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► **To cite this version:**

Rachid Alami, Mamoun Gharbi, Benjamin Vadant, Raphaël Lallement, Adolfo Suarez. On human-aware task and motion planning abilities for a teammate robot. Human-Robot Collaboration for Industrial Manufacturing Workshop, RSS 2014, Jul 2014, UC Berkeley, United States. hal-01110191

HAL Id: hal-01110191

<https://hal.science/hal-01110191>

Submitted on 27 Jan 2015

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On human-aware task and motion planning abilities for a teammate robot

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Abstract—Human-robot collaboration requires to equip the robot with explicit reasoning on the human and on its own capabilities to achieve its tasks in a collaborative way with a human partner. This paper presents and discusses three human-aware planners which can provide to a teammate robot the ability to synthesize pertinent and acceptable behaviour in an industrial context. The illustrative context is inspired by a realistic project to involve collaborative mobile manipulators in the assembly of some components of the Ariane launcher.

I. INTRODUCTION

Endowing the teammate robot with explicit reasoning on the human and on its own capabilities to achieve its tasks in a collaborative way with a human partner is a key issue. We present and discuss here a number of decisional abilities which globally belong to the human-aware task planning problem in order to facilitate human and robot interleaved task achievement. These planning functions have been incrementally investigated in the framework of a larger initiative which consists in building and deploying a robot control system especially designed for a cognitive robot which shares space and task with a human.

We illustrate such capacities through the use of a realistic example. The question was to identify a set of tasks and situations where it is possible to introduce robot advanced robot planning functions which could facilitate a close collaboration between a robot and a worker in a factory. The planners we propose integrate in their model human abilities as well as the constraints imposed by the presence of humans, their needs and preferences. Cost-based search plan techniques can then be devised to elaborate plans and behaviours which not only satisfy a given goal but also promote “good” plans.

II. A CONTEXT FOR HUMAN-ROBOT COLLABORATION IN AN INDUSTRIAL SETTING

Aircrafts assembly includes the installation of electrical systems. These are mainly individual or bundled wires of several meters in length used to power and to control all the electrical elements (sensors, actuators and controllers). A large number of brackets are manually positioned and fixed to the structure. They hold the electrical systems to the structure at short intervals in order to restrict their movement during flight.

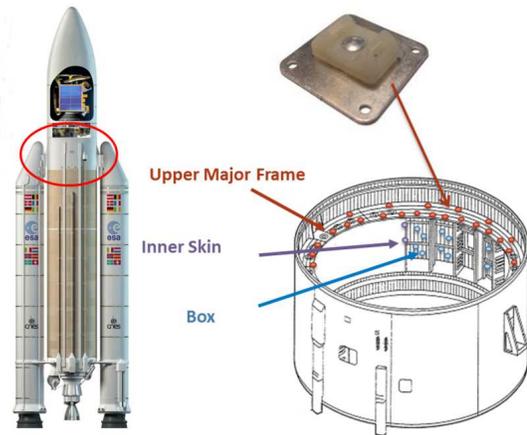


Fig. 1. Ariane 5 launcher (left) and the upper skirt (right). The upper skirt is the section located on the top of the main cryogenic stage and below the payload area (satellites). An enlarged view of a bracket is shown above.

Figure 1 shows an Ariane 5 launcher (left) and the upper skirt (right). The complete bracket assembly operations are performed manually and individually at the time.

The introduction of a collaborative robot to assist the operator on the bracket mounting process is considered. In particular two tasks could be performed in collaboration:

- First, the fetching of both the brackets and the products (solvent, glue) used to fix them. These items are stored in boxes or specific containers and the operator typically walks back and forth from their storage position to the bracket insertion position. The introduction of a collaborative mobile manipulator allows the operator to reduce his travel distances and to focus on higher added value tasks. There is consequently a need for the robot to navigate in order to achieve fetch)and-carry tasks and to hand over objects to the workers.
- Second, the correct bracket position can be pointed out by the robot. For this operation, thanks to its ability to localise itself very precisely in the environment, the robot could be used to indicate to the human the exact spot where the task should take place (e.g. by projecting an image using an augmented reality technique). Besides, the robot

should adopt a posture which does not disturb the worker or prevent him to achieve his own task in a convenient way.

We propose here below, three human-aware planners which could provide to the mobile manipulator robot capacities to synthesize a pertinent behaviour. These planners are based on previous published work. Our goal here is to adapt them and discuss their relevance to the specific context of this study:

- 1) a planner called “hand-over placement planner” (section III) which is able to compute, depending on the context, where a human-robot hand-over operation can be performed. Indeed, depending on the situation, the “standard” solution, which consists in computing a path for the robot to reach the human and deploy its arm, can be insufficient. The worker can be in a place where he is not reachable by the robot or he can be under time pressure. In such cases, we would like the robot to compute a “rendez-vous” place and configuration of both agents (the worker and the robot) and to pro-actively head towards it;
- 2) a human-aware motion planner (section IV) which is able to produce safe and human-friendly motion (navigation and/or manipulation) in the workshop between human workers and also to compute placements and postures of the robot which limit discomfort of the workers when they are in a working place;
- 3) a high-level task planner (section V) which provides to the robot the ability to schedule on-line its next actions as a teammate resulting in what can be seen as a “shared plan” involving interleaved human(s) and robot(s) actions. Here again there is a benefit to produce a plan that not only achieves the goal but also reduces burden and unnecessary actions of the human workers.

III. A HANDOVER PLACEMENT PLANNER

In this section we address the problem of handing over small objects to the human while taking into account feasibility and interaction constraints.

Problem: Let us consider the configuration space C formed by the cartesian product between the robot configuration space C_r and the human configuration space C_h . Formally the inputs of the problem are the initial configurations of the robot q_r^{init} and of the human q_h^{init} . The problem also takes as input their kinematic model and the representation of the workspace.

Thus, solving the handover problem consists in computing a handover configuration $q_{handover} = (q_r, q_h) \in C$ and a motion plan composed of two paths: the robot path (τ_r) and the human path (τ_h).

The configuration $q_{handover}$ belongs to a restriction of C regarding the constraints listed below:

- a) *Collision free:* at $q_{handover}$, the robot and the human have to be collision free. (subspace C_{free})
- b) *Reachability:* at $q_{handover}$, the object to be exchanged has to be reachable by both partners. (subspace C_{reach}).

c) *Stability:* at $q_{handover}$, the robot and the human have to be stable regarding newton law of mechanics. (subspace C_{stab})

d) *Accessibility:* this constraint corresponds to the existence of a collision free path between $q_{handover}$ and q_{init} .

The planner implements a cost-based search in order to find $q_{handover}$ and a path for both agents (the human and the robot) to reach it.

Our approach: In order to account for the safety of the interaction and the legibility of the robot’s intentions, Kulic and Croft [19], Sisbot and Alami [30] introduced a set of HRI constraints that, basically, rely on and extend notions from the *proxemics* theory Hall [11].

In the handover context, we formulate these constraints in three sets (Mainprice et al. [23]). First, we consider comfort constraints (computed as a cost c_{comf}) that prevent - or, more precisely, try to avoid - generating awkward human postures. Second, we consider motion constraints to generate reasonable effort on the human side. These constraints depend on two parameters (displacement, and standing) and are computed as a cost c_{mot} . Finally, we also account for fluency constraints, limiting the total duration (computed as a cost c_{length}) of the handover, and favouring efficient plans.

Some of these desired properties such as the human displacement and the action duration may contradict one another. To balance the impact of the different properties on the output plan, we introduce a “mobility” parameter reflecting the human physical capabilities and his eagerness to obtain (or to give to the robot) the object.

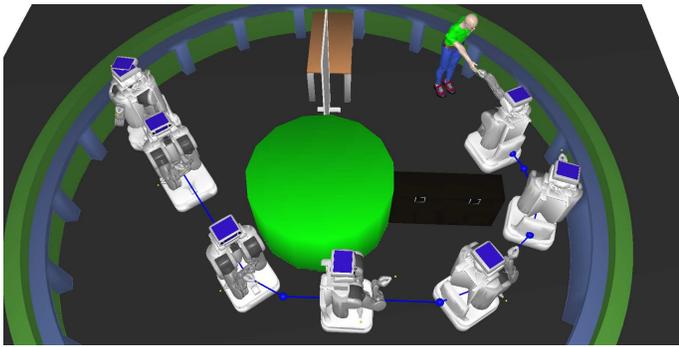
Indeed, the handover duration may generate discomfort if it does not match with the human possible *eagerness* or *urgency* to get the object. High “mobility” values will balance motion and comfort constraints to favour quicker plans, resulting in the final cost defined as :

$$c = (c_{mot} + c_{comf}) * (1 - m) + c_{length} * m$$

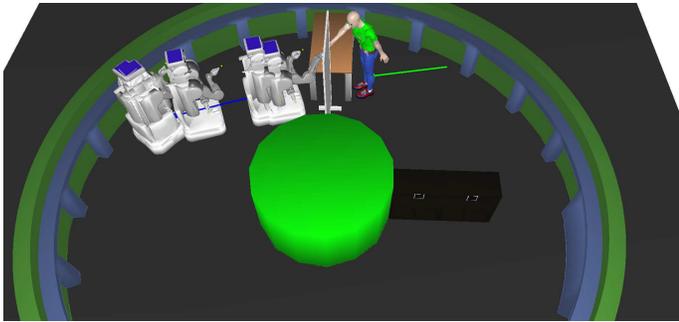
where $m \in [0 1]$ is the “mobility” factor.

Our approach relies on a combination of grid-based and sampling-based algorithms that consider the workspace obstacles and the kinematic models of both the human and the robot. In the initialization phase, navigation and accessibility grids are computed for the human and for the robot. Then an iteration is started, where the first step is to find a suitable human position. Next, a handover configuration (including both human and robot kinematics) is found based on this human position. Finally, a path is computed for the robot. If one of those steps fails, the algorithm loops back, otherwise a cost c is computed and if the solution is better than previous ones, it is stored. The process is stopped when the maximum allowed time reached or when it detects than no improvement is obtained.

Example: Figure 2 illustrates two possible solutions produced by the planner. We consider that the robot has already a bracket in its hand and need to give it to the human. In the case where



(a)



(b)

Fig. 2. Figures (a) and (b) represent 2 different situations where the needs of the human are different. In (a) the human needs the bracket to be delivered as fast as possible, the robot chooses the path with shortest estimated time and consequently involves also a contribution of the human to the effort. In (b) the human cannot move (due to his current occupation), the robot “does all the job”.

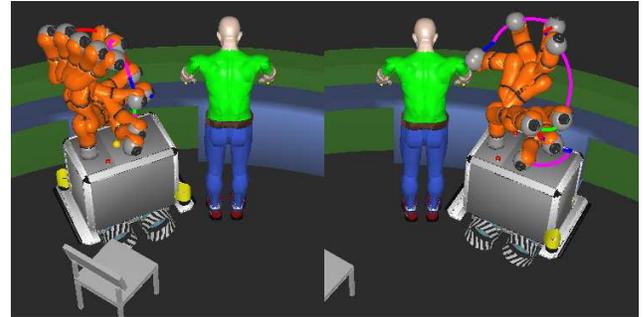
the human is busy in his current place, the shared effort should be reduced to minimum by setting the “mobility” parameter to 0 resulting in a solution (see fig. 2a) where the human needs only to rotate to get the object (this small rotation is also computed). In the case where the robot is informed that its human partner is eager to get the object as soon as possible, the “mobility” parameter is set to 1 and the resulting solution (see fig. 2b) will involve a “shared effort” from both the human and the robot.

IV. PLANNING HUMAN AWARE MOTION

Human-aware motion planning integrates in the environment description the position and posture (and possibly the motions) of the humans present in the robot vicinity. Since the emergence of Rapidly exploring Random Tree (RRT) algorithms, computing a path between two configurations has become a fairly simple task. It can be time-consuming but, except in highly constrained situations, it is almost always successful. However, the consideration of human-centered constraints calls for more specific planning schemes.

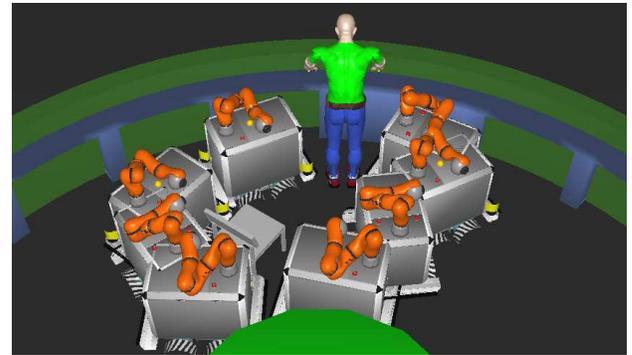
For instance, given a task including navigation and manipulation, the problem consists in finding a set of motion steps that are safe, readable and comfortable.

Safe Motion: To obtain a safe motion, using a simple RRT could be enough. By avoiding collision with the environment and the humans, the robot makes sure that nothing is damaged.



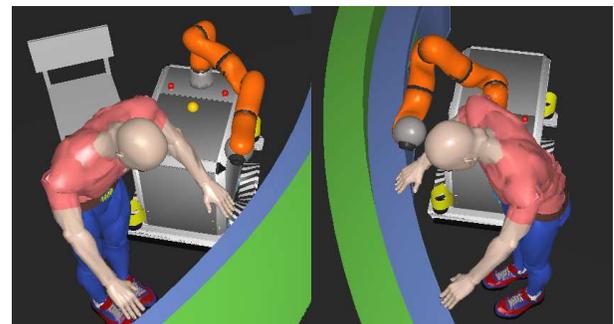
(a)

(b)



(c)

Fig. 3. The 3 steps: disengagement; navigation, reengagement/placement in shared space with the human. In figure 3a, the robot puts its arm in a safe position for navigation. Then in figure 3c, the robot navigates to the goal position but, instead of taking the shortest trajectory (i.e. between the human and the chair), the generated path passes away the chair in order to optimize the HRI cost of the motion. Finally, figure 3b represents the last step which is positioning the arm correctly for the task. Please notice that the configuration of the arm is prepared far from the human and then rotated toward him : this is an effect of the optimization of the HRI cost.



(a)

(b)

Fig. 4. Figures 4a and 4b correspond to the start and goal configurations.

Readable Motion: A one step motion planning instance, based only on a start position and a goal robot position, can result in a path that is difficult to interpret. We basically decompose such a motion into several, distinguishing steps where the robot and a human are really close and perform manipulation motion, and steps where the robot navigates in an environment populated by humans. In the example illustrated by figure 3, we define three steps: a “disengagement”

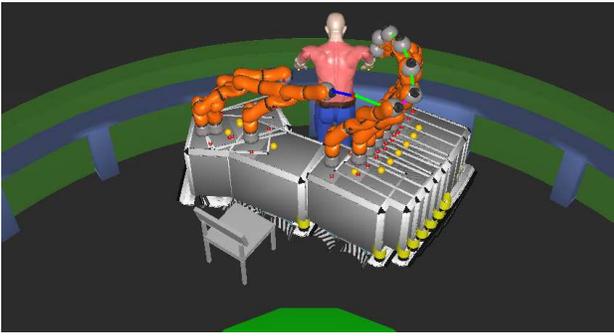


Fig. 5. Figure representing the same task as Figure 3 but planned with a simple RRT (Rapidly-exploring Random Tree [21]). The robot passes really close to the human.

motion, a navigation step, and a “reengagement” motion to reach the final configuration where the human and the robot are very close one to the other.

Comfortable Motion: In a order to take into account such constraints, we propose to use a TRRT (Transition-based RRT [15, 22]) algorithm with a human-aware cost-grid centered on humans

Example: In our example, the robot has to go from one side of the human to the other. The RRT generates a trajectory that is pretty close of the human whereas our method creates a trajectory that goes around the chair to avoid to navigate too close to the human (if possible). We illustrate this example with the Figure 3. In comparasion, in Figure 5, the path is computed based on a standard a RRT.

V. ELABORATING SHARED PLANS

This section involves the ability for the robot to elaborate a plan, *i.e.* a set of actions to be achieved by the robot and its human partners. This is the role of a so-called Human-Aware task Planner (HATP) [2, 20].

Such plan elaboration can be implemented based on Hierarchical Task Network (HTN) refinement which performs an iterative task decomposition into sub-tasks until reaching atomic actions [24]. The planning domain defines a set of methods describing how to decompose a task and can be seen as the How-to knowledge of the robot.

In HTN planning framework most part of the knowledge about the domain is provided in a procedural way to the planner which, in the industrial case, is really suitable because there are experts that have a higher view on the work to accomplish.

There are two types of tasks: methods and actions. A method is composed of subtasks (methods or actions again) that are partially-ordered. Those ordering constraints allow to force precedence of a task over other tasks. However a method can have several of such partially-ordered tasks which allows to give several ways to accomplish the task the method solves. On the other hand an action is a elementary task, that can not be decomposed, and that can be executed by the system. One important issue is to produce plans for the robot actions as

well as for the other participants (humans or robots). It can be tuned by setting up different costs depending on the actions to apply and by taking into account a set of constraints called social rules.

Agents and action streams: The robot plans not only for itself but also for the other agents. The resulting plan, called “shared plan” is a set of actions that form a stream for each agent involved in the goal achievement. Depending on the context, some “shared plans” contain causal relations between agents. For example, the second agent needs to wait for the success of the first agent’s action to be able to start its own action. When the plan is performed, causal links induce synchronization between agents.

Action costs and social rules: A cost and a duration function is associated to each action. The duration function provides a duration interval for the action achievement and is used, in one hand, to schedule the different streams and, in the other hand, as an additional cost function. In addition to these costs, HATP also takes into account a set of social rules. Social rules are constraints aiming at leading the plan construction towards the best plan according to some human preferences. The social rules we have defined so far deal with:

- undesirable states: to avoid a state in which the human could feel uncomfortable;
- undesirable sequences: to eliminate sequences of actions that can be misinterpreted by the human;
- effort balancing: to adjust the work effort of the agents;
- wasted time: used to avoid long delays between the actions of the human partner;
- intricate links: to limit dependencies between the actions of two or more agents.

In our planner, an action can be executed by one or several agents, in this last case it is called a joint action. The “social rules” are used as a filtering rules to penalize plans that would not ease the interaction between humans and robots. For instance, one of those rules controls the plan intricacy. It applies a cost for every causal link that goes from a stream to another since it would require synchronization during the actual execution. There is also a penalty which comes from the joint actions. In the current version, we decided to apply an exponential cost depending on the number of agents involved in a joint action. This highlights the difficulty of such actions as it requires all agents to be available at the same time and to contribute to a synchronized process. However, those rules only apply penalties. So even the best plan can be intricate when it is of absolute necessity.

Example: The aim of this example section is to highlight the features of our planner. It consists of a task where two humans have to fix brackets with the help of a robotic assistant. The robot’s aim is to ease the process, the humans will only focus on the task while the robot brings the parts and tools for all operations. The problem is such that some parts are easier for the human to do, such as pick a bracket from a box of tangled

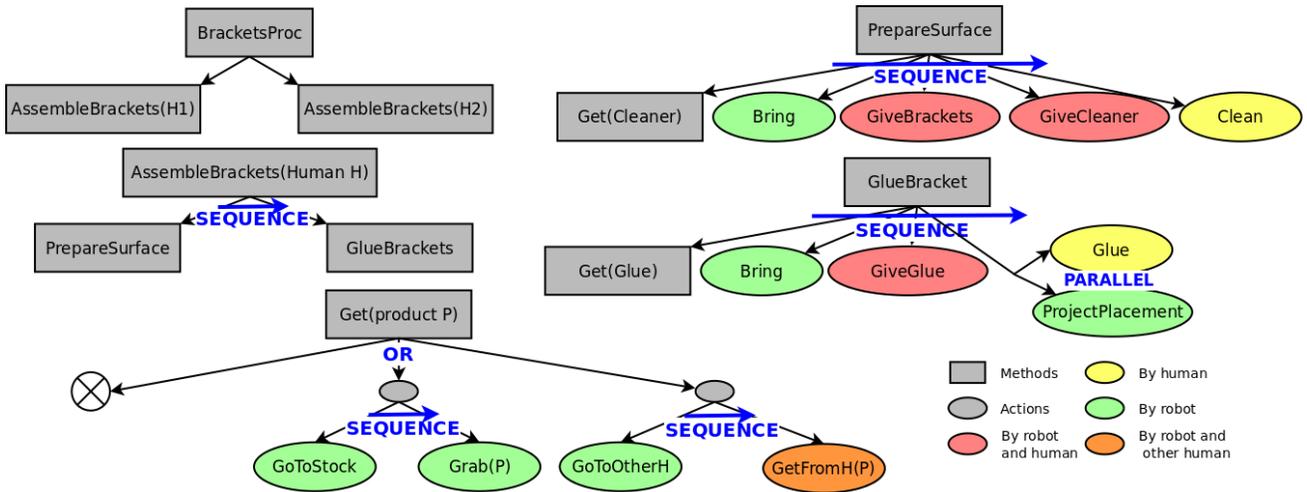


Fig. 6. This decomposition contains methods (grey rectangular shapes), and actions which are represented by colored ovals (with a specific color per agent or for joint actions involving two agents). The top-level method is `BracketsProc` which is decomposed in two methods one for each human. `AssembleBrackets` is hence called once per human, and contains the two main operations to assemble a bracket: clean the spot and glue the bracket. Both `PrepareSurface` and `GlueBracket` need a product to be carried out (respectively the cleaner/solvent and the glue). The robot has then two ways to fetch a product: go to the stock and grab it, or get it from the other human. The crossed circle (bottom right in the figure) represents the case where the human already has the needed product.

brackets, which is too challenging for the robot. On the other hand the robot plays a role in the assembly since it places itself near the human and project the exact position where to put the bracket as it is capable to locate itself more precisely than what a human could do.

The goal, is to assemble a bracket but in order to glue it in the right position some operations are needed: first the spot should be cleaned by the human, the robot should then give the bracket to the human, the robot then places itself near the human (see previous section) and projects on the scene the exact spot where the bracket should be placed. The human can then place and glue the bracket. However the glue and the solvent (the cleaning product) are only in limited quantity so the robot has to bring them at the right moment to one worker or the other. At the beginning of the experiment there are two tubes of solvent and one tube of glue. Their initial location might change from a run to the other, but they can be on one of the humans' desk or in one of the two stocks (the stock that is close to the desks or the one that is far).

The domain description to this problem is depicted in figure 6. Considering all the possible decompositions and variable bindings we get a total of 160 possible plans. The solution found reduces as much as possible the use of `GetFromH` and make the robot go to the stock to fetch the products, even if the geometric path seems longer. Indeed the penalty of joint actions is a lot higher than the cost to go to the stock. We set a high penalty to prevent the robot from disturbing the humans. The "best" task plan solution is presented in figure 7.

VI. RELATED WORK

We briefly discuss here related work. Concerning the human-robot handover, Strabala et al. [32] uses experimental set up to find the cues that lead to a handover. Cakmak et al.

[6] show that the intent of the handover can be made explicit through a spatial and temporal contrast: by moving from a passive posture to a handover posture at the right moment, the robot is able to show his intent. Complementing this approach, Cakmak et al. [5] have tried different postures for the robot to handover objects, where the naturalness of the posture and its consistency with previous occurrences play a major role beside the object position while handing it over.

Another ability is to share tasks and objectives with the humans, Nikolaidis and Shah [27] and Nikolaidis and Shah [26] show the importance and pertinence of having the the human and the robot share mental model to achieve a collaborative task.

In the context of planning Human-Robot interactive motion, an evaluation of the relative configurations and motion has been proposed in Kulić and Croft [18]. Sisbot et al. [31] use a cost function inspired from proxemics theory Hall [13] in order to generate paths which limits the discomfort of the human and promotes legibility of robot behaviour. Koay et al. [16] show how the posture of the humans influences his appreciation of the motion of the robot towards him. Another approach is the generation of legible trajectories and motions for the robot in a human environment. In Bennowitz et al. [3], Chung and Huang [7], the robot learns how the humans are navigating in order to limit its interference in their path. Sasaki and Hashimoto [29] chooses to use the human path: the behavior of the robot seems then more logical to the humans. When the robot is interacting with humans while navigating, it has to maintain a certain distance with the humans defined in the concept of proxemics Hall et al. [12]. A recent survey has been produced by Kruse et al. [17].

On the matter of task planning, there are a numerous approaches. From state space planning such as STRIPS Fikes and

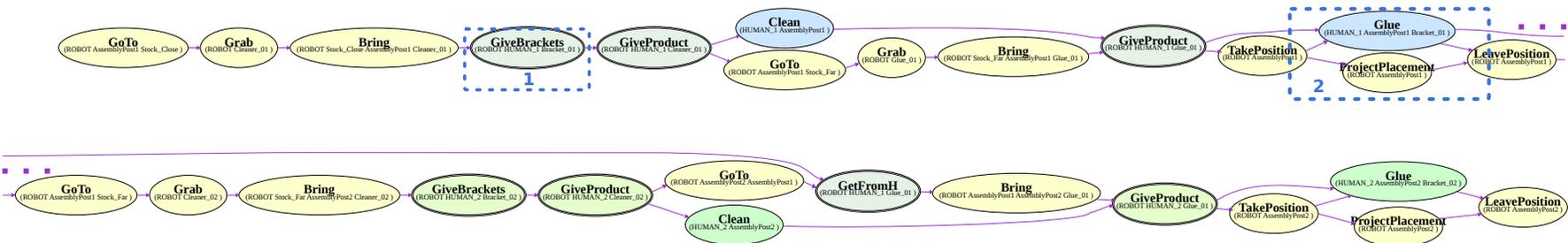


Fig. 7. The best solution task plan; yellow actions belong to the robot (ROBOT), the blue ones belong to the first human (HUMAN_1) and the green ones to the other worker (HUMAN_2). One can see that the robot does most of the job since it is responsible for carrying the different products and parts. The action depicted in the blue dashed rectangle 1 is a handover. It is a joint action which involves the robot and the first human. The second rectangle presents actions that the robot and the agent do in parallel. In this case actions are needed before and after to synchronize the actions and to ensure that the robot stays during all the gluing process.

Nilsson [9], to plan-space planning such as UCPop Penberthy et al. [28], to hierarchical task planning such as SHOP Nau et al. [25] and many others. However there are very few planners that actually explicitly consider the human while planning. To consider the human means to have it as an agent of the system but also to take in account special constraints to ease its interaction with the system. Some works Hoffman and Breazeal [14] try to predict the next action the human might do to prepare the system to those events. On the other hand Cirillo et al. [8] tries to predict the actions on a wider timescale. Instead of predicting its actions we decided to plan for the human, following the idea from Alami et al. [1], in order to have plan where both robots and humans act together depending on their capabilities. Finally some system do consider the human at all the levels Breazeal [4] and Fong et al. [10].

VII. DISCUSSION

We have presented a set of human-aware task and motion planners and illustrated how they can be pertinent to endow a collaborative robot with capacities to reason about humans and produce efficient and acceptable behaviours.

We have also shown that it is interesting in some situations to have the robot plan for itself but also for the human. This can be used when the robot is asked to perform a given action of set of actions that belong to a collaborative activity. They can also be used in order to endow the robot with pro-active behaviour based on an estimation of what the human can do.

Finally, we have presented how cost-based plan search can be used in such a context, in motion planning but also in task planning.

VIII. ACKNOWLEDGMENTS

This work has been conducted within the EU SAPHARI project (<http://www.saphari.eu/>) funded by the E.C. Division FP7-IST under Contract ICT-287513.

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