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Automatic Real-World Assembly of Machine-Designed Structures

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***Abstract*— Several approaches have been presented which allow robots to build structures to adapt themselves or their environments. To autonomously build these structures, a design must be made, from which instructions for the fabrication process can be derived. For a constrained fabrication process, e.g. considering the limited range of a robot, this transfer can be cumbersome. We present a local building process based on a sequence of two distinct operations, which implicitly encodes the shape of a structure. Given this encoding, the structure can readily be built with a real-world robotic system.**

We show automatic design of structures reaching out of the robot's range and fulfilling stability and strength constraints using an evolutionary design algorithm. The final design can then be built with a robotic arm from wooden cubes and hot melt adhesives. We demonstrate the whole process including the construction of a structure from more than thirty cubes with our real-world setup. We expect that automatic design and construction can further improve the physical adaptability of robotic systems.

I. Introduction

Making robots versatile and enabling them to achieve unanticipated tasks is an ongoing challenge in robotics. Improving the adaptability of robots can on the one hand be done on the control side, for example using learning algorithms to improve the performance for different tasks with a fixed physical design. On the other hand, a robot can be built such that it is able to adapt its physical shape to changing requirements, which is the research direction we are investigating in this paper.

To enable a robot to adapt its shape, it must be constructed such that it can perform this operation. Further than that, given a task, a target shape and a reconfiguration procedure must be developed or at hand. This allows the robot to transform from its initial shape to a second shape suitable to solve the task. Several approaches have previously been proposed for physically adaptive robotic systems. Self-assembling systems are designed to develop larger structures from an arbitrary initial distribution of modules using different types of actuation and control methods [1]–[3]. Modular self-reconfigurable robots consist of a set of modules, which can realign and change connections between themselves to alter the overall shape of the assembly [4]–[7]. A wide range of connection mechanisms has been applied to modular self-reconfigurable systems.

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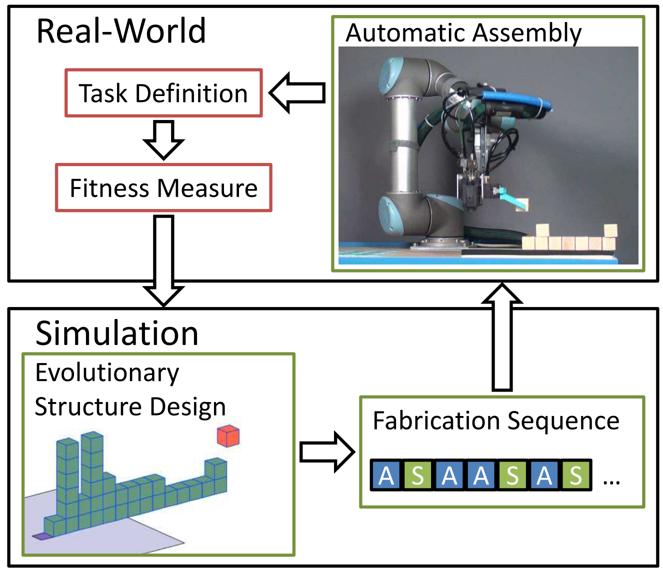


Fig. 1. Automatic design and real-world assembly: Given a task and a corresponding fitness measure, all further steps can be performed automatically. First, an appropriate structure is designed. Then, the corresponding fabrication sequence can readily be executed by the robot.

Another method to extend the physical shape of robots is the use of passive elements. Such systems were presented using trusses [8] or self-hardening foam [9]. We previously presented our approach dubbed Robotic Body Extension (RBE) which is based on the use of the unconventional material Hot Melt Adhesives (HMAs) [10]. HMAs are polymer-based thermoplastics [11]. They were used on the one hand to connect parts and on the other to additively fabricate freeform structures. These processes allow a robot for example to adapt its end-effector to different tasks and combining it with other passive or active objects [12].

For the automatic design of robotic systems, genetic algorithms are a popular choice. The renowned work by K. Sims [13] demonstrated the power of such a design approach in simulation. Much research later focused on the transfer from simulations to the real world. The field of evolutionary hardware applied evolutionary algorithms to hardware design optimization tasks [14]. In evolutionary robotics they were used to design simple robots and their controllers [15], e.g. Lipson and Pollack have used evolutionary algorithms to design simple robots for locomotion tasks and directly built the fittest examples using rapid prototyping techniques [16]. Recent work applied evolutionary algorithms to the automatic design of soft robots [17], [18].

The focus of this paper is the transfer from simulated design to real-world construction, and how real-world constraints (e.g. structural stability and strength) can be considered in this process. As shown in Fig. 1, from an initial task definition, a quantifiable fitness measure has to be derived to start the automatic design and construction process. The task considered in this paper is reaching to a distant location outside of the robot's range. The fitness is primarily dependent on the proximity of the structure to the target location.

Using this fitness measure, the evolutionary structure design algorithm can automatically design a useful and stable structure as well as the corresponding fabrication sequence. From this sequence, the instructions for the robot can directly be derived, and the robot automatically assembles the designed structure. The construction process only requires two local operations, adding a building block or shifting the whole structure, which are always executed at the same place within the robot's range. Using only these local operations ensures that critical constraints such as for example the range of the robotic arm are not violated throughout the building process.

The rest of this paper is structured as follows. Section II introduces the local operations as well as the details of the evolutionary design algorithm. Construction of the designed structures in real-world is shown in section III. The performed experiment and its results are presented in section IV, and section V contains conclusions and future work.

II. Evolving Structures

This section introduces the evolutionary design algorithm for passive structures which can be directly fabricated by an HMA based robotic setup. Therefore, the final design should not only consider the design target, but also stability and feasibility of the construction process. In order to avoid the need to transform the final design into a series of construction instructions — a process which is often hard to formalize — an implicit encoding for the structure is chosen. Rather than encoding the shape of the final structure, the encoding consists of a series of fabrication instructions which implicitly define the final structure. Therefore, in simulation the opposite (and more straightforward) process is required, deriving the final shape from the fabrication instructions.

A. Encoding Construction Sequence

The fabrication instructions can be two processes, first, adding a cube, and second, shifting the whole structure as illustrated in Fig. 2. Both of these processes are always applied at the same location, referred to as building position. This location is inside the robot's range, and therefore the process can always be executed irrespective of how far the built structure already reaches out of the robot's range.

If add is chosen, a cube is added from the top at the building position. The only exception is when the cube has to be placed through a narrow gap (i.e. between two neighboring cubes), which is not feasible in the real world implementation. In such a case the add instruction is discarded. The shift instruction is parametrized with a direction; the magnitude is fixed to the side length of one cube. In

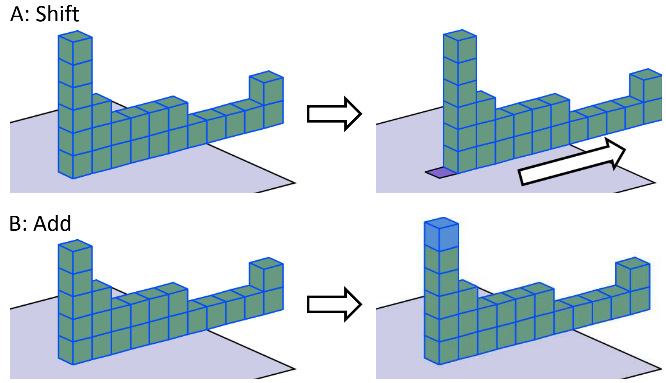


Fig. 2. The automatic construction is based on two local operations. A: Shifting the whole structure. B: Adding a cube on top of the structure.

the work presented here, the shift direction is limited to the positive or negative x-direction. Resulting from this, the design space is constrained to two dimensional structures. The presented concepts could however be extended to three dimensions. To guarantee that the robot can always reach to the structure to shift it, the shift process is only executed if there is a cube at the building position, which the robot can always reach to grasp and shift the structure.

As introduced before, the genome encodes the fabrication process. It is a sequence of fixed length and each gene contains an operation (add, shift, or none), and in the case of the shift operation also a parameter indicating the direction in which the structure is shifted. The operations are executed in the order given by the genome.

B. Updating the Genome

To combine the genes of two parents, a one-point crossover is performed. This means that both genomes are split at the same arbitrary location and the first part of the first genome is combined with the second part of the second genome to form a new genome. For mutations, each gene of the genome is reinitialized with a given mutation probability. As a second type of mutation, the whole genome can be circularly shifted, which corresponds to a change in the position of the genome at which the building process is started. The number of positions shifted is drawn at random from a uniform distribution.

After mutation and crossover, the stability of each structure has to be validated. While the selected encoding ensures that the building process later on can be executed, there are no guarantees on the stability of the resulting structure, which however is critical for the given task. Therefore stability is checked after each mutation or cross-over. If the new structure is not stable, it is discarded and the update step repeated. There are two criteria to be met: The HMA connections between two cubes can only bear a certain stress before failure, and the whole structure must not topple when it is shifted over the edge of the fabrication workspace. Since both criteria must not only be fulfilled by the final structure, but also during intermediate construction steps, they have to be checked for all substructures after partial execution of the

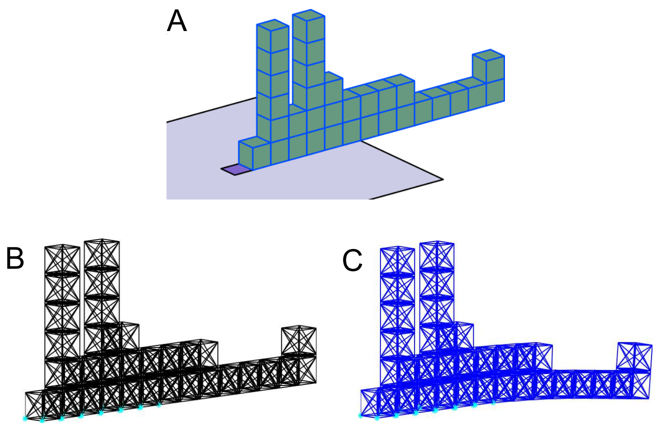


Fig. 3. Stability criteria are checked by the evolutionary design algorithm using a truss approximation of the target structure (A). B shows the truss approximation, cyan stars mark fixed nodes attached to the ground. The structure deformed under its own weight is shown in C (deformations scaled up five times). B and C were generated using [19].

construction sequence. The frequent use of the corresponding algorithm requires a fast execution of these checks.

To calculate the stresses in all HMA connections, the structure is transformed into a truss as illustrated in Fig. 3. Each cube is represented by eight nodes, which are connected by a total of 28 links, and the cubes are connected with 16 links per connection site. Using a linear elastic material model with different Youngs moduli for wood (links within cubes) and HMA (links between cubes), the deformations and stresses can efficiently be calculated [19]. Given the stresses in all links representing an HMA connection, an equivalent stress is calculated and compared to the HMA bonding strength [20].

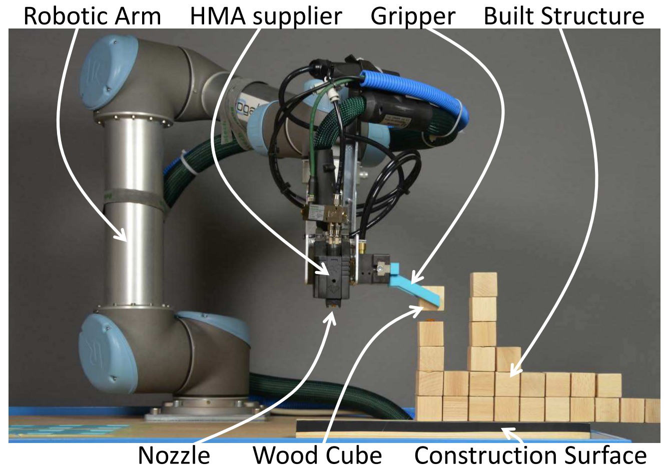
Checking the second stability criterion, that the structure does not topple, is done by calculating the horizontal position of its center of mass. As long as it lies above the construction surface, the structure will not topple.

C. Fitness Function

The evolutionary design algorithm requires a quantifiable fitness criterion. The selected design task throughout this paper is reaching to a distant location outside of the robot's range. Therefore, the dominating factor is the proximity to a specified target location at some horizontal distance from the building position. To discourage unnecessary construction efforts, an increasing penalty is imposed on increasing numbers of cubes n_{cubes}. Furthermore, stability reserves are rewarded by penalizing large maximums stresses $\sigma_{\max}$ in the HMA connections. The fitness f is described by a function of the following form:

$$f = w_{\text{dist}} \cdot (d_{\max} - d_{\text{struct}}) - w_{\text{cubes}} \cdot n_{\text{cubes}} + w_{\text{stress}} \cdot \left(1 - \frac{\sigma_{\max}}{\sigma_{\text{crit}}}\right)$$

where w are the weights of the three parts, $d_{\max}$ is the distance from building position to the target and d_{struct} the distance from the structure to the target location. In order to achieve a different task, this fitness function would have to be replaced with another one reflecting the new goal.



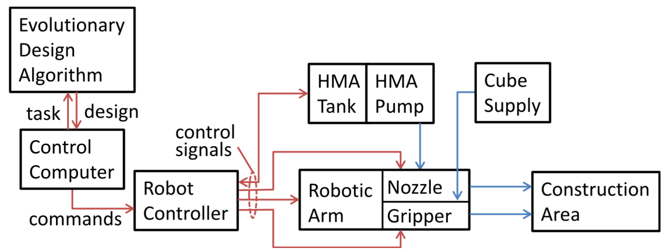


Fig. 4. The hardware and control setup for the automated assembly. A control computer forwards the commands from the design algorithm to the robot controller. The robot controller sends the according signals to the robotic arm and its gripper as well as the pneumatic valve of the HMA supplier. The HMA is pumped to the nozzle and a steady supply of wood cubes is assumed.

III. REAL-WORLD CONSTRUCTION

The goal of this project is a construction process which enables to build automatically designed structures in the real-world. Furthermore, the structures which the robot builds should not be limited to its reachable space unlike structure formation using 3D-printers. In our setup, the structures are built from wooden cubes, which can be manipulated by the robot using a parallel gripper. To assemble these cubes, the robot is equipped with an HMA supplier. The HMA material forms strong bonds between the cubes when cooling down to room temperature.

To facilitate the transfer from automatic design to construction, the design space was limited to a sequence of two feasible operation types as introduced in section II-A:

1) Add a cube at the center of the construction area
2) Shift the current structure

Since both operations are always executed at the same location, they can always be executed without violating any constraints of the real robotic arm. Both processes can be executed using our hardware setup shown in Fig. 4. It consists of three main components: A robotic arm, an HMA supplier and a two fingered parallel gripper. Further than that, an HMA reservoir with pump ensures a steady supply of hot HMA material and it is assumed that a supply of wooden cubes is available. The robotic arm is a six axis Universal Robotics UR5, which is mounted on a table. A Robatech Concept B glueing system is used with a pneumatically

TABLE I

PARAMETERS FOR AUTOMATIC DESIGN

Parameter	Value
cube side length	3 cm
target location	[4,0,15] side lengths
construction area length	12 side lengths
number of generations	100
genome length	75
population size	30
gene mutation probability	10 %
genome shift probability	2 %
σ_{crit}	1.2 MPa
w_{dist}	1
w_{cubes}	0.01
w_{stress}	1

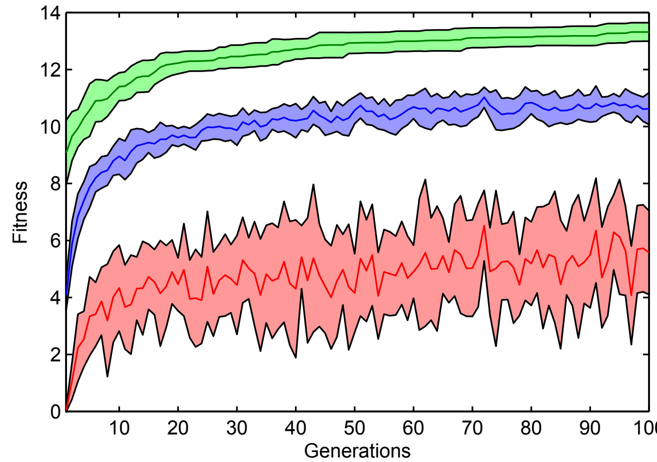


Fig. 5. Averaged fitnesses (green: best, blue: mean, red: worst) with standard deviation (shaded areas) for 10 simulation runs as detailed in section IV-A.

controlled nozzle mounted to the robot's end-effector in parallel to the two-fingered gripper. The building materials are wooden cubes ($s = 0.03\,\text{m}$, $m = 19\,\text{g}$) and HMA (ALFA H 5500/30), which is supplied at 160 °C. The whole system is controlled from an external desktop computer, which is connected to the robot controller via Ethernet.

The control computer receives the genome of the designed structure from the evolutionary design process and translates the encoded add and shift operations into robot commands. Shifting the structure only requires a horizontal motion of the arm holding on the structure and a small vertical lift, to ensure the structure does not lock between gripper and ground. The add process depends on the previously built structure surrounding the desired add location. Since the added cube has to be connected to all its neighbors, some of its surfaces, or surfaces of the existing structure, have to be covered with HMA before the cube can be placed. The approach path when placing is also chosen depending on surrounding cubes to avoid collisions. The output of the process is the final structure as initially designed by the evolutionary design algorithm.

IV. EXPERIMENTS

The performed experiment demonstrates the complete process from automatic design to the physical construction of the final structure. For the design process, the evolutionary algorithm presented in section II is employed. The resulting design was then assembled by our real-world setup, using wooden cubes connected with HMA.

A. Automatic Design

The design task for the evolutionary algorithm was to reach as close as possible to a target location outside the construction workspace of the robot. A stable structure for this purpose had to be evolved. For comparison, ten simulation runs were performed with the parameters set as shown in table I. The simulations were run for 100 generations each. Fig. 5 shows the fitnesses increase through the course of the simulation. The best design achieved a fitness $f = 13.66$.

Fig 6-A shows the three most successful individuals from ten simulation runs. The course of evolution from the first to the last generation of the best run is shown in Fig. 6-B. It can be seen that with increasing generation number the structure approaches closer to the target position (red) while improving stability and compactness. The third part of Fig. 6 illustrates some intermediate steps of the construction process leading to the final structure. The fittest structure was eventually selected for construction in real-world.

B. Real-World Assembly

After the simulation, the structure with best fitness score was assembled using the real-world setup presented in section III. Fig. 7-A shows the intermediate steps of the construction process, which correspond to the simulation results from Fig. 6-C. While the shift process can directly be executed by gripping the structure and linearly moving it by the side-length of one wooden cube, the implementation of the add process is more complex. Three cases have to be distinguished, depending on the previously built structure. First, if a cube is already placed below the adding location, a vertical connection is required. Second, if a cube is already placed at one side of the adding location, a lateral connection has to be made. The third case is the combination of the two former cases. It is therefore shown in the time-series pictures of Fig. 7-B. One side of the wooden cube is prepared with HMA (2 in Fig. 7-B). After a rotation (3–4), it can be picked with HMA on its side (5) for the lateral connection. Glue is added to the add location for the vertical connection (6), before the cube is placed at the add location (7–8). A cooling time of 20 s is required for the HMA to form a strong bond between the neighboring cubes. The whole process can also be seen in the video file submitted with this paper. The whole fabrication process requires 36 min.

C. Discussion

The presented experiment shows the feasibility of automatic design and construction of structures reaching outside the range of the robotic arm. The structures built so far consist only of wooden cubes connected with HMA, i.e. they are completely passive. Previous work has shown the construction of automatically designed robots [16], [17].

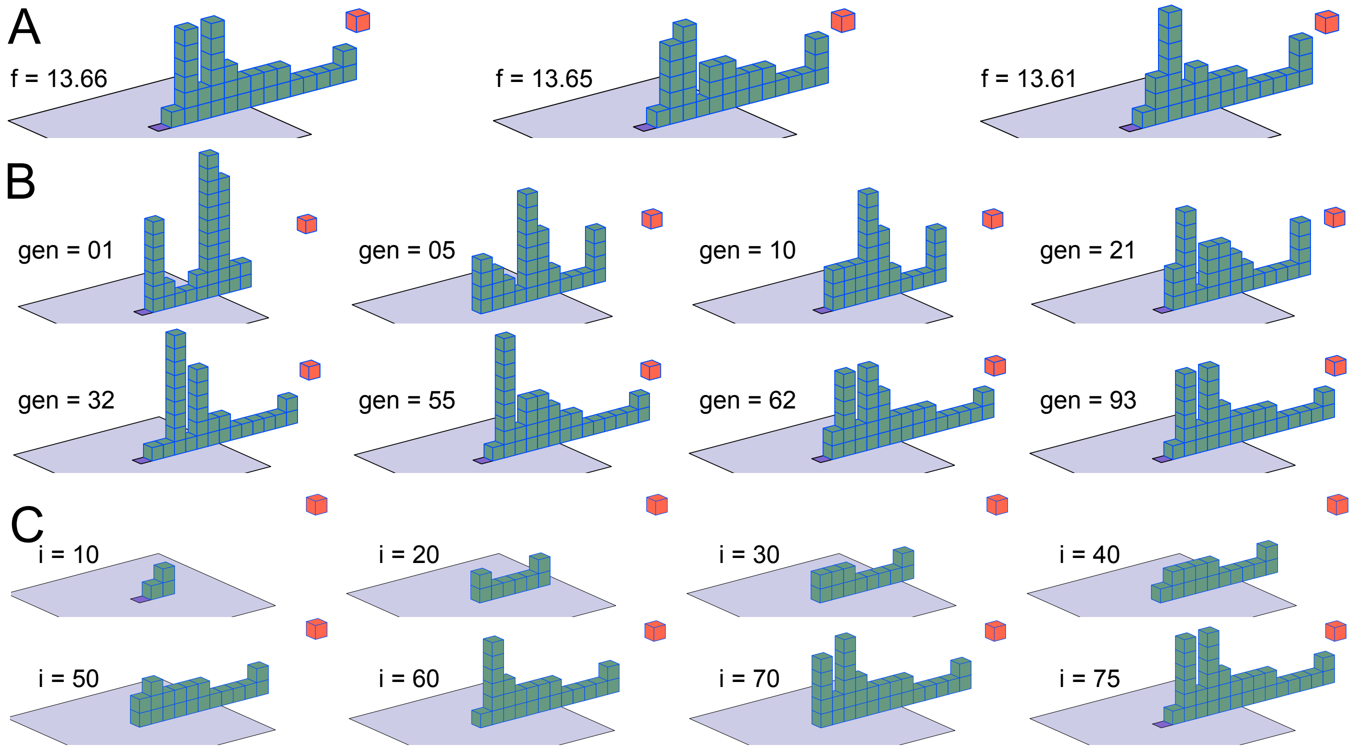


Fig. 6. Results of the automatic design experiments. The structures are marked with green cubes, the red cubes represent the target locations and the purple rectangles the construction surfaces. A: Fittest structures of the ten simulation runs. B: Evolution of the fittest structure ($f = 13.66$ in A) over 100 generations. C: Intermediate construction steps of the fittest structure. The final structure is completed after 75 instructions i.

Although the construction processes in both cases required only minimal human intervention (e.g. "snapping in the motors" [16]), the transfer to reality was not completely automated. Also construction using 3D-printers or laser-cutters limits the size of structures to the workspace of these devices. The construction process presented in this paper is automated except for the material supply and can produce structures reaching outside the range of the robotic arm.

The design algorithm can also ensure stability properties of the passive structures. Such structures can potentially be useful for tasks such as reaching or structuring the environment (e.g. to build a bridge of some sort), and previous work has shown the feasibility of further extensions. The first option is the additive fabrication of freeform structures from HMA material, which increases the design possibilities for passive structures [10]. A second option is the combination of passive structures with active units, e.g. containing motors or sensors, to build active systems [12].

Some limitations come from the underlying assumptions of the current setup. All structures designed and constructed were limited to two dimensions. An extension to three dimensions will significantly enlarge the design space. The required modifications to the design algorithm are minimal, but affect the computational complexity of the problem. With some adaptions to the basic operations, also an extension of the real-world assembly seems possible. Another important assumption is the availability of wooden cubes. The robot relies on the manual supply of wooden cubes at a predefined location. Since it is not equipped with any sensors and all actions are performed in a feedforward manner, it requests confirmation of the user before picking a cube. This process could be automated, but the essential requirement for a reliable supply with construction materials (wood and HMA) cannot be relaxed.

The lack of sensor information could limit the precision required to build larger structures. The local add and shift processes as applied in the current demonstration only rely on the last construction steps. In the demonstration using more than thirty cubes the errors did not sum up in such a way that would lead to the failure of a construction step.

V. CONCLUSION

This paper presents the implementation of a combination of an evolutionary design algorithm and a robotic construction mechanism based on the use of HMAs, which allows to automatically design and construct structures reaching outside the robot's range. The design algorithm ensures the stability of the structure and the chosen encoding inherently guarantees feasibility of fabrication process.

The simulation results show the development of structures towards a target location. The rewards for low connection stresses and efficient use of construction materials result in relatively compact and stable structures. The experiments with the real-world robotic setup show the feasibility of the construction process, which is a sequence of 75 operations and uses more than thirty cubes which have to be successfully connected.

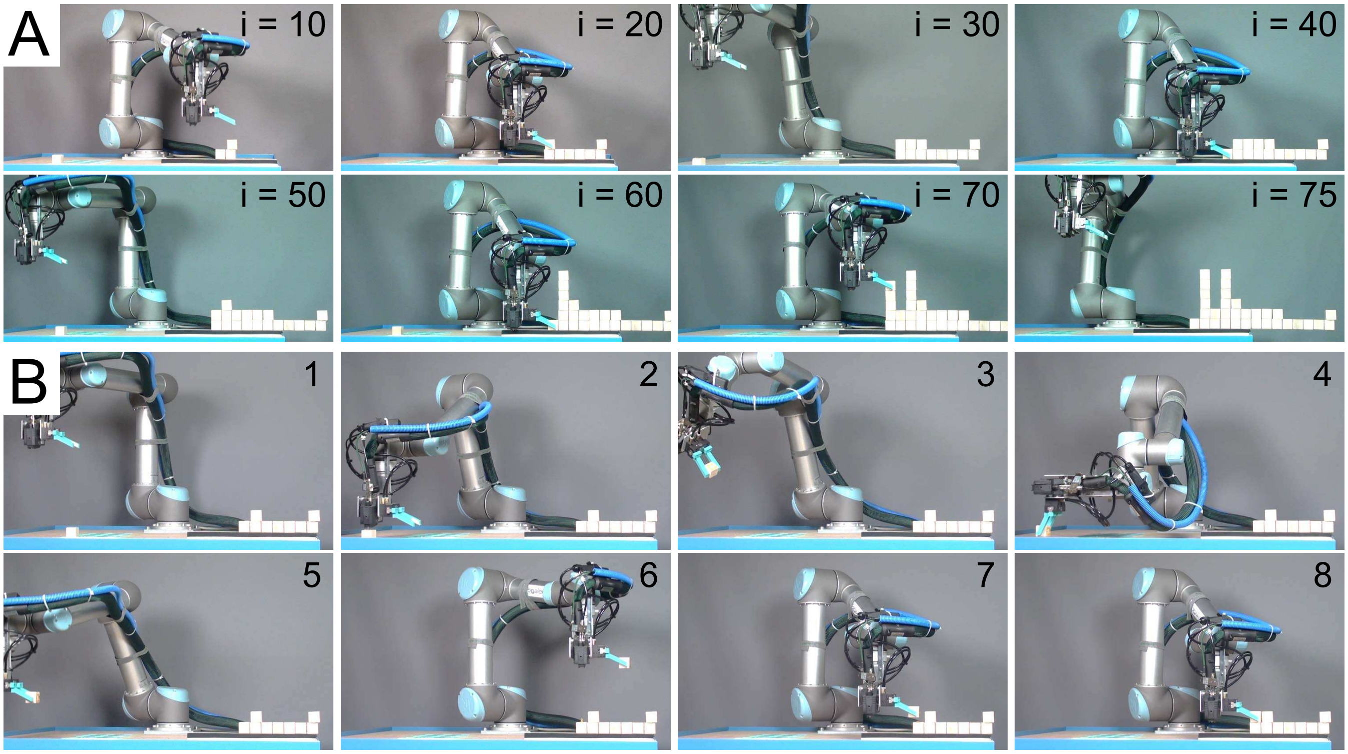


Fig. 7. Real-world assembly of the fittest structure. A: The same intermediate construction steps as in Fig. 6-C are shown. The structure is only supported within the construction area (marked with black tape). B: Time-series pictures of an add-operation with two neighboring cubes. HMA has to be applied at the side and below the added cube.

Future work on this project will contain the construction of three-dimensional structures, which requires an adaptation of the design algorithm and an extension of the real-world implementation. Both aspects will contribute to the other goals of building larger structures and increasing the task complexity. Other potential extensions of this work are the introduction of sensory feedback for fabrication and the interaction with other objects present in the task space.

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