Development
of an Autarkic Design-to-Robotic-Production and -
Operation System for Building Off-Earth Habitats

Rhizome

Deliverable D5

Documentation of final design of subsurface habitat using swarm robotics and HRI

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Change Control

Version #	Date	Author	Organisation	Main change(s) made
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Change History

Describe here briefly the reason and type of changes made since previous version.

Acronyms and Abbreviations

ESA	European Space Agency
TU Delft	Delft University of Technology

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Publishable Summary

We studied and developed methods for the construction of the subsurface habitat using human-robot collaboration and swarm robotics. The work and corresponding results are divided into three main topics. The first involves the development of a lower-level control method that enables physical interaction and collaboration between the human and robotic arm for performing several key subtasks related to construction. The second involves a higher-level machine learning method that can incorporate human preferences into the robot control. The third involves a feasibility study for attaining the required robot mobility on the construction site.

1. Introduction

One of the key challenges of space exploration is limited resources and agents available to perform various tasks. While on-Earth specialised tools and robots efficiently perform specific tasks, off-Earth each agent must be able to perform a variety of tasks. Working without complex machinery often requires multiple agents to team up in order to be able to perform certain tasks. For example, lifting and moving heavy objects, performing assembly that requires more than two hands etc., all require at least two agents and good coordination between them. While humans can team up, their numbers are limited in off-Earth scenario and therefore robotic agents have team up with them instead.

Robots may not be as smart and adaptable as humans yet, but they have some advantages over the humans, such as precision, speed and payload capacity. In this project we exploited both advantages by establishing smart human-robot teams for an off-Earth habitat construction task, where 3D printed component has to be assembled together at the building site. Four key sub-tasks for the given construction task have been identified. First, the component pick-up sub-task requires human cognitive capabilities to physically guide the robotic hand for successful grasping and lifting (see Fig. 3A and B). Second, during the carrying sub-task, the human should control the motion on the trajectory, while the robot should carry most of the component weight along that path (see Fig. 3C and D). Third, the component's orientation must be aligned to fit the appropriate place in the structure (see Fig. 3E). Finally, when the human must temporarily attend to other tasks, such as inspection of the building progress, the robot must remain in a fixed position and orientation (not shown).

2. Physical human-robot interaction (HRI) method

The aim of the HRI aspect of the proposed method is to construct the rhizomatic structures for the habitat out of 3D-printed concrete voronoi building components. These building components, which have variable shapes, are picked up from the printing location and carried to the place where the envelope of the habitat is being built. The carried component must be then placed and fitted to the specific location. To implement this task, intelligent collaborative robots are envisioned to safely assist humans in this project, in which the robot handles the heavy-load aspects, while the human takes over the cognitively complex aspects of the task (Fig. 1).

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grasping and lifting (see Fig. 2A and B). Second, during the carrying sub-task, the human should control the motion on the trajectory, while the robot should carry most of the component weight along that path (see Fig. 2C and D). Third, the component's orientation must be aligned to fit the appropriate place in the structure (see Fig. 2E). Finally, when the human must temporarily attend to other tasks, such as inspection of the building progress, the robot must remain in a fixed position and orientation (not shown).

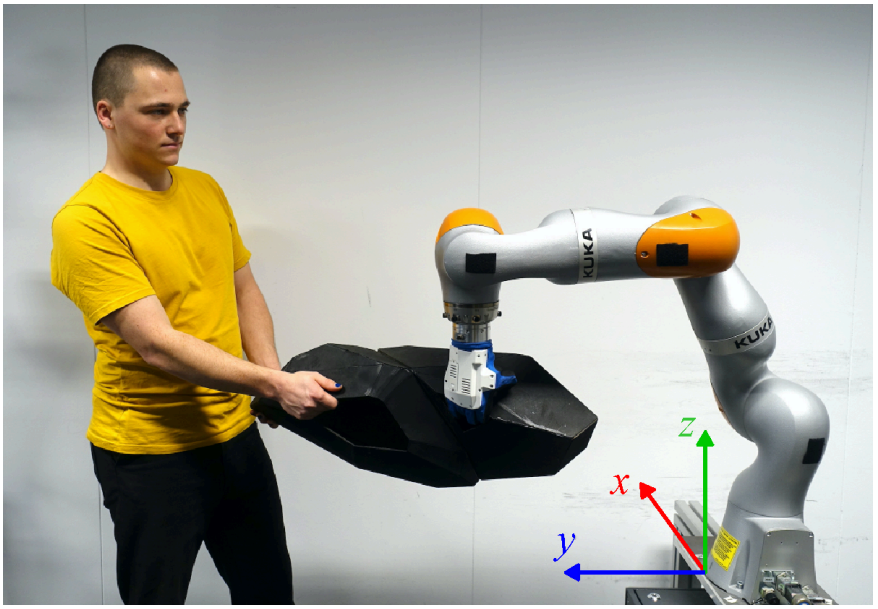


Fig. 1: Experiment setup for collaborative construction using the developed HRI method. Robot base frame axes are indicated by coloured arrows.

The developed method for HRI consists of five modes that cover the requirements of the four identified sub-tasks. To enable the human to switch between these modes we developed a voice interface based on the recognition of language commands. The five designed modes of operation are: *locked*, *free*, *main*, *orientation* and *lift & lower*. 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 component pick-up sub-task, where the human guides the grasping of the voronoi component. Main mode is used for collaboratively carrying the voronoi component 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 component to fit in the wall. Lift & lower mode allows for lifting and placing the object at the beginning and at the end of the task.

Main mode (Mode 1)

In Main mode, the human can determine the position of the to-be-assembled component in the horizontal plane (i.e., the 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 the z-axis of the robot base frame. The reference trajectory is not time/phase-dependent but state-dependent, where the state is defined by the position along the x-axis and y-axis as $z = f(x,y)$, where the relationship f between the

state (*x*,*y*) and desired z-axis trajectory can be learned using human demonstration [Peternel, et al., 2016]. The initial value of the trajectory should correspond to the height of the component pick-up location. The final value of the trajectory should correspond to the height of the location where the voronoi component 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 to ensure that the reference z-axis trajectory is followed, and that the impedance controller compensates for the unknown gravity of the component. This way, the robot is carrying the weight of the voronoi component, but the human can freely control the motion. Since the trajectory is independent of time, humans 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, to prevent the component 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 temporarily increases 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.

Locked mode (Mode 2)

In locked mode, all translational and rotational stiffnesses are set to high values. Thus, the user cannot change the reference position along the 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's pose, while the human temporarily attends to other tasks, such as inspecting the wall to see where the currently grasped component might best fit. Furthermore, the robot starts in this mode when the system is initialized or restarted.

Free mode (Mode 3)

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 component 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.

Orientation mode (Mode 4)

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 component 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 component before it is placed in the wall.

Lift & lower mode (Mode 5)

These two modes make the robot lift or lower the object when it is grasped or when it must be placed in the right location.

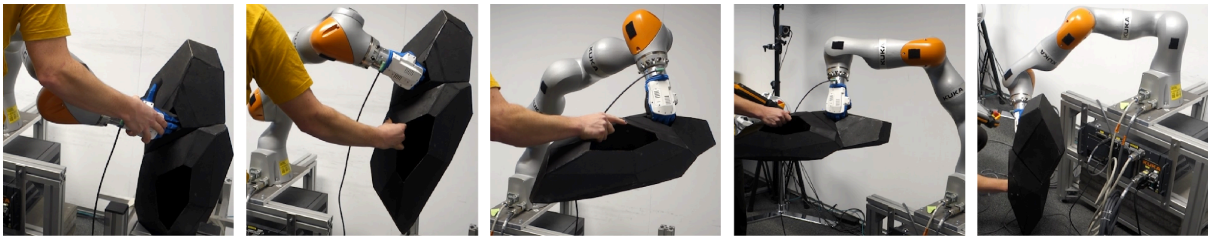


Fig. 2: Photos from the experiment showing different stages and modes of operation during the construction task. A) Object grasping stage (Mode 3), B) object lifting stage (Mode 5), C) object orientating stage (Mode 4), D) object carrying stage (Mode 1), object placing stage (Mode 4).

Robot interaction control system

The behaviour defined for each mode is controlled by a robot interaction control system. This controller includes both an impedance controller for ensuring the desired stiffness behaviour and a null-space controller that handles the redundant degrees of freedom. The developed robot interaction control system is based on Cartesian impedance control [Peternel, et al., 2018]. 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 the environment/human.

Since we are using a robot with redundant degrees of freedom (DoF), i.e., more joints than Cartesian DoF, we must account for the joint configuration to not obstruct the task executions or human safety. To do this, we used an additional Cartesian impedance controller in null space [Khatib, 1987] that controls the elbow position (i.e., fourth joint). For example, the elbow of the robot is positioned in such a way that it avoids obstacles in the environment and the collaborating human.

Experiment

The aim of the experiment was to conduct a full demonstration of the method by using all modes of operation in a construction task using printed voronoi components. The experiment setup included KUKA LBR iiwa 7 R800 compliant robot arm with 7 DoF. 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 building component prototypes we created for the experiment are scaled versions of the voronoi components used for the wall construction. These components were made from laser-cut 3 mm cardboard and had different shapes. Each component fits together in a specific order, like a puzzle. To

emulate sticking the components together, we installed magnets inside them. On each component, one surface was left open for the robotic hand to grasp the component.

The course of the experiment is illustrated in Fig. 2., where the goal was for the human and the robot to pick and carry an unassembled component from a table (left photo of Fig. 2) and assemble it on the ground (right photo of Fig. 2). The main movement in the horizontal plane was along the y-axis (see Fig. 1). The z-axis trajectory used for the experiment was defined as a combination of two half parabolas over the 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. Two virtual walls, parallel to the x-z plane, were added at the start and at the goal position of the trajectory, to help keep the end-effector within the desired workspace. In addition, a cylinder-shaped virtual wall was added around the robot base to prevent self-collision. The construction task was executed using all four modes at different stages. The results showed that all modes worked as designed and that humans and robots can perform the examined construction task with the proposed method.

3. Human preferences learning method

We developed a method based on machine learning and optimization that can incorporate human preferences while learning new skills from the collaborating human. The method uses human demonstrations to infer the preferences, which are extracted from the measured data (position, velocities, etc.) using the inverse reinforcement learning (IRL) approach [Jain, et al., 2015]. We identified and four main preferences that are fundamental to the construction task considered in the project: *carrying velocity*, *height from the ground* during the carrying, minimum *distance to obstacles* during the carrying, *side* on which the obstacle is passed. These preferences are incorporated into the robot trajectory planner based on mathematical optimization, where each preference adds a specific term to the cost function that guides the optimization process. The optimization also enables generalization to various conditions that were not directly demonstrated by the human, thus providing the robot with a significant degree of adaptability to new situations.

We conducted experiments on a Franka Emika 7-DoF robot arm to validate the developed method. The experiment task was to move an object from the initial position to the final position with an obstacle in the workspace. This emulates the cluttered and unstructured workspace conditions of a typical construction site. See Fig. 3 for an illustration of the experiment. The results showed that the method can account for all preferences when generating a robot trajectory. Furthermore, the method can generalize to different conditions and new situations, e.g., different starting and ending positions, different obstacle positions, etc.



Fig. 3: Experiment setup for validating the human preferences learning method.

4. Feasibility study for attaining robot mobility

We conducted experiments on a fixed-base collaborative robotic arm. However, the construction site has a large workspace, and consequently, collaborative robots require a larger range. Thus, it is important that collaborative robots have sufficient mobility to achieve that range. To inquire about the feasibility of mounting a collaborative robotic arm on mobile platforms, we examined the key required specifications and requirements. The main results of this feasibility study are presented below:

- A collaborative robotic arm (study case: KUKA LBR iiwa 14)
  - Arm mass: **29.5 kg** (carrying capacity of **14 kg**)
  - Controller cabinet mass: **23 kg**
  - Robotic gripper mass: **5 kg** (this reduces effective arm's carrying capacity by 5kg)
  - Accessories (cables, etc.) mass: **2.5 kg**
- Legged mobile platforms (e.g., humanoid robots, quadrupeds, etc.) are versatile but also complex, less energy-efficient and have limited payload [Tsagarakis, et al., 2017], thus are not considered an ideal option for our case.
- The existing commercially available wheeled mobile platforms provide a good starting point [Kim, et al., 2020]. However, they are designed to operate in factory environments with level floors and structured environments. On the other hand, an off-world construction site would involve rough terrain with slopes and unstructured environments.
- The best option appears to be to design a custom mobile platform to be robust enough to operate in rough and unstructured environments. Some key considerations:
  - Actively powered wheels
  - Additional "passive" metal legs for fixation
  - Number of wheels, design, and configuration to be determined

  - Desired payload (in addition to propelling itself in rough/sloped terrain): **60 kg**[1]

Another important consideration is the power supply for the mobile robotic system. There seem to be two feasible options: battery-powered or cable-powered. We discuss the pros and cons below:

- Battery-powered robotic platform advantages:
  - No obstructions by the cable
  - No workspace limitations
- Battery-powered robotic platform disadvantages:
  - Shorter work time since recharge time is needed (could use spare batteries→ extra mass for the mission and replacing time required)
  - Extra load to be carried by the rover
- Cable-powered robotic platform advantages:
  - Unlimited work time (if the generators provide a sustained power supply)
  - Less load to be carried by the rover
- Cable-powered robotic platform disadvantages:
  - Inconveniences with the cable (possible entanglements, cable damage, etc.)

Workspace is limited by the length of the cable.

Appendix

[1] Note that these estimates are made based on the exstining industrial collaborative robotic arm that is not optimized for space exploration prupose, and thus represent a »worst-case« scenario. Optimization and custumization of hardware can result in a lower mass for the actual mission. In particular, the controller cabinet mass could be significantly reduced.

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