encounter.

The following lessons learned were taken from TJex and served as premises for the preparation of TEval: (1) the technical framework is sufficient to create (hard-coded) work agreements that govern the behavior of the robots, (2) the number of work agreements governing notifications should be gravely reduced, (3) work agreements should be context-sensitive, taking the capabilities of the robots into account, and (4) robots should only share information that is relevant.

B. *T-Eval 2017*

TEval took place in the port of Rotterdam, the Netherlands, at the Deltalinqs training facility. This time, participants consisted of 7 professional and 1 voluntary fire fighter. The take-aways from TJex led to the implementation of the following selection of work agreements for TEval:

1) If the task load of the operator is 'high', the robot should only notify the team leader about a new POI if the relevance of the POI is 'high' [4], [29].
2) If the robot pauses its current task to take on a different task of which the priority is 'high', it should notify the team leader about its task switch.
3) If the robot is tasked with a new task, and its capabilities are insufficient to perform the task, it should notify its operator.

The work agreements were implemented in a hard-coded manner in the TRADR robots. During the TEval trial runs, work agreement 1 fired a few times, but since it was only active if the team leader experienced a high task load, and because an activation of the work agreement *prevented* the robot from sending a notification, none of the team leaders noticed any effect of the work agreement. Work agreement 2, unfortunately, showed a bug, causing the TRADR system to crash, and so it had to be turned off during the runs. Work agreement 3 was well-received by the operators, who found it a very helpful functionality.

Additional interviews were held with the fire fighters present. They were introduced with the researchers' vision of future human-robot teaming and the concept of work agreements. During this session, the researchers asked the participants about their current practice in fire fighter teams, whether they work according to work agreements, and if so, what these might be. The fire fighters stated that their work agreements are primarily about the structure of the team, communication between team members, timing of tasks, prioritizing of tasks, and task allocation. Moreover, work agreements depend on the mission, context, and personal aspects. For instance, in complex missions, there is more communication between all team members, including the team leader, both in terms of frequency and detail. Moreover, in some tasks it is acceptable and/or desirable for the fire fighters to act more independent, whereas when the life of victims is in danger, fire fighters should act first and communicate later. Furthermore, less experienced team member will receive more guidance through the more complex or critical situations. The fire fighters found that in general, it is important to have (an explicit) agreement about the manner of communication and task allocation between the different team members, and that this will probably also be the case when the team includes robotic team members.

Individual differences existed between the team leaders regarding the manner in which work agreements should be specified. For example, team leaders mentioned that they would like to receive notifications even if their CTL is high. One team leader said: "I want to be in the loop at all times, and receive information about every POI", whereas another team leader mentioned, "I only want to be notified about the urgent POIs; if POIs are not urgent, then I would like to have them put into the system, and when I have the time, I will have a look at them". This shows that the specific work agreements can vary among team leaders, and that in this case, work agreement 1 would be accepted by the second team leader, but not by the first. This confirms the need for adaptive work agreements. Based on this finding, the work agreements implementation was extended with a graphical user interface enabling team leaders to adjust the work agreements, as shown in Fig. 6. The interface allows human actors to accept a work agreement as is (check box) or change its antecedent (i.e. the one about task load).

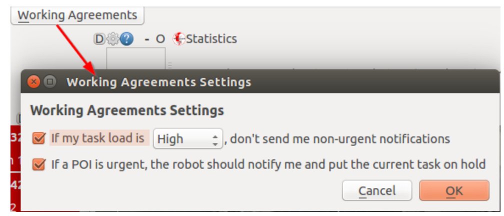

Fig. 6. Dialog to accept and change work agreements.

V. DISCUSSION & CONCLUSION

This paper presented a novel framework for the implementation of work agreements in (semi)-autonomous robots so as to support effective human-robot teamwork. Work agreements allow for the dynamic adaptation of task allocation and coordination within the team to the momentary context, taking relevant values and norms (such as safety, health and privacy) into account. The framework was iteratively developed, tested, and improved by implementing the work agreements in a human-robot team for the USAR setting. Results showed that the framework supported the specification of a large set of work agreements, and that the work agreements effectively restricted autonomy of the robotic team members. Furthermore, focus groups with potential end users provided important insights in the usefulness of work agreements, and indications of the types of work agreements that would be regarded relevant for adoption in a USAR robot. Examples of work agreements deemed relevant to the participants include notifications about POIs detected at the scene and about the robot's capabilities to perform a particular task. Team leaders especially indicated that they would like to adapt the work agreements to their personal needs and preferences.

When work agreements are used to their full extent, a larger collection of work agreements will be required to take care of all state characteristics, responsibilities, capabilities, and interactions between the humans and robots in the team. Even though it is not possible and practical to define all possible concepts for the antecedent beforehand, we believe that through new evaluations, applications, and situations in which the work agreement-framework is used, the ontology evolves, and new concepts can be added in an iterative manner. As a result, there is no need to create an exhaustive ontology before putting the work agreement framework to use - the ontology can be appended with new concepts on a need-to-know basis.

A limitation of this work was that the work agreement module at the time of evaluation did not (yet) allow for the creation of work agreements by the team members themselves. Based on the interviews with the team leaders, it is to be expected that the ability for them to adapt the work agreements to their personal preferences would strengthen the effectiveness of the work agreements. Another limitation of this research is that the effectiveness of the work agreements has not yet been quantitatively validated.

Future research will focus on the effects of work agreements on the performance effectiveness of the team. Furthermore, the framework could benefit from several extensions, including the possibility to prioritize work agreements over other work agreements to avoid conflicts, and allowing for work agreements between groups of creditors and debtors instead of between single actors. Yet another potential extension would be the inclusion of an external governance of the work agreements. In the current framework, each actor is responsible for checking the activeness of its own work agreements and resolving potential conflicts between activated work agreements. This does not have to be a problem; yet having proper conflict recognition and resolution is not trivial and should be considered when developing actors that can decide on their own work agreements.

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