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Reactive Planning for Coordinated Handover of an Autonomous Aerial Manipulator

Jérôme Truc* and Daniel Sidobre* and Rachid Alami*

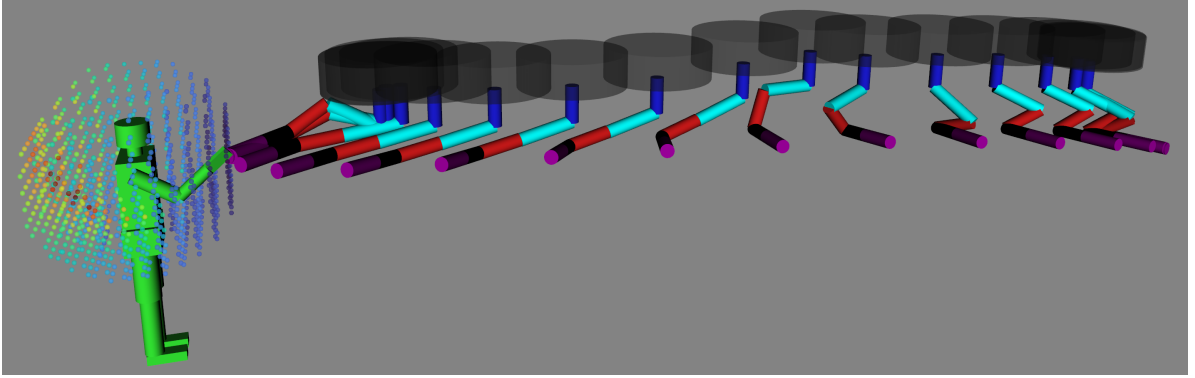


Figure 1: AAM coordinated motion for handover. Left: Human receiver and *human_grasp_grid*.

Abstract

In this paper, we present a coordinated and reactive human-aware motion planner for performing a handover task by an autonomous aerial manipulator (AAM). We present a method to determine the final state of the AAM for a handover task based on the current state of the human and the surrounding obstacles. We consider the visual field of the human and the effort to turn the head and see the AAM as well as the discomfort caused to the human. We apply these social constraints together with the kinematic constraints of the AAM to determine its coordinated motion along the trajectory.

keywords Human-Robot interaction, Coordinated motion planning, Autonomous aerial manipulators

1 Introduction

Autonomous Aerial Manipulators (AAMs) combine the flexibility of 3D motion and object grasping using their arm. They have all the necessary components to move and interact in a human-populated environment. KHAOS presented in [Truc et al.(2022)] provides a solution to generate human-aware trajectories for social navigation of aerial robot. These trajectories may allow an AAM to navigate in an environment populated with humans and various dynamic obstacles. It considers the kinematic constraints of the AAM and social constraints such as the visual field and the discomfort generated to humans. We know that these constraints are valid in the proximity of humans and can therefore be used for a handover task. Abrupt motions or interruptions in a

robot's motion can be uncomfortable for the human and affect the human's understanding of its intention. We therefore need a system able to control smooth motion [Yang et al.(2022), Corsini et al.(2022)].

In this paper, we address the handover problem, which involves coordinating the navigation approach, base and arm pre-positioning, and final motions of an AAM to transfer an object to a human safely and without causing too much discomfort. After presenting the state of the art, we propose an AAM model. Then we propose a method to determine the complete final state of the AAM for a handover task. From this, we propose an extension of KHAOS to generate the complete human-aware trajectory of the AAM with the particularity of coordinating the motion of its arm and its base. Finally, we present results of trajectories generated with this extension to show the capabilities of our planner in simulation.

2 Related work

Handover is a generic term used in robotics to describe a joint action to exchange an object. In our case, this action is performed between a human and a robot where each can have the role of the giver or the receiver [Fiore et al.(2016)]. A recent review [Ortenzi et al.(2021)] classifies the handover into two main phases, pre-handover and physical exchange of the object. This paper concerns the pre-handover phase, which itself comprises many stages. First, it is necessary to determine the grasp of the object envisaged by the human, which will induce the grasp by the robot itself [Saut et al.(2010)]. This grasp depends first of all on the geometry of the object [Miller et al.(2003)]. Complex environments can influence the grasp choice especially when

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objects are close to obstacles [Berenson et al.(2007)]. An interesting approach consists in generating a representative list of grasp and then choosing a good one [Saut and Sidobre(2012)] possibly using neural networks [Yang et al.(2020)]. Since the gripper does not allow to relocate the object, the initial grasp is maintained throughout the task. Therefore, it is necessary to predict the evolution of the human's posture and its close environment for a good object exchange configuration [Li and Hauser(2015)]. The handover location is chosen as part of a shared effort between the human and the robot [Mainprice et al.(2012)] using a sampling-based planner and a cost map taking into account visibility, human posture, and safety [Mainprice et al.(2010)]. The way to approach a human is studied in [Koay et al.(2007)] where people generally prefer a frontal approach, while in [Dautenhahn et al.(2006)] they show a preference for a left or right approach. The exchange area can be reduced by considering the constraints of the human arm [Vianello et al.(2021)] to avoid musculoskeletal disorders. It can be applied to the robot arm in order to achieve a more sociable behaviour [Rasch et al.(2018)].

To guide the robot's choices for a handover and to help the human understand these choices, it is important for both to communicate their intentions. Human's gaze provides a lot of information and can affect handover timing [Moon et al.(2014)] combined with head motion [Gharbi et al.(2015)]. Aerial robots have very limited means to communicate and can be considered as pets by humans [Cauchard et al.(2015)]. Many signals are therefore transmitted by their motion, in particular by the shape of their trajectories [Szafir et al.(2014)] or their gestures [Jensen et al.(2018)]. Humans move and give objects by coordinating the motions of their legs and arms [Cakmak et al.(2011)]. Numerous systems stop the motion between navigation and handover phases. To our knowledge, there is no work in Human-Robot Interaction (HRI) on the coordinated motion of an AAM interacting with a human during a handover. It is necessary to look at the fields of motion planning for mobile manipulators as presented in a review from Sandakalum et al. [Sandakalum and Ang Jr(2022)] and co-manipulation to have find work relating to the generation of coordinated motion of a robot equipped with a mobile base and a manipulator arm.

A complete and complex model of the human is needed to take into account ergonomic requirements for a worker collaborating with a mobile manipulator [Peternel et al.(2017)]. The coordinated motion of a mobile manipulator is planned offline for precise welding tasks [Vazquez-Santiago et al.(2021)] or in real time [Li and Xiong(2021)]. Only the real-time solutions are suitable in the HRI context. Several behaviors to coordinate the motion of a mobile manipulator are possible, they favor the motion of the base or the arm [Xing et al.(2021)]. The concept of manipulability defined by Yoshikawa [Yoshikawa(1985)] allows to define a good behavior [Zhang et al.(2016), Huang et al.(2000)], which avoids singularities from a

control point of view but does not necessarily ensure a good motion in a HRI point of view.

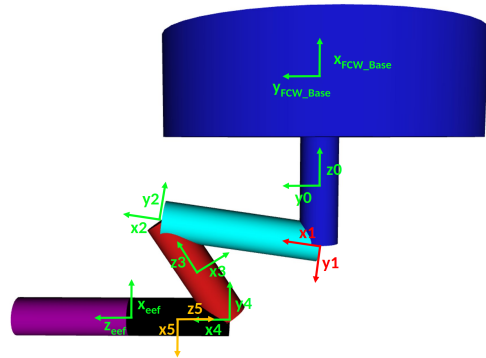


Figure 2: AAM model used for collision checking and the platform frames consisting of the multi-rotor (larger blue cylinder), the equipped arm (small blue, cyan, red and black cylinders) and object to be exchanged (purple cylinder). Each reference frame represents a rotary joint about the z_i axis.

3 AAM model

To demonstrate the possibilities of the proposed planning system, we realize simulations with a model build from a hexa-rotor base vehicle and a Jaco arm illustrated in Fig. 2. Jaco's arm has 6 degrees of freedom with a maximum reach of 0.9m. The 6 propellers of the base are tilted and provide the stability and precision needed to operate in close proximity to a human. In Fig. 2 larger blue cylinder corresponds to the bounding cylinder of the hexa-rotor. The small blue, cyan, red and black bounding cylinders correspond to the parts of the kinematic chain of the arm. Finally, the purple cylinder represents an example of an object to be exchanged. We also introduce the different frames that define the location of the AAM joints as well as the *end_effector* holding the object to be transferred (purple cylinder). Each reference frame represents a rotary joint about the z_i axis.

4 Reactive final state estimation

We detail in this section our proposed method to define the complete final state of the AAM for a handover in a reactive way. Taking into consideration the human, the static and dynamic environment as well as the dimensions of the object to be transferred.

To approach the human in good conditions of safety and comfort during handover, many parameters must be taken into account such as: human's posture, human and robot grasp positions, the geometry of the object to be exchanged, the robot's geometry and abilities and the various obstacles in the surrounding space. To deal with these points, we propose a solution based on 3D cost grids and inverse kinematics. A first grid named *human_grasp_grid* and centered on the human with whom handover is considered, aims to determine the best possible handover position for the human's current posture and surrounding obstacles. For each posi-

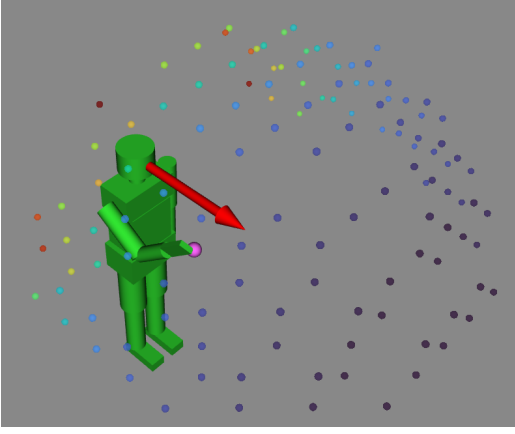


Figure 3: *base_goal_grid* (resolution = 0.2 m) when the human is looking ahead. Warm (cold) colours represent high (low) costs respectively. Pink sphere corresponds to the position of the *human_grasp_grid* used to generate the *base_goal_grid*.

tion of the *human_grasp_grid*, various configurations of the object to be exchanged are tested. From the position of the object, it is possible to determine the position of the end effector and thus generate a second grid named *base_goal_grid* in order to determine the best position for the base of the AAM. By selecting the position of the *end_effector* and the base, it is possible to define the configuration of the AAM's arm by inverse kinematics. Everything is updated in real time to allow the system to be reactive and adapt to the various changes of the situation.

human_grasp_grid The *human_grasp_grid* shown around the human in Fig. 1 thus represents potential human grasp positions for the envisaged handover. Each position is associated with a cost calculated using the following cost function:

$$C_{human_grasp_grid} = \frac{C_{closest_human_hand} * (C_{vis} + C_{turn})}{C_{torso_dist}} \quad (1)$$

where $C_{closest_human_hand}$ is the distance from the grid cell to the nearest human hand, C_{vis} is the visibility cost defined in [Truc et al.(2022)] considering human's visual field and the effort to turn the head to see the robot, C_{turn} is an angle originating in the human torso and formed between the front of the human torso and the cell and C_{torso_dist} is the distance from the cell to the human torso.

By using this cost function, it is ensured that a target is found not far from one of the human's hands ($C_{closest_human_hand}$), even if it is not reachable, and that distant positions (C_{torso_dist}) are favoured for safety. Visibility and effort to see (C_{vis}) are also considered to take into account the human's gaze, while a C_{turn} cost is introduced specific to the effort required for the human to turn around regardless of the direction they are looking.

shared_object Once the *human_grasp_grid* has been generated, we start to traverse it starting from the low-

est cost. This gives us a position where the human can catch the *shared_object*. In our implementation, we consider a cylindrical object that will be caught at one end by the human and other end by the AAM's *end_effector*. The position corresponds to one end of the *shared_object*, and we need to define the location of the other end. To do this, we sample the surrounding space by incrementing an angle around the position to define a preferred configuration of the *shared_object*. At the end of this operation, we obtain a list of configurations for the *shared_object* to which we apply the following cost function:

$$C_{shared_object} = \frac{C_{vis}}{C_{human_head_dist}} \quad (2)$$

where C_{vis} is the visibility cost defined in [Truc et al.(2022)] considering human's visual field and the effort to turn the head to see the robot and $C_{human_head_dist}$ is the distance between the end of the *shared_object* caught by the AAM's *end_effector* and the human's head

base_goal_grid From the list of configurations of the *shared_object*, we now know the possible positions for the *end_effector*. Starting from the position where C_{shared_object} is minimal, we generate a new cost grid named *base_goal_grid* which this time allows us to determine the position of the AAM base. The cost function used is similar as C_{shared_object} , simply $C_{human_head_dist}$ becomes the distance between the base of the AAM and the human's head.

The result can be seen in Fig. 3 where the position of the *human_grasp_grid* that is being considered is represented by a pink sphere close to the human's right hand. We can notice the absence of a position at the back of the human as this would force the base to be too close to the human, which is not acceptable with our parameters. Lowest costs corresponding to cold colours correspond well to the positions furthest from the human and in his visual field.

AAM's arm The last step is to determine the configuration of the AAM's arm. This is done by the use of inverse kinematics starting from the position of the *end_effector* and linking the position of the base. The orientation of the *end_effector* is fixed by the grasp on the *shared_object*, so the solution of the inverse kinematics is unique. The calculation is performed for each cell of the *base_goal_grid* to select the most interesting configuration. To do this, we sum the visibility cost ($\sum_{i=1}^N C_{vis}$ with N the number of links in the arm) of each part of the arm to keep the lowest cost configuration. Thus, we favour the visibility of the arm by the human.

5 AAM Coordinated motion

To deal with the case of coordinated motion for an AAM performing a handover task, we propose an extension of KHAOS presented in [Truc et al.(2022)]. Complete

state representation of the AAM is given as follows:

$$\text{AAM state} \left\{ \begin{array}{l} x_B, y_B, z_B \\ v_{x,B}, v_{y,B}, v_{z,B} \\ q_{w,B}, q_{x,B}, q_{y,B}, q_{z,B} \end{array} \right\} \text{ for the Base}$$

$$\left\{ \begin{array}{l} \mu_{i=1..6} \end{array} \right\} \text{ for the arm}$$

$$\left\{ \begin{array}{l} x_O, y_O, z_O \\ v_{x,O}, v_{y,O}, v_{z,O} \\ q_{w,O}, q_{x,O}, q_{y,O}, q_{z,O} \end{array} \right\} \text{ for the Object}$$

which includes the positions x_B, y_B, z_B (and x_O, y_O, z_O), the speeds $v_{x,B}, v_{y,B}, v_{z,B}$ (and $v_{x,O}, v_{y,O}, v_{z,O}$), and then the quaternions $q_{w,B}, q_{x,B}, q_{y,B}, q_{z,B}$ (and $q_{w,O}, q_{x,O}, q_{y,O}, q_{z,O}$) for the base (and the object) respectively. Manipulator arm joint states are also represented by μ_i .

Noisy trajectories KHAOS is based on a stochastic optimizer that generates a large number of noisy trajectories around its input trajectory to be optimized. It then sorts the randomly drawn positions according to human-aware costs, and the robot's kinematic constraints to update the optimised trajectory. Initially used to generate a trajectory for the base of an AAM, we first propose to use a KHAOS trajectory applied to the object to be transferred to the human. Instead of the positions of the base, it is therefore the positions of the object that are noisy. In addition to the object positions, we also noise the joint states μ_i of the arm. From the positions of the object and the arm joint states μ_i , we can determine the position of the base by direct kinematics.

Human-aware costs and kinematic constraints

Costs and constraints used in the initial KHAOS version [Truc et al.(2022)] are reused in this extension for coordinated motion. Namely, C_{dis} is representative of the discomfort caused to humans considering relative speed and distance between humans and AAM, C_{vis} considering the visual field of the human and the effort to turn the head and see the robot, $C_{obstacle}$ related to collisions with the environment and finally the kinematic constraints of the AAM are applied to the object and the AAM's base. In addition we propose two additional costs: $C_{torque} = \sum |\dot{\mu}_i|$ to limit torque variations of the arm along the trajectory and $C_{gap} = z_O - z_B - d$ to manage the difference in altitude between the base and the object where z_O is the altitude of the object, z_B is the altitude of the base and d is a configurable distance allowing the gap between the object and the base to be set.

All these costs are used to sort the noisy states of the AAM and generate a human-aware trajectory that respects the kinematic constraints of the AAM. The trajectory thus provides a smooth and coordinated motion of the AAM.

Simulation results Using the previously proposed AAM model, Fig. 1 shows a first coordinated handover. The approach is frontal and the human's field of view has little impact. We observe a smooth motion allowing the robot to perform a handover task without having to stop between navigation and arm deployment phases.

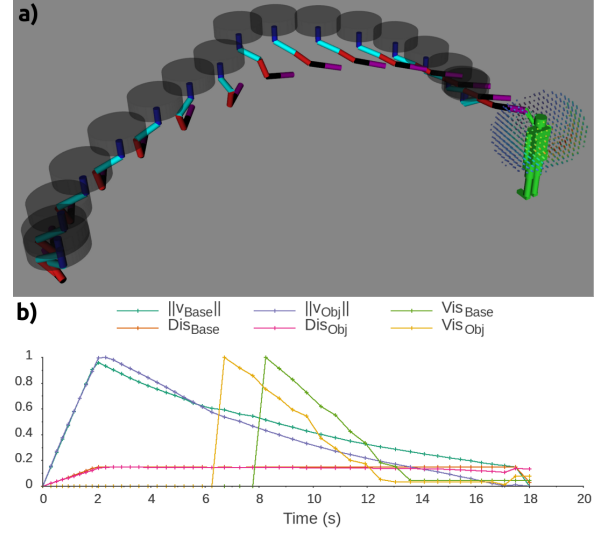


Figure 4: Human's visual field effect when the AAM approaches from the side: a) AAM coordinated motion deviated to move into the human's field of view before approaching. b) Magnitude speed, Discomfort cost and normalized visibility cost over time for AAM base and object. The maximum discomfort value is set to 0.15, limiting the AAM speed.

The influence of the human's field of view is shown in Fig. 4 where the AAM starts several metres to the left of the human. The trajectory is deviated so that the AAM appears and signals its presence to the human before completing its approach. We observe that the speed of the AAM accelerates strongly at the start and is quickly limited by the discomfort constraints limited to 0.15 in this example. The AAM becomes visible about 10s before the end of its motion where the visibility cost is maximized. Thereafter, the visibility cost is progressively reduced, indicating the planner's ability to make the AAM visible during the handover.

Finally, Fig. 5 shows the AAM starting several metres behind the walls where the human is located. The human is located in a confined space simulating a situation where he is working on an electrical panel while waiting for the AAM to bring him a tool (purple cylinder). The current state of the human and the surrounding obstacles do not allow direct access for a handover. The planner therefore proposes a final state for the AAM located at the back of the human by approaching the tool close to his left hand, which is the most available hand in this configuration.

6 Conclusion

We present an extension of KHAOS [Truc et al.(2022)] to address the handover problem. Initially designed to generate the human-aware trajectory of a multi-rotor respecting its kinematic constraints, we extend the system to an autonomous aerial manipulator (AAM). We introduce a method to compute the AAM final state reactively for a safe handover while limiting the discomfort caused to the human. We use the constraints initially applied in KHAOS, especially the consideration of

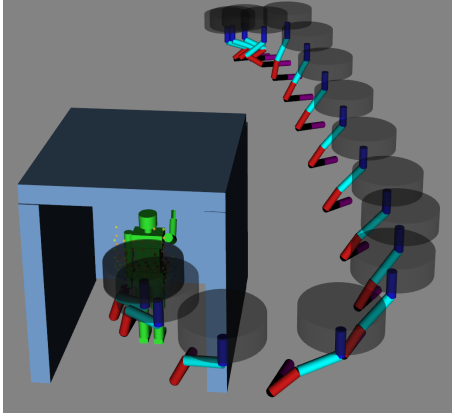


Figure 5: Human working on an electrical panel in a confined space. AAM starts several meters behind the walls and proposes handover behind the human’s back.

the kinematic constraints of the AAM, the discomfort caused to humans and their visual field. Two additional constraints specific to the AAM arm and the object to be transferred to the human are introduced. We thus generate a human-aware trajectory for the coordinated motion of the AAM that is smooth and safe while benefiting from the reactivity of KHAOS.

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