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A Multi-Modal Control Method for a Collaborative Human-Robot Building Task in Off-Earth Habitat Construction

Hugo Loopik and Luka Peternel

***Abstract*— Space exploration is characterized by a limited amount of resources and tools. This particularly stands out in habitat construction, where heavy machinery like cranes are unavailable and manual work still plays a key role. To mitigate this, we propose a human-robot collaboration method for habitat construction tasks, which involve several key sub-tasks: grasping objects of various shapes, carrying them, and aligning them for assembly. The proposed method is based on an impedance controller and includes four modes of operation, that are tailored for specific sub-tasks. Each mode prescribes a robot stiffness behavior, needed for collaborative execution. The human operator can easily switch between the mode in real-time via a voice interface. To demonstrate the functionality of the proposed method in the construction task, we performed an experiment using KUKA LBR iiwa robot arm and qb robotics SoftHand robotic hand. These results indicate that the method offers a practical solution for human-robot collaborative construction tasks.**

I. Introduction

In the past, human-made living structures on Earth were predominately built manually out of bricks or other small building blocks. Nowadays, construction cranes and other tools significantly help with the building process, especially when bigger and heavier modules are used. Nevertheless, when trying to build a habitat in an off-Earth environment like Mars, much of the heavy machinery and tools are unavailable, due to the limited payload of the spaceship. Furthermore, if the habitat is built inside a cave to offer protection from solar radiation [1], the construction process is also confined to smaller places, where machinery would not fit. Hence, the construction process has to be adjusted to these limitations.

The Rhizome project of the European Space Agency plans to build a human habitat in existing lava caves on Mars [1]. The aim of the project is to build these living structures out of 3D-printed concrete voronoi building modules [2]. These building modules, which have variable non-rectangular shapes, need to be picked up from the printing location, and carried to the place where the wall of the living structure is being built. The carried module then has to be fit in the existing wall. Collaborative robots are envisioned to safely assist humans in this project, in which the robot handles the heavy load aspects, while the human can take over the cognitively complex aspects of the task (see Fig. 1).

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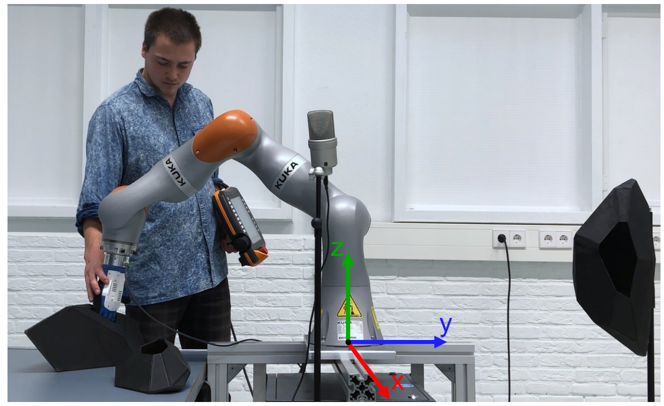

Fig. 1: Experiment setup for collaborative building in an off-Earth habitat construction scenario. Black objects are prototypes of voronoi building modules. The robot base frame is indicated with arrows.

Human-robot collaboration (HRC) provides safe and efficient methods for tasks where the advantages of humans and robots can be combined [3]. The state-of-the-art HRC methods enable different robot behaviors required for the examined task: assembly of mechanical components [4], carrying objects [5], handover of objects [6] and sawing of objects [7]. Nevertheless, the identified construction task is composed of a specific set of sub-tasks, which require different modes of operation in a unified framework.

We identified four key sub-task for the given construction task. 1) The module pick-up sub-task requires human cognitive capabilities to physically guide the robotic hand for successful grasping. 2) During the carrying sub-task, the human should control the motion on the trajectory, while the robot should carry most of the module weight along that path. 3) In the end, the module's orientation must be aligned to fit the appropriate place in the wall structure. 4) When the human temporarily attends to other tasks, such as inspection of the building progress, the robot must remain in a fixed position and orientation.

Therefore, we developed a specialized control method for collaborative human-robot construction, with multiple modes of operation. In this process, the human is able to control the mode of operation by a voice interface. The carrying path and the state of the task are controlled by physical interaction. The modes change the stiffness behavior of the robot, so the human can fix/release position, orientation, or a combination of both. The state of the task is defined by the horizontal position of the robot's end-effector. On the other hand, the robot controls the position trajectory along the vertical axis, based on the current state, to perform the carrying of voronoi modules.

In state-of-the-art methods for human-robot co-manipulation [4], [7], [5] the robot trajectory follows a defined position. In other words, each time/phase stamp of trajectory has a unique position. In the proposed approach, only the position in vertical axis is defined in order to perform the carrying aspect. Each horizontal position has a prescribed vertical axis position. However, the position in horizontal plane is free for the human to choose, to follow different paths required for flexible construction.

We demonstrated the developed method with experiments using KUKA LBR iiwa collaborative robot arm and qb robotics SoftHand performing the given construction task.

II. Methods

The developed method for HRC consists of four modes that correspond to the four identified sub-tasks. The human can switch between these modes using voice commands. While the *main mode* provides most of the functionality, the other three modes supplement it to ensure that the identified sub-tasks in the construction task can be performed. Modes change the prescribed stiffness behavior of the robot, which is then governed by an interaction control system composed of an impedance controller and a null-space controller.

A. Modes of operation

The four designed modes of operation are: *locked*, *free*, *main* and *orientation*. *Locked mode* fixes the robot's position and orientation, and is used when the human needs to temporarily attend to other tasks. *Free mode* unlocks the robot's position and orientation, and is used for the module pick-up sub-task, where the human guides the grasping of the voronoi module. *Main mode* is used for collaboratively carrying the voronoi module between the pick-up location to the assembly location. *Orientation mode* unlocks the orientation and locks the position of the robot. It is used for aligning the voronoi module to fit in the wall.

The activating/locking and freeing of different axes is done by changing the translational and rotational Cartesian stiffness between high and low values. For the activated/locked condition, we used 800 N/m and 40 Nm/rad, respectively. For the free condition, 0 N/m and 0 Nm/rad were used, respectively. Each mode and corresponding combination of stiffness settings are shown in table I.

TABLE I: stiffness in the different operational modes

Mode:	***Main***	***Locked***	***Free***	***Orientation***
K_x	Low	High	Low	High
K_y	Low	High	Low	High
K_z	High	High	Low	High
$K_{\theta,\phi,\psi}$	High	High	Low	Low

1) Main mode: In the *main mode*, the human is able to determine the position of the to-be-assembled module in the horizontal plane (i.e., x-axis and y-axis of the robot base frame). Simultaneously, the robot carries the weight by controlling the vertical part of the reference trajectory in z-axis of the robot base frame. The reference trajectory is not time/phase dependent but state dependent, where state is defined by the position along the x-axis and y-axis:

$$z = f(x, y), \tag{1}$$

where the relationship f between the state (x, y) and desired z-axis trajectory can be learned using human demonstration [8]. The initial value of the trajectory should correspond to the height of the module pick-up location. The final value of the trajectory should correspond to the height of the location where the voronoi module should be placed in the wall.

To enable the human to control the state of the task, the robot should be compliant in the x-axis and y-axis, therefore the stiffness in the horizontal plane is set to zero. The vertical stiffness is set to a high value in order to ensure that the reference z-axis trajectory is followed, and that the impedance controller compensates for the unknown gravity of the module. This way, the robot is carrying the weight of the voronoi module, but the human can freely control the motion. Since the trajectory is independent of time, the human can do the task at their preferred pace and can even backtrack if needed. The rotational stiffness around all three axes is also set to a high value, in order to prevent the module from swinging around.

We also created an obstacle-avoidance functionality in the main mode, where obstacles can be incorporated into the controller. This functionality adds virtual boundaries around the detected obstacles and prevents the human from entering them. Practically, when the end-effector is guided inside the virtual boundary, the reference position stays at the boundary, while horizontal stiffness is temporarily increase in the direction perpendicular to the boundary. Based on this, the interaction control system commands a force that moves the robot out of the obstacle zone, ensuring a safe operation.

2) Locked mode: In *locked mode*, all translational and rotational stiffnesses are set to high values. Thus, the user cannot change the reference position along z-axis, or move/rotate the end-effector of the robot arm in any way. This mode can be activated anywhere during the operation to pause the main task. It can be used to fix the robot pose, while the human temporarily attends to other tasks, such as inspecting the wall to see where the currently grasped module might best fit. Furthermore, the robot starts in this mode when the system is initialized or restarted.

3) Free mode: In *free mode*, all translational and rotational stiffness are set to zero, so the human can freely move the endpoint to any position and orientation. This mode is used to move the hand to the module that is to be grasped. The human operator also uses the voice interface to open and close the robotic hand, while guiding the more cognitively complex grasping sub-task.

4) Orientation mode: In *orientation mode*, the translational stiffnesses are set to high values, and the rotational stiffnesses are set to zero. This means the human can rotate the module that the robot is carrying. Due to high translational stiffness, no positional movement is possible, which makes it easy to only adjust the orientation. This mode is useful for aligning the voronoi module before it is placed in the wall.

B. Robot interaction control system

The behavior defined for each mode is controlled by a robot interaction control system. This controller includes both an impedance controller for ensuring the desired stiffness behavior and a null-space controller that handles the redundant degrees of freedom.

1) Impedance control: The developed robot interaction control system is based on the Cartesian impedance control. A benefit of this impedance controller is that the stiffness in each direction and orientation of Cartesian space can be controlled separately. Impedance control is based on a virtual spring-damper system to govern the interaction between the robot's end-effector and environment/human. The interaction force/torque $\boldsymbol{F}_{ext} \in \mathbb{R}^{6\times 1}$ is defined as

$$\boldsymbol{F}_{ext} = \boldsymbol{K}(\boldsymbol{x}_r - \boldsymbol{x}) + \boldsymbol{D}(\dot{\boldsymbol{x}}_r - \dot{\boldsymbol{x}}), \quad (2)$$

where $\boldsymbol{x}_r \in \mathbb{R}^{6\times 1}$ is a desired reference pose, and $\boldsymbol{x} \in \mathbb{R}^{6\times 1}$ is the actual end-effector pose measured by the robot. $\boldsymbol{K} \in \mathbb{R}^{6\times 6}$ and $\boldsymbol{D} \in \mathbb{R}^{6\times 6}$ are the stiffness and damping matrix, respectively. The position and orientation axes are defined as $\boldsymbol{x} = \begin{bmatrix} x & y & z & \theta & \phi & \psi \end{bmatrix}^T$. The damping matrix was defined to achieve critical damped system and depended on the current stiffness matrix as $\boldsymbol{D} = 2 \cdot 0.7\sqrt{\boldsymbol{K}}$. Since the collaborative robots are controlled by the torque in the joint space, we used the following joint space controller

$$\boldsymbol{\tau} = \boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{C}(\boldsymbol{q}, \dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{g}(\boldsymbol{q}) + \boldsymbol{J}(\boldsymbol{q})^T \boldsymbol{F}_{ext}, \quad (3)$$

where $\boldsymbol{\tau} \in \mathbb{R}^{7\times 1}$ is the joint torque vector, and $\boldsymbol{q} \in \mathbb{R}^{7\times 1}$ is the joint position vector. $\boldsymbol{M} \in \mathbb{R}^{7\times 7}$, $\boldsymbol{C} \in \mathbb{R}^{7\times 7}$ and $\boldsymbol{g} \in \mathbb{R}^{7\times 1}$ are the mass matrix, the Coriolis and centrifugal matrix and the gravity vector, respectively. $\boldsymbol{J} \in \mathbb{R}^{6\times 7}$ is the Jacobian matrix used to transform the end-effector force in joint torques.

2) Null-space control: Since we are using a robot with redundant degrees of freedom, we have to account for the joint configuration in order to not obstruct the task executions or human safety. To do this, we used an additional Cartesian impedance controller in null-space that controls the elbow position (i.e., fourth joint). The null-space joint torques for the elbow position control are calculated similarly to the main impedance controller: $\boldsymbol{\tau}_{el} = \boldsymbol{J}_{el}(\boldsymbol{q})^T \boldsymbol{F}_{el}$. The resulting joint torque $\boldsymbol{\tau}_{motor}$ that is sent to the motors is given as

$$\boldsymbol{\tau}_{motor} = \boldsymbol{\tau} + (\boldsymbol{I} - \boldsymbol{J}^T \bar{\boldsymbol{J}}^T)\boldsymbol{\tau}_{el}, \quad (4)$$

where $(\boldsymbol{I} - \boldsymbol{J}^T \bar{\boldsymbol{J}}^T)$ is null-space expression, $\bar{\boldsymbol{J}}$ is inertia weighted pseudo-inverse of the Jacobian and $\boldsymbol{\tau}$ comes from (3).

III. Experiment

To test the developed control method, we performed an experiment involving the identified construction task using printed voronoi modules. The aim of the experiment was to conduct a full demonstration of the method by using all modes of operation. First, the used hardware will be mentioned, and the setup will be described. Then the demonstration itself will be explained in more detail.

The experiment setup is shown on Fig. 1 and included KUKA LBR iiwa 7 R800 compliant robot arm with seven degrees of freedom. This robot has torque control capability, which is required for impedance control and the proposed method. It has a good ratio between weight (24 kg) and payload (7 kg) for off-Earth construction scenarios. The end-effector of the robot was equipped with the qb robotics SoftHand, which is robust, and enables mechanical adaptability to the grasped object and environment. These properties make it fit well within the proposed method, where the human guides the grasping. Mechanical robustness and adaptability are essential. For the voice interface that enables the human to switch between the modes by spoken-language commands, we used the G-Track Condenser microphone.

The prototypes we created for the experiment are scaled versions of the voronoi modules used for the wall construction. These modules were made out of laser-cut 3 mm cardboard and had different shapes. Each module fit together in a specific order, like a puzzle. To emulate sticking the modules together, we installed magnets inside them. On each module, one surface was left open for the robotic hand to grasp the module.

The goal of the demonstration was for the human to carry an unassembled module from a table (on the left of the image) and assemble it in the wall structure (on the right). The main movement in the horizontal plane was along y-axis. The z-axis trajectory used for the experiment was defined as a combination of two half parabolas over task state (i.e., x-axis and y-axis), that meet at their maximum, in the middle of the workspace of the robot arm. Since both the horizontal stiffnesses are zero during the *main mode*, the human is free to select the path in the horizontal plane. Furthermore, two virtual walls, parallel to the x-z plane, were added at the start and at the goal position of the trajectory, to help keeping the end-effector within the desired workspace. To execute the task, all four modes had to be used at different stages.

IV. Results

The main results of the experiment are shown in Fig. 2. We can see the human was able to use the voice command interface to switch between the four modes during different stages of the construction task. The system initiates in the *locked mode*, where the endpoint was near the voronoi modules that had to be assembled. After four seconds, the *free mode* was activated and the human started to move the robotic hand towards the voronoi module. As can be seen in the bottom graph, all stiffnesses were low (i.e., zero) in this mode to enable the human to align the hand for grasping. After the human gave a voice command to close the hand and the voronoi module was grasped, the *main mode* was activated to carry the object toward the goal. A video is recorded during the experiment and is online available [9].

Note that the human already switched between the *main mode* and *orientation mode* once before the carrying at 38 seconds. This was done to orient the module in a more comfortable configuration for the carrying. The main carrying movement was done between 47 and 55 seconds. When the

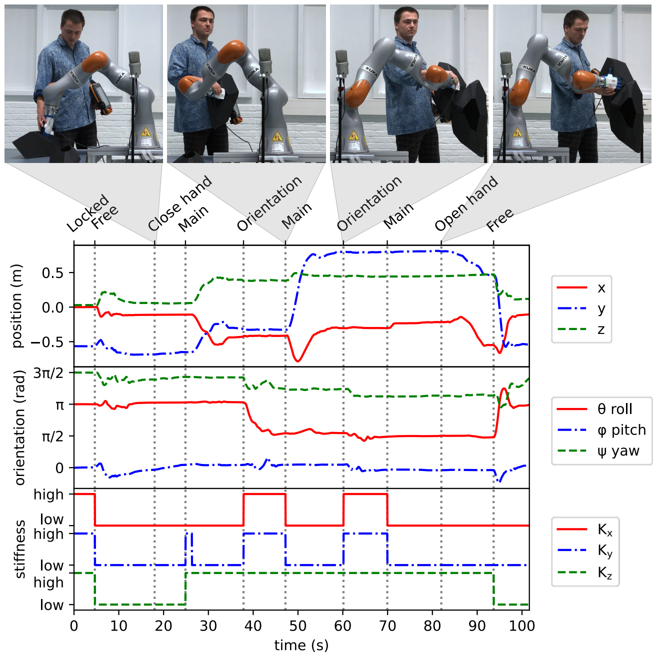

Fig. 2: Main results of the experiment. The top images show different stages of the task. The notations at the top of the graphs indicate the mode used at a specific stage. The graphs show position, orientation (in Euler angles), and Cartesian stiffnesses of end-effector, respectively. The separation between modes is highlighted in the graphs by vertical dotted lines.

goal position on the wall structure was reached at 60 seconds, the *orientation mode* was used again to align the module for assembly. After that, the robotic hand was opened by a voice command. At that point, the voronoi module was assembled, and the human activated the *free mode* to remove the robotic hand from the module. Finally, the *main mode* was activated again to go back for another module.

In the top graph of Fig. 2, we can see some x-axis position movement around 50 seconds during the main carrying movement in y-axis. This was a result of the human avoiding an obstacle (i.e., the robot base) and had to move the voronoi module around it to avoid collision.

The effect of the virtual boundary is visible when the *main mode* was entered for the first time around 25 seconds, when K_y was high for a brief time. This is caused by the end-effector to automatically move inside the desired workspace before the collaborative carrying commenced. As soon as the voronoi module moved towards the positive y-direction, the stiffness in this direction becomes zero, as prescribed by the *main mode*.

Additional results are shown in Fig. 3, where we show the movement path in y-z plane during the carrying sub-task. It can be noticed that the human guided the robot back-and-forth in some sections, which indicates that the trajectory is not time/phase dependent but state dependent. These backtracking movements can also be seen in Fig. 2 around 33 seconds, as well as between 84 and 94 seconds.

V. Discussion

The functionality of the method was demonstrated during the experiment. According to the position, orientation and

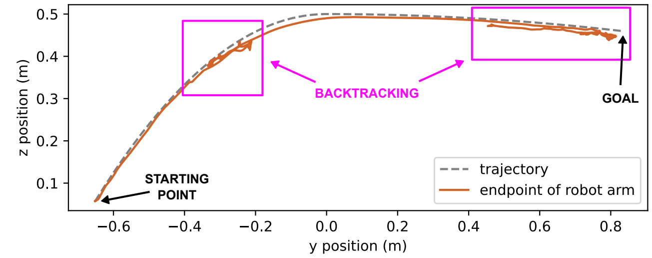

Fig. 3: Position of the endpoint in y-z plane during the carrying sub-task (between 25 and 94 seconds). The y-axis was aligned with the main movement direction and was freely controlled by the human. The z-axis was vertical and aligned with the gravity vector. This caused the robot to control a predefined trajectory along this axis to carry the load.

stiffness behavior in the results, all modes worked as intended. The human was able to collaboratively perform the examined construction task with the robot in a safe manner.

The main limitation of the existing study, with respect to the Rhizome project goal, is that the robot arm had a fixed base and therefore a limited workspace. The lava caves on Mars where the habitat should be constructed are expected to be quite large, so there might be a considerable distance between the location where the voronoi modules are printed and the location where they should be assembled. When voronoi modules are carried over a longer distance, the robot arm requires a mobile platform. Existing studies on human collaboration with the mobile robot [10] can for instance be used to improve the proposed method. This will be the main direction of our future work.

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