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Ingredients and a Framework of Dexterous Manipulation Skills for Robots in Human Centered Environment and HRI

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1. Introduction

Presence and importance of robots in human centered environment have grown significantly in recent years. For example, there are various ongoing as well as successfully completed projects, where the robots are expected to have different roles, such as cooperative partner [11], co-worker [12], companion and health care assistant [13], with dexterous manipulation capabilities to be well fitting in everyday human environment [10], to perform human-level manipulation tasks [5], etc. One of the common requirements of all such robots is to perform tasks in the human shared workspace. This is where the notion of dexterous manipulation becomes more prominent, because most of the times: (i) objects are designed to be used by human, hence the robot needs human like grasping and carrying capabilities, (ii) such tasks require manipulation of objects for the human partner or in human presence, therefore the robot needs to reason from the human perspective.

In Ref. [7], an overview and the requirements of dexterous manipulation have been presented in an *object-centered* manner. Therefore, the presented control architecture mainly focuses on grasp. In Ref. [3], a *hand-centric* dexterous manipulation taxonomy has been presented, which can be used to identify a manipulation strategy for executing a certain task. However, with the significant elevation of interest in the domain of human-robot interaction and socially intelligent robots, now there is a need to revisit the dexterous manipulation problem from *human-centered* perspective. The additional aspect of presence of human in the loop requires a set of human-centered constraints and preferences to be taken into account. For example, consider that the robot has to show some object to a human by grasping and holding it somewhere. In this rather simple task of *show*, the robot has to reason from the perspective of the human and to plan "how to grasp" and "where to hold or place the object" so that the other person can see it. Hence, for the same task, the goal configurations of the object and the robot depend on the relative position of the human. This makes such human-centered manipulation planner different from those developed for the robots in the industrial settings. We classify a subset of the human-level manipulation tasks in the human-centered environment, which require human like skills and reasoning from a human perspective, as *human-centered dexterous manipulation tasks* (*HC-DMT*). Example of such tasks could be *to give*, *to make accessible*, *to show* or to even *hide* or *put away* some object from the human. In general, such tasks require to incorporate the reasoning for dexterous manipulation beyond the reasoning about stability of grasp, placement and trajectory planning by adding the importance aspect of the human-centered reasoning based goal configuration planning.

In the next section, first we will identify some basic constraints, which a human-centered dexterous manipulation task planner should take into account. Then in section 3, we will outline some of the key system components of such task planners. Followed by this, in section 4, we will present a generalized framework for such task planning system. In section 5, we will point one instantiation of the task planning framework and present some results with different robots, in different situations for a set of different types of tasks. This will

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be followed by conclusion and pointer to future work.

2. Human Oriented Constraints on Configuration for Dexterous Manipulation Tasks in Human Environment

In this section, we will identify a subset of additional constraints, beyond the basic constraints of stability of grasp and placement, which a human-centered dexterous manipulation planner should be able to take into account.

(i) Constraint of Anthropomorphic Hand's Grasp: For various day-to-day tasks, the robot is supposed to perform manipulation actions by considering the feasibility of object to be grasped by the human. For example, put an object on the table so that the human partner can take it when required. Hence, there is an important constraint of graspable by the human hand, which the robot should be able to reason about.

(ii) Constraint of Simultaneous Compatible Grasps: For many tasks, hand-over of an object is necessary. This hand-over can be between two hands of the same agent or between two agents. In such cases, to facilitate the object hand-over tasks, the robot should be able to reason on how to grasp so that the object could also be grasped simultaneously by the other hand of the robot or by the human hand.

(iii) Object Feature based Constraints on 'To Grasp': For various tasks, it is necessary to take into account the alignment of a particular feature of the object with reference to the human. For example, for the task to show the label of the cold drink to the human, the robot should not grasp it in the way, which hides the label by its gripper.

(iv) Visuo-Spatial Constraint on 'To Place' Positions: This corresponds to the constraints on where the object could be placed. Various high level requirements of the task define the placement position of the object and such restrictions on the positions to place restricts the possibilities of a solution. For example, the constraint to place an object on a table is different from the visuo-spatial constraint from the human's perspective to place an object on the table so that the human can see and take it.

(v) Visuo-Spatial Constraint on 'To Place' Orientation: This corresponds to the constraints on how the object could be placed/held, so that some features of the object will be visible or graspable by other agent. For example, if the task is to give a cup of tea, the robot should be able to orient it in the way, so that the cup's handle will be towards the human.

(vi) Constraint of Robot's Gripper Alignment: For performing a task for the human, it is important to consider the aspect of being natural and social. For this, one of the factors is how the robot's gripper/hand is aligned towards the human. For example, if the robot will give/show some object by holding it in a way the gripper is pointing towards the robot, this might look awkward gesture and lack of dexterity from the human's perspective.

3. Dexterous Manipulation Tasks Planner System Requirements

In this section, we will identify some of the basic required components for developing a *human-centered dexterous manipulation tasks planner* (*HC-DMT-P*).

(i) Perspective Taking Reasoner: Basic notion of perspective taking refers to the ability to infer what is visible and reachable by the other agent. It is one of the key components, which facilitates reasoning for human-centered manipulation tasks. A dedicated system component is required to reason from the perspective of the human, to find the places, objects, and features visible and reachable by the human. So, that various visuo-spatial constraints associated with a task can be validated during the planning process. For example, if the task is to give some object, it will be the role of this component to provide the places that are commonly visible and reachable for the human and the robot, by analyzing from the human's perspective.

(ii) Dexterous and Anthropomorphic Grasp Planner: Ability to grasp objects of different shapes and sizes is important towards achieving dexterous manipulation capabilities. Moreover, Such grasp planners should be able to plan the grasps not only by the robot but also by the human (anthropomorphic hand). For example, for making an object accessible to the human, the task planner has to analyze the feasibility that the human will be able to grasp and take the object if placed in a particular position and orientation.

(iii) Placement Planner: Our notion of placement incorporates two types: (i) Put on support, e.g. make an object accessible to the human partner by putting it on the table close to the human. (ii) Hold in space, e.g. show an object to the human by picking and holding it at a place visible to the human. In both the cases of *put* and *hold*, from the planning point of view, the task planner needs the goal position and orientation of the object with respect to a given frame or human, based on various constraints. This will be the job of a placement planner.

(iv) Inverse Kinematics Planner: Given a start configuration of the robot in an environment (which is not a fixed and free workspace as the robot is working in human-centered dynamic environment), there is a need of inverse kinematics (IK) planner, which can quickly tell whether a particular attempt to grasp or place is feasible or not. Note that such IK planners are not supposed to be the complete trajectory planner. They are supposed to provide the collision free end configuration of the robot, for which the trajectory has to be planned.

(v) Trajectory Planner: Given a pair of start and end configurations of the robot, a trajectory planner will be required to plan the collision free trajectory. Depending upon the requirements, such trajectory planners might also take into account human-centered constraints towards generating comfortable and natural trajectories from the human's perspective.

(vi) Collision Checker: Most of the components mentioned above will required a collision checker, such as to find a collision free placement, grasp, configuration or trajectory. Moreover, since the human-centered environments are dynamic, such collision checkers should be fast and efficient to check almost in real time the potential collisions in the changing environment.

4. Towards a Generalized Framework for Human-Centered Dexterous Manipulation

Let us consider a dexterous manipulation tasks as a series of *pick* and *place* actions, i.e. the robot has to take (grasp or pick) the object and then place (put or hold) it, as shown in **Fig. 1**.

4.1 Closed loop planning for the pick and the place parts of a manipulation task

As shown in Fig. 1, C^{robot}_{grasp}, i.e. how to grasp restricts C^{robot}_{place}, O^{object}_{place}, P^{place}_{object} i.e. how and where the robot could place the object and vice-versa. In fact, the planning framework should reflect this notion of grasp placement interdependency, i.e. how we take hold of something depends what we want to do with that [16] [19]. Further, it has been shown that initial grasp configuration depends upon the target location from the aspect of task [1], as well as on the initial and the goal positions [18]. Therefore, if in a task there are both pick and place actions are involved, they should be planned as one task in a closed loop, instead of planning for picking and placing parts separately by treading them independent.

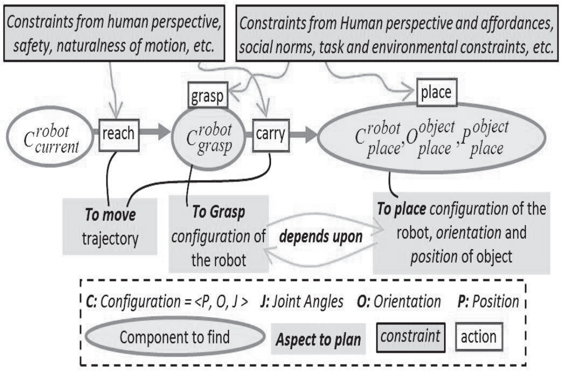

Fig. 1 We consider a typical *Huma-Cetered dexterous manipulation tasks* (*HC-DMT*) in human-centered environment, as a subset of reach, grasp, carry and place (hold/put) actions from the current configuration of the robot. Such *pick-and-place* tasks require to synthesize joint configurations, orientations and positions of robot and object at different stages of planning. The figure shows various influencing aspects and their inter-dependencies during different stages of planning for the task. It shows that how to get hold of an object depends upon where and what to do with the object. Therefore, grasp and placement planning should be in a closed loop, because of their interdependency. Further, planning for trajectory and planning for goal configurations might have different sets of constraints; hence, they should preferably be planned by well separated components to avoid unnecessary complexity

4.2 Separation of Configuration and Trajectory Parts of Planning

For performing *pick-and-place* type manipulation task, we the human, do posture based motion planning [14] [15]. Before planning a path to reach, we first find a single target posture. Then a movement is planned from the current posture to the target posture. As shown in Fig. 1, for manipulation tasks, at least there should be two components to plan: (i) the goal configuration of the robot and (ii) the trajectory to achieve that goal configuration. In addition to analogy of how we, the human, plan, there are other reasons to separate the planning of these two components. The goal configuration should incorporate various high-level constraints from human and social perspective, environment, nature of the task, robot, etc. Such constraints could change, which are not required to always introduce and incorporate at the trajectory planning level. For example, if the task is to show some object to the human, it should be the responsibility of a separate configuration planner to provide the goal configurations of the robot and object from the human perspective. Then, a dedicated trajectory planner should find a solution to reach that goal configuration. Depending upon the requirement it can be typical collision free motion planner or a planner that also takes into account some of the human centered aspects in motion, such as Ref. [6]. With this approach, if we have to ask the robot to show an object to two humans at the same time, that constraint could be easily passed into the configuration planner to get a goal configuration that is visible by both the humans. Then the same trajectory planner can be used to reach that configuration.

Therefore, we should avoid adapting the trajectory planner for each new task the robot will be expected to perform in day-to-day scenario. This will facilitate to choose different trajectory planners, depending upon the requirement or the robot, without replacing the part, which finds the socially accepted and expected goal configuration for a task. This also facilitates to better adapt the task planner for different tasks by providing the flexibility of introducing/removing any set of constraints to get a desirable type of final configuration without making any change in the trajectory planner and vice versa. However, these components should still function within a closed loop in the sense, if a particular configuration is not achievable by the trajectory planner, an alternative configuration should be found.

In summary, the core idea is, different stages of task planning should be aware about the relevant constraints and parameters to avoid the undesirable complexity the trajectory planner might gain with introducing configuration oriented various human-level tasks and constraints.

4. 3 A Generalized Dexterous Manipulation Task Planning Framework

Fig. 2 illustrates a generalized framework for planning a human-centered dexterous manipulation tasks (HC-DMT). In this framework, a task has to be represented in terms of various high-level constraints and their parameters. A subset of such key constraints from human-centered aspect has been discussed in section 2. Then a dedicated task planner (block 2) interprets those

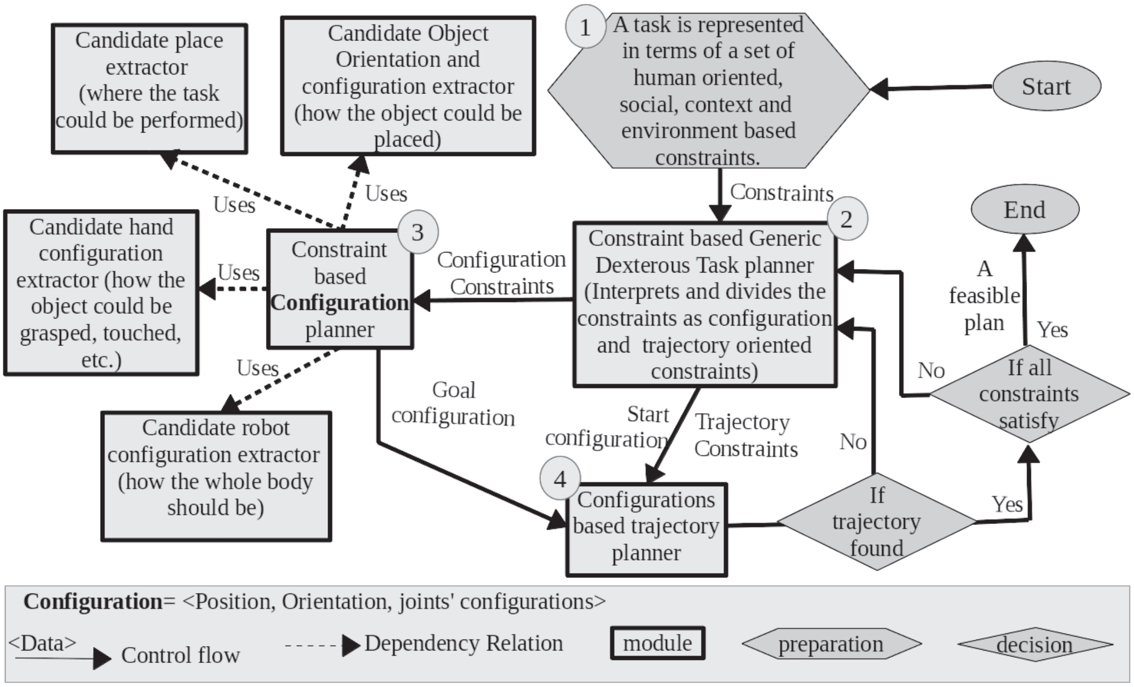

Fig. 2 A generalized framework for human-centered dexterous manipulation tasks (HC-DMT) planning. Task is represented as a set of constraints (block 1) from various perspectives. The generic dexterous task planner (block 2) interprets those constraints and distributes them appropriately to extract the goal configuration and to plan the trajectory. Note the well separated parts of planning the configuration (block 3) and the trajectory (block 4), functioning in a closed loop

constraints, converts them for lower level modules, divides and distributes them appropriately to different modules. A dedicated configuration planner (block 3) (as shown in Fig. 1, a configuration in this context consists of position, orientation and the joint angles of agent or object) finds a single or a set of goal configurations, which satisfies the constraints. To do so, the configuration planner might use other modules dedicated to grasp or placement computation (as shown by unnumbered blocks connected to block 3). A dedicated trajectory planner (block 4), uses the two configurations, the start and the found goal configurations, to find a feasible trajectory of the robot (whole body or arm only depending upon the requirement). If all the constraints are satisfied, a solution for the task is said to be found, otherwise as appropriate, as new configuration or trajectory might be requested. Note the well-separated components of configuration and trajectory planning parts, functioning in a closed loop.

5. Instantiation and Results

As discussed earlier, we, the human, first find a target posture and then plan a motion to achieve that. This target posture is found by evaluating and eliminating candidate postures based on constraint hierarchy: a set of prioritized requirements defining the task to be performed. Hence, manipulation planning is not only a trade-off among costs, but a constraint hierarchy. Only the postures satisfying a primary constraint are further processed to test the feasibility of additional constraints.

Inspired from this, we have begun towards developing a human-centered dexterous manipulation task planning system in Ref. [9]. The task planner interprets a hierarchy of constraints (representing the task to be performed), then finds a goal configuration and at appropriate stage involves a trajectory planner to find a feasible solution. One of the advantages of our approach is, it introduces relevant constraints at different stages of planning, which serves for faster convergence, by reducing the search space significantly before introducing the next level constraints. For example, a subset of constraints to represent the task of make *an object accessible* to the human will consists of: the object should be visible and reachable by the human, the object should be on a support, the object should be graspable by the human's hand, object's symbolic top should be maintained upright from the human's perspective, etc. All these constraints are used at different stages of the task planning to find the goal configuration of the robot and the object, by not only planning and reasoning for the robot but also from the human's perspective.

Fig. 3 Reasoning on the possibilities of the simultaneous grasps of different objects by two agents (by the robot's gripper and anthropomorphic hands) for the tasks requiring object hand-over

Fig. 4 (a) PR2 robot shows an object to the human, while ensuring that the object is maximally visible to him. Note that it also maintains the symbolic front and top of the object from the human's perspective. (b) PR2 robot gives an object to the human, at a place easily reachable to him, also ensuring the grasp feasibility of the object by him

Dedicated modules are used to realize different components of Fig. 2: a multi-fingered hands grasp planner [17], to compute a set of grasps, with a stability score, for objects of different shapes (see **Fig. 3**); Mightability Analysis (what an agent might be able to see and reach, without and with some efforts) [8], for visuo-spatial perspective taking based candidate placement position extraction; Ref. [4] for planning collision free path; Ref. [2] for obtaining a smooth trajectory for execution, etc.

Next, we show some of the results of different robots performing human-level tasks demonstrating the feasibility and strength of the framework.

Fig. 4 (a) shows the solution for the task of *show an object* to the human partner by PR2 robot. The constrains to make the object maximally visible and to maintain its symbolic front visible from the human's perspective, resulted into this planned placement orientation of the object towards the human. Fig. 4 (b) shows the *give object* task execution. The robot is giving an object to the human at a comfortable place, while ensuring the feasibility of grasp by the human. **Fig. 5** shows the *show object* task planned for another robot

Fig. 5 HRP2 robot shows a hidden object to the human, by holding it at a place that requires the human to put least effort to see it

Fig. 6 PR2 robot makes an object accessible to the human. The object was earlier not reachable to the human. The planner finds a feasible solution to pick (top), and places it (bottom), so that now the human will be able to easily see and take it, whenever required

Fig. 7 Jido robot hides an object. It also shows the interesting aspect of grasp-placement interdependency. The selected grasp in initial scenario (top), facilitates the final computed placement, to place the object by a different contact facet to make it completely hidden from the human's perspective (bottom)

HRP2. **Fig. 6** and **Fig. 7** show the successfully planned and executed solution for two other tasks, *make an object* accessible and *hide an object*.

The interesting aspect is the same system is able to produce a solution for different scenarios, tasks and robots. The same configuration planner has been used to plan different desired goal configurations for different tasks and for a same task in different situations, without affecting the trajectory planner. Different types of trajectory planners for different robotics platforms have been used, without affecting the configuration planner. The key is, different tasks, which can even be opposite in nature, should be represented in terms of constraints. For example, one of the constraints for the show task is that the object should be easier to be seen by the human, whereas for the hide task, it is opposite, that the object should be difficult to be seen by the human. Such semantic representation of the task could even be learnt by the robot from demonstrations [20].

6. Conclusion and Future Work

We discussed that there is a need to revisit the typical dexterous manipulation planning approaches to better incorporate the requirements and constraints from the perspective of the human partner, when the robots have to work in the human-centered environment. Such human-centered dexterous manipulation task planners should also be able to plan for configuration and the trajectory parts reasonably separated, to avoid their unnecessary interdependency and complexity. On the other hand, planning for the *pick* and *place* parts should be done by taking into account their interdependency. Further, in this paper, we have identified the basic constraints and key system requirements towards presenting a generalized framework for human-centered dexterous manipulation task planner. We have shown an instance of such planner and demonstrated the feasibility of planning for different tasks by different robots in different situations. One of the interesting future works is to explore other types of tasks and human oriented constraints, which require compliance with human motion and to investigate how the presented framework can be adapted to incorporate those aspects.

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