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Assembly Planning from Observations under Physical Constraints

Thomas Chabal¹, Robin Strudel¹, Etienne Arlaud¹, Jean Ponce^{1,2}, Cordelia Schmid¹

Abstract—This paper addresses the problem of copying an unknown assembly of primitives with known shape and appearance using information extracted from a single photograph by an off-the-shelf procedure for object detection and pose estimation. The proposed algorithm uses a simple combination of physical stability constraints, convex optimization and Monte Carlo tree search to plan assemblies as sequences of pick-and-place operations represented by STRIPS operators. It is efficient and, most importantly, robust to the errors in object detection and pose estimation unavoidable in any real robotic system. The proposed approach is demonstrated with thorough experiments on a UR5 manipulator.

I. INTRODUCTION

The problem of replicating with a robot an assembly of known shapes using photos as guidance is as old as AI itself, and its first solution probably dates back to the famous “copy demo” of Patrick Winston and his MIT AI Lab colleagues in 1970 [27]. This is the problem once again addressed in this presentation, but this time the focus is on the difficulties associated with the (unavoidable) failures of the vision system in planning the assembly of the copy, and how to tackle them.

Concretely, we assume that we are given a set of *primitives* in the form of 3D shapes with known shape and appearance, and two color pictures, a *target* photo I of some stable stack of these objects on a table in the workspace of the robot, to be copied, and a *layout* image J of available primitives laid elsewhere on the table. Some off-the-shelf vision module extracts from the photos the identity of the primitives as well as their position and orientation in space, and passes them to the planner which then constructs a sequence of pick-and-place operations represented by STRIPS operators, which is then executed by the robot to copy the initial stack, see Figure 1.

We use *Cosypose* [13] as our vision module. As of this writing, it represents the state of the art in object detection and pose estimation and has won five awards at the ECCV’20 6D object pose challenge. Yet, as any vision system, it is prone to errors such as missed detections and inaccurate pose estimation when deployed in real (if simple) robotic tasks such as addressed in this paper, notably due to the numerous occlusions present in typical assemblies (some of the primitives involved may in fact be completely hidden from the camera).

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Project website: <https://www.di.ens.fr/willow/research/assembly-planning/>



Fig. 1. Example result of our approach. A UR5 manipulator assembles a configuration of known primitives (right - foreground). The configuration is specified by a single photograph of the assembly (left - background).

We use a simple combination of physical stability constraints, convex optimization and Monte Carlo tree search to build pick-and-place plans robust to such failures of the vision system, see Figure 2. Our assembly planner has been implemented on a UR5 robot manipulator, and our experiments demonstrate that it can cope with cases where multiple primitives in the target assembly go undetected (see Figures 4 and 5).

II. RELATED WORK

A. Assembly

Building structures with a robot is a longstanding problem in robotics [27]. Ikeuchi et al. [11] take as input images before and after a change in an assembly of objects to determine a single action to obtain the change, which is then executed on a robot. More recent works [4], [16] study richer scenes with objects in contact, where scenes are described as a graph of contacts with nodes objects and edges contacts. The graph is then processed by a learned graph neural network that predicts pick and place positions [16] or Q-values [4] to search for an assembly sequence. Recent work [19] proposes to disassemble predefined structures to obtain a construction plan by inverting actions and reassemble structures with RL policies.

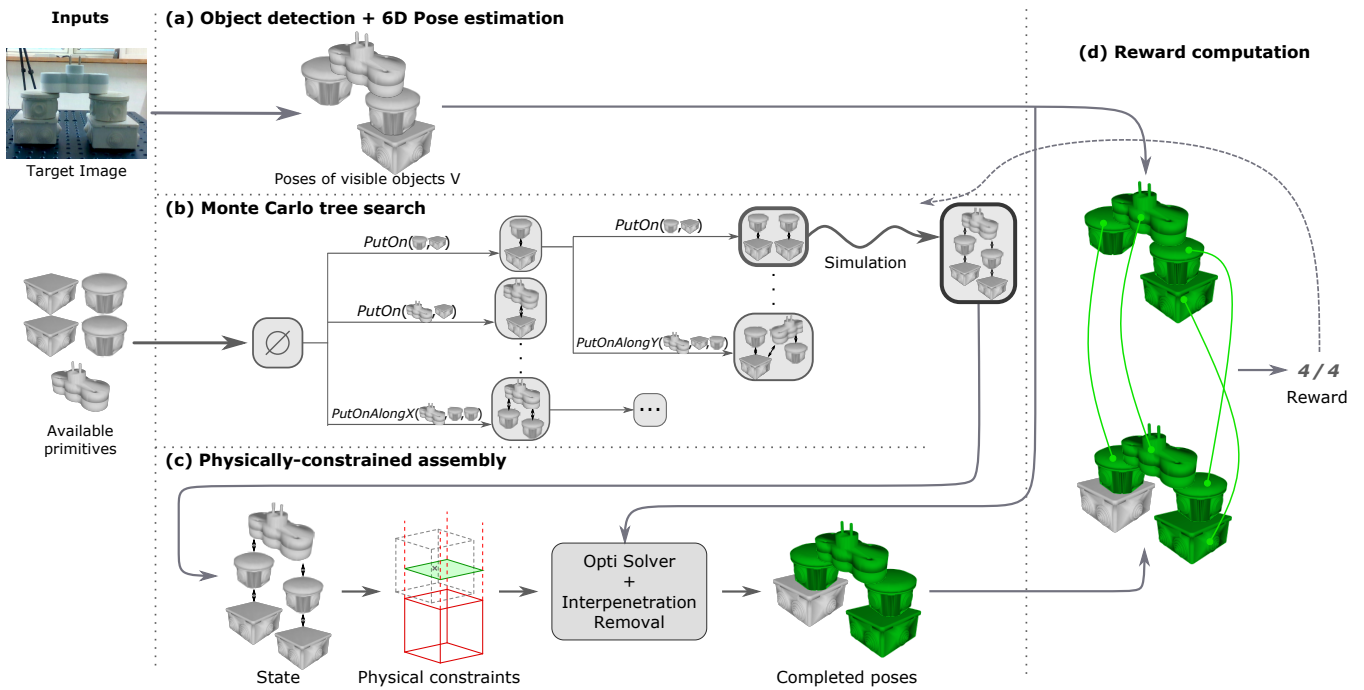


Fig. 2. Overview of our method. (a) Given an image of the assembly to build, we extract 6D pose estimations of partially visible objects. (b) An assembly plan of the primitives is built as a sequence of STRIPS operators guided by a Monte Carlo tree search. (c) The precise pose of each primitive is computed using the assembly plan and physical feasibility constraints. (d) The assembled primitives are compared to the poses extracted from the picture in (a). The difference is used as a reward for MCTS.

While previous works rely on a complete knowledge of the goal structures defined by CAD models with known poses, we have access to the CAD models of the primitives but infer their identities and poses from a single RGB image. Our method is more widely applicable. However, the problem is more challenging as an image only provides partial, incomplete information about the goal structure due to unavoidable mistakes in the identification and pose estimation, for example due to occlusions. Here, we propose a novel approach to exploit physical constraints to recover the identity and pose of missing objects.

B. Task Planning

Assembly requires to plan a sequence of actions, a problem typically addressed with task planning for which high-level tools were developed in the last decades. STRIPS [3] introduces predicates defining object states and operators to modify these states. STRIPS operators have then been extended by [5], [6], [20] to encompass a richer set of states and interactions. For rearrangement tasks, task planning operators have been used [18] or combined with motion planning in task and motion planning (TAMP), a more general framework to perform both high-level and low-level reasoning on motions [17], [25]. Yet, these methods usually assume full knowledge of the environment the robot acts in, which limits their applicability to controlled and predefined scenes. Other approaches rely on depth maps on simple scenes without occlusions [2], [1] or on QR codes placed on objects to recover their poses [18]. We propose to build on STRIPS planning tools, but obtain object poses using only

a single RGB image.

C. Pose Estimation

Object pose estimation is an active field in computer vision. Existing approaches rely on an estimation based on either keypoints [8], [22] or templates [15], [26], [28]. We use CosyPose [13], a template-based estimator, to perform pose estimation. CosyPose builds on recent render-and-compare methods developed such as DeepIM [15] or BB8 [21]. It is a two-stage method that first detects object bounding boxes with a Mask-RCNN backbone [7] and then regresses the pose of each object by comparing synthetically rendered images to the target object.

Estimating object identity and pose in challenging conditions, see for example Fig. 4, is prone to failure due to clutter and occlusion. Here, we propose an approach which uses physical stability as a constraint to recover missing objects and their poses from a set of available primitives.

D. Monte-Carlo tree search (MCTS)

Monte-Carlo tree search (MCTS) based methods have shown great performance in notoriously hard boardgames such as Go [23] and chess [24]. It allows to explore large portions of a tree during the search by exploiting reward information from collected rollouts. It has recently been used to rearrange dozens of cubes on a plane with full knowledge of the goal [14]. In this work, we use MCTS to plan sequences of STRIPS operators and assemble 3D structures.

III. OUR APPROACH

We assume throughout that the assemblies we want to copy are formed by stacking objects chosen from a set \mathcal{B} of N primitive shapes. Our plans are *linear*, in the sense that objects are placed on top of one another in sequence, so each plan consists of exactly N pairs (p_i, q_i) , where $1 \leq i \leq N$, p_i denotes the *pick pose* of primitive number i in the layout image J where the object lies on the table, and q_i is the *place pose* of that primitive in the final assembly, estimated by either the vision module or our planner (Fig. 2).

We assume that the primitives are well separated in the layout image, so that our vision module identifies them correctly and assigns them accurate pick poses p_i (this has been the case in our experiments). On the other hand, we denote by \mathcal{V} the *visible* primitives in the target image I , that is, those that have been identified and assigned a place pose q_i by the vision module, and by $\mathcal{H} = \mathcal{B} \setminus \mathcal{V}$ the remaining *hidden* primitives. The place poses q_i associated with hidden primitives are recovered by our planner using physical stability constraints.¹

We formulate an assembly plan as a sequence of STRIPS operators guided by a MCTS search as presented in Section III-B (Fig. 2b). The STRIPS based plan provides a candidate arrangement between objects and we still need to obtain precise poses for each object. To do so, we optimize over the object poses constrained by the candidate arrangement and physical stability as described in Section III-C (Fig. 2c). Lastly, a reward is computed according to the match between the candidate and target structure (Fig. 2d).

Note that if all object poses could be detected accurately, we could just stack the objects according to their pose in the structure in ascending height order without searching for an assembly plan. The difficulty of our problem comes from the unavoidable failures of the vision system.

A. From target image to object poses

As mentioned before we use a vision module to identify (some of) the objects forming the target assembly and estimate their place pose $q^{\mathcal{V}} = (q_j)_{j \in \mathcal{V}}$. We use Cosy-Pose [13] for that purpose in our experiments. Although it achieves state-of-the-art performance on the recent challenge BOP [10], its results are of course imperfect in real-world conditions, see Fig. 4, 5: it may miss some objects, hallucinate others, or estimate incorrect poses. We filter out objects whose detection scores are below a high confidence threshold. We obtain partial information about the structure to assemble in 3D from $q^{\mathcal{V}}$ and we show in the next sections how to build a plan and recover the poses $q^{\mathcal{H}}$ of objects missed by the object detector.

B. Assembly planning with STRIPS based MCTS

Single-view observations of assemblies often include objects being partially or even completely occluded. We exploit the information on the pose of the detected objects $q^{\mathcal{V}}$ to

¹In practice we of course apply some global offset to place poses to avoid collisions with the original structure.

define a reward function, which increases with the number of objects correctly placed in the known poses. We then find a sequence of STRIPS operators assembling the complete set of objects into a physically feasible structure which maximizes the reward function and allows to recover the pose of hidden objects $q^{\mathcal{H}}$.

STRIPS: MCTS is a search method over a discrete set of actions. The definition of this set impacts the efficiency of the algorithm. For instance, discretizing the search in a 3D volume results in a very large action space. We instead consider STRIPS operators [3] as the set of admissible actions, a pragmatic choice that allows to reason about object relations in 3D while limiting the search space. Here, we restrict the target objects to be placed along the X or the Y axis in a 3D Manhattan world, with rotations being multiples of $\frac{\pi}{2}$. This hypothesis could be avoided by defining more general STRIPS operators.

In more details, STRIPS represents the state of objects by a set of predicates that define high-level geometric relations among them as depicted in Figure 2b. Given objects (a, b, c) we consider the following states: *OnTable*(a), a is on the table; *Clear*(b), no object above b ; *On*(a, b), a is on b ; *OnAlongX*(a, b, c) (resp. *OnAlongY*(a, b, c)), a is on b and c along the X axis (resp. Y axis); and *Rot*(a), a is rotated by 90° . The state of objects can be modified by $M = 4$ operators applied only on objects that have not been moved yet: *PutOn*(a, b) put a on b ; *PutOnAlongX*(a, b, c) (resp. *PutOnAlongY*(a, b, c)) put a on b and c along the X axis (resp. Y axis); *Rot*(a) rotate a by 90° . With this representation, there are at most MN possible actions at the root node, a number that shrinks after a few actions and enables an efficient search.

MCTS: We perform a guided search over sequences of STRIPS operators with MCTS as shown in Figure 2b. A node of the tree corresponds to a STRIPS state and a branch is an admissible STRIPS operator. We denote by $n(s)$ the number of visits of node s , $g(s, a)$ the successor of s given action a and $R(s)$ the cumulative reward or return of a node. To guide the search and select actions, we use the standard upper confidence bounds applied to trees (UCT) formula:

$$U(s, a) = Q(s, a) + C \sqrt{\frac{\log n(g(s, a))}{n(s)}}, \quad (1)$$

where $Q(s, a) = \frac{R(g(s, a))}{n(g(s, a))}$ is the empirical estimate of the return and C is the exploitation-exploration trade-off constant, which we set to $\sqrt{2}$. UCT controls the trade-off between exploration of unvisited nodes and exploitation of nodes with highest returns. Once we reach a leaf node where all actions have not been explored yet, we execute random operators until all the target objects have been moved. For each node, we filter operators to exclude physically unfeasible structures or structures that do not match the structure from \mathcal{V} . The sequence of STRIPS operators define the topology of the candidate structure \mathcal{S} , e.g. the objects forming the base, the ones on top of them or the objects linking two stacks of

an arch. We still need to obtain precise poses of objects to define a reward for the candidate structure. To do so we solve an optimization problem on the set of object poses with constraints defined from the sequence of STRIPS operators described in the next section and illustrated in Figure 2c. Once the reward is computed, it is backpropagated from the leaf node to update information in the nodes of the sequence.

C. Estimating missing poses by leveraging physical constraints

Optimizing into an assembly plan: Given the set of visible poses q^V and a candidate sequence of STRIPS operators \mathcal{S} , the goal is to find a precise assembly plan where all candidate object poses q^S are defined. The optimization objective is the sum of errors between q^S and the set of visible object poses q^V extracted from the target image I . To simplify the notations, we will assume the first $P = |\mathcal{V}|$ objects of the candidate structure are matched to \mathcal{V} and the remaining q_i^S for $P < i \leq N$ correspond to poses of hidden objects \mathcal{H} in the target image. We define the problem (\mathcal{P}) as follows:

$$\min_{q_1^S, \dots, q_N^S \in \mathbb{R}^6} \sum_{i=1}^P \|q_i^S - q_i^V\|_2^2 \quad \text{s.t.} \quad \mathcal{C}(q_1^S, \dots, q_N^S) \leq 0, \quad (2)$$

where $\mathcal{C}(q_1^S, \dots, q_N^S)$ corresponds to physical constraints described in the next paragraph. Note that this is a convex optimization problem as the criterion is convex and the constraints are linear. It has at least one solution unless the constraints $\mathcal{C}(q_1^S, \dots, q_N^S)$ cannot be satisfied, in which case the stack is unfeasible. However, in most cases where the target is partially known, i.e. $P < N$, the objective is not strictly convex and has an infinite number of solutions. Constraining the problem with \mathcal{C} restricts the optimization to a set of physically feasible solutions, a highly desirable property when searching for an assembly plan. (q_1^S, \dots, q_N^S) then corresponds to a candidate set of poses to assemble the target according to the STRIPS sequence from Section III-B. **Stability and penetration constraints:** We define a set of stability constraints for each of the STRIPS predicates defined in Section III-B. Each constraint is defined thanks to linear inequalities, for example when stacking a block j on top of other blocks $i \leq j$ with the *PutOn* operator, we use the following constraints. Let (x_i, y_i, z_i) be the center of mass of object i and $(s_{i,x}, s_{i,y}, s_{i,z})$ the size of its bounding box, the constraints can be written as:

$$\begin{cases} x_i - s_{i,x}/2 \leq x_j \leq x_i + s_{i,x}/2, \\ y_i - s_{i,y}/2 \leq y_j \leq y_i + s_{i,y}/2, \\ z_{i+1} = z_i + (s_{i,z} + s_{i+1,z})/2, \end{cases} \quad (3)$$

for all $i = 1, \dots, j - 1$. These constraints enforce stability of the structure built by ensuring that the center of mass of the stacked object j is placed at a stable position. We denote $\mathcal{C}(q_1, \dots, q_j) \leq 0$ the set of stability constraints to be satisfied by the poses q_1, \dots, q_j . Similar constraints are written for each operator, each ensuring that objects are assembled in a stable structure.

We also add object penetration related constraints to ensure physically plausible solutions. For instance, if objects



Fig. 3. Objects from the T-LESS dataset [9] used in our constructions.

a and b with enclosing bounding boxes of size (s_a, s_b) are interpenetrating and $x_a \leq x_b$, we may assume that a must be on the left of b and add the new constraint $x_a + s_a/2 \leq x_b - s_b/2$ to $\mathcal{C}(q_1^S, \dots, q_N^S)$. In this way, we linearize penetration-avoidance constraints and can solve the previous problem with our updated constraints in order to recover penetration-free solutions.

Reward: We consider an assembly to be successful when all the poses of visible objects \mathcal{V} are matched, e.g. when $\|q_i^S - q_i^V\|_2 \leq \epsilon$ for all $i \leq P$, see Figure 2d.

We define the reward as the fraction of objects matched to target poses as follows:

$$r(q_1^S, \dots, q_N^S) = \frac{1}{P} \sum_{i=1}^P \mathbb{1}_{\|q_i^S - q_i^V\|_2 \leq \epsilon}, \quad (4)$$

where 1 corresponds to a candidate structure matching all visible objects.

IV. EXPERIMENTS

TABLE I

PLANNING COMPUTED FOR VARIOUS STRUCTURES ON POSES RETRIEVED BY COSYPOSE, AVERAGED ON 20 RANDOM SEEDS.

	Structures		
	A	B	C
Number of detected objects	5 / 5	6 / 8	8 / 11
Success Rate (%)	100	100	100
Number of MCTS rollouts	1±0	159±136	882±686
Computation time (s)	0.04±0.01	3.0±2.5	34.0±26.1
Average reward per rollout	1.0±0.0	0.04±0.07	0.011±0.008

TABLE II

EFFECTIVENESS OF OUR PENETRATION REMOVAL MODULE TO OBTAIN FEASIBLE PLANS. METRICS ARE AVERAGED OVER 20 RANDOM SEEDS.

	Collision Removal	Structures		
		A	B	C
Success Rate (%)	\times \checkmark	100 100	65 100	70 100
Number of rollouts	\times \checkmark	1±0 1±0	124±89 159±136	1109±818 882±686
Computation time (s)	\times \checkmark	0.05±0.02 0.05±0.01	1.6±1.2 3.0±2.5	39.2±28.8 34.0±26.1

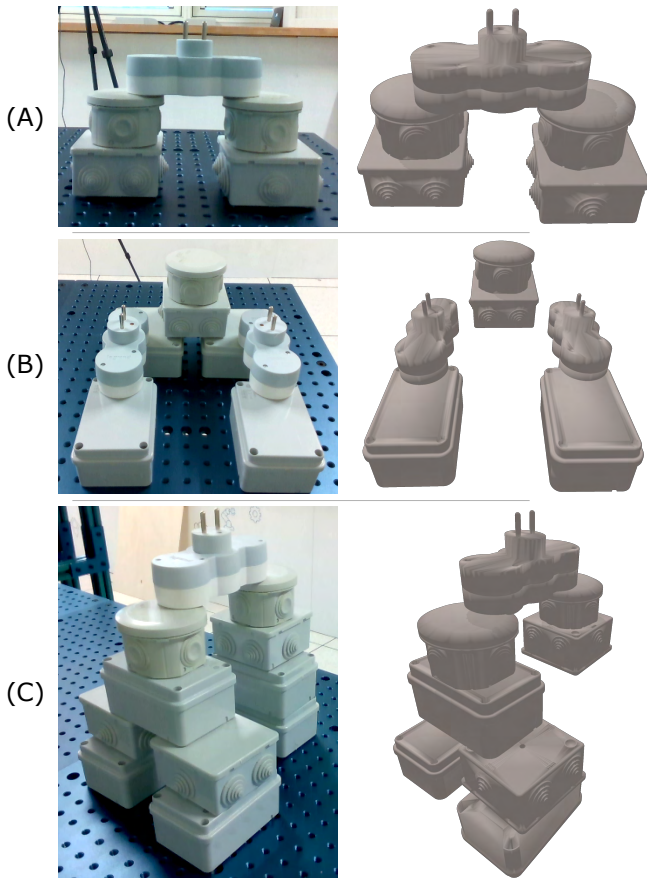


Fig. 4. Structures used for our evaluations. Left column: target images; right column: objects and poses seen by the detector and pose estimator. From top to bottom: structures A to C.

A. Experimental setup

We build structures made of objects selected from the T-LESS dataset [9], as shown on Figure 3. We record RGB images with two Realsense D435 cameras pointing respectively to the target structure and the primitives laid on the table (Fig. 2). As mentioned earlier, we use CosyPose [13] as our vision module, with a 95% threshold on detection confidence in our experiments. The poses of both cameras are assumed to be known through calibration in the robot coordinate system.

The assemblies are performed by a UR5 robot manipulator with a parallel gripper that successively picks primitives on the table at positions estimated by CosyPose and places them at the poses computed by our planner. We perform both off-line experiments, using a real image of a scene as input but without an actual run on the robot, and on-line ones with the robot executing the plan. The robot trajectory itself is computed by an off-the-shelf planner [12]. Our off-line experiments use one target image per structure and average the metrics on 20 random seeds for the search. For experiments on the actual robot, we build between 10 and 15 instances of each structure where the pose of each object is slightly randomized manually to test the method robustness. We average our metrics on all these instances. We

TABLE III
NUMBER OF ROLLOUTS FOR RANDOM SEARCH (R.S.) OR MCTS WITH SPARSE OR DENSE REWARD AND GUIDANCE. ALL THE METHODS HAVE A SUCCESS RATE OF 100% AND THE METRICS ARE AVERAGED OVER 20 RANDOM SEEDS.

Search method	Reward	Guided	Structures		
			A	B	C
R.S.	—	✗	1±0	133±87	7100±6931
R.S.	—	✓	1±0	148±116	2077±2237
MCTS	Sparse	✗	1±0	99±89	10980±12686
MCTS	Sparse	✓	1±0	106±96	1139±810
MCTS	Dense	✗	1±0	111±117	10346±7720
MCTS	Dense	✓	1±0	159±136	882±686

TABLE IV
RECONSTRUCTIONS ON A UR5 ROBOT MANIPULATOR, AVERAGED ON 10 INSTANCES PER STRUCTURE FOR A AND B AND 15 FOR C.

	Structures		
	A	B	C
Number of visible objects	5.1±0.3	6.2±0.4	7.7±0.7
Valid initial poses rate (%)	90	80	80
Number of MCTS rollouts	1±0	138±137	557±1050
Structural stability rate (%)	90	60	13
Target objects matching rate (%)	90	60	13

study three structures of increasing complexity, as depicted in Figure 4, including an essentially 2D arch with little occlusion, for which pose estimation works well, as well as more challenging 3D stacks with several partially or fully hidden objects.

B. Robustness to missing primitives

We first verify off-line that our approach is able to cope with incomplete structure information and still find assembly plans that correctly match the target structure. Table I shows that our algorithm finds assembly plans for every stack in a reasonable number of MCTS rollouts, even for the difficult structure C whose assembly sequences are composed of at least 8 operators. Results on structure A confirm that assembling a structure whose poses are all known is immediate, with only one rollout required to find the solution. Interestingly, the average reward per rollout decreases as the number of unseen objects grows. As the branching factor of MCTS increases while the number of valid plans remains constant, the planner has to explore more possibilities, resulting in an important slowdown.

C. Ablation study

Interpenetration removal: We use here the same setup as in the previous section but study the effect of different parts of our algorithm. Table II shows that the object penetration removal module is essential for the robustness of our planner,

which may fail up to 35% of the time without it in the case of missing primitives. Using this module comes with little cost, both in terms of time and number of rollouts. It even accelerates the search by eliminating plans with penetrating poses and guiding the search towards higher quality and feasible assemblies in the case of structure C.

Search method and reward: We compare our MCTS approach and *dense* reward definition (Eq. [4]) with both a random search and MCTS with a *sparse* reward, equal to one only when all the target poses are matched, e.g. $r_{sparse}((q_i)_i) = \prod_{i \in \mathcal{V}} 1_{\|p_i - q_i\|_2 \leq \epsilon}$. We also study the impact of guiding the search by favoring, whenever possible, the actions on previously detected objects from \mathcal{V} . As we know their target poses, we can readily place them in the assembly with confidence. For the structure A whose poses are all known, no search is required and all the methods are equivalent. Table III shows that guiding the search for structures B and C yields a factor of magnitude speedup in terms of number of rollouts. Except in one case for structure B, MCTS always outperforms random search, quite significantly for structure C. Using a dense reward instead of a sparse one often improves performance, especially for structure C, but by a relatively small margin.

D. Experiments on a real robot

Assemblies: We build our structures with a real robot manipulator, where we assemble 10 instances of structures A and B and 15 of structure C (Fig. 4) and report results in Table IV. First, the number of detected objects varies between instances of the same structure: several false positive detections may appear while other objects go undetected. For instance, CosyPose detects an extra object in one instance of structure A, accounting for 10% of reconstruction failures. In general, detection-related errors represent 10% to 20% of failures in our study. Still, the method remains efficient and succeeds in finding plans in a reasonable number of rollouts when pose estimation detects a sufficient number of objects. Note here that the variance on the number of rollouts is high, due to the changing number of detected objects between instances of a category, which impacts the difficulty of planning.

The reconstruction success rate is 90% for structure A, 60% for B and 13% for C. In every case, structures that are correctly assembled and stable also match the target objects well. We have identified 4 sources of failures during the assembly. First, bad pose estimations on the target images occur in 20% of the assemblies and prevent planning. Second, inaccurate robot moves combined with plans placing objects close to the edge of objects underneath led to falls in respectively 20% and 13% of instances of B and C. Third, 20% of plans for structure C place objects too close to each other, and our motion planner is unable in these cases to find collision-free paths for placing them and then opening the gripper. Last, our approximation of objects by boxes leads to failures for 27% of assemblies of C: our planner generates stable structures given the box models, but these are too large

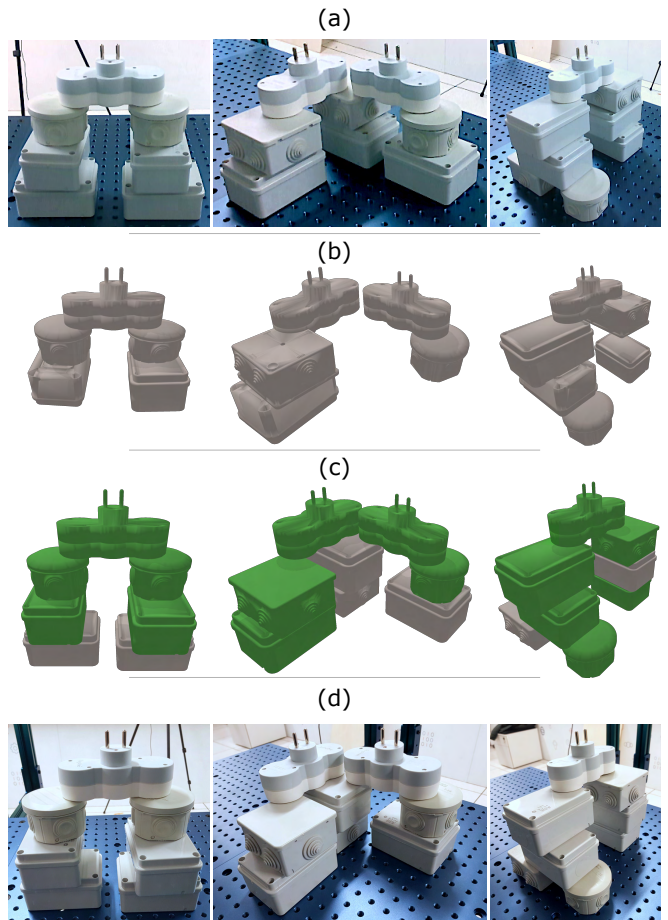


Fig. 5. Examples of additional structures rebuilt with our method. (a) Input image of the structure to be assembled, (b) identification and 6D pose estimation with CosyPose, (c) result of our task planning, where green objects were detected by the pose estimator and grey ones were added by our planning, (d) result of the assembly with a real robot.

compared to the real objects, causing the structure to collapse during assembly.

Qualitative results: Figure 5 shows examples of some additional structures that our method is able to assemble from an image, a bigger 2D arch as well as more complex 3D stacks with occluded objects. Our method deals with a wide range of assemblies and recovers the pose of missing objects in physically plausible poses that lead to successful assemblies on a real robot. Our supplementary video includes several examples of assembly runs.

V. CONCLUSION

This work introduces a method to assemble blocks and reproduce structures specified by a single RGB image. We find assembly plans from incomplete information about the structure due to unavoidable occlusions by leveraging physical reasoning and show that our method assembles a variety of structures on a real robot. While we focus on assembling in a 3D Manhattan space, this is not a limitation of the approach and we believe more complex structures can be assembled by using richer STRIPS operators and stability constraints.

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