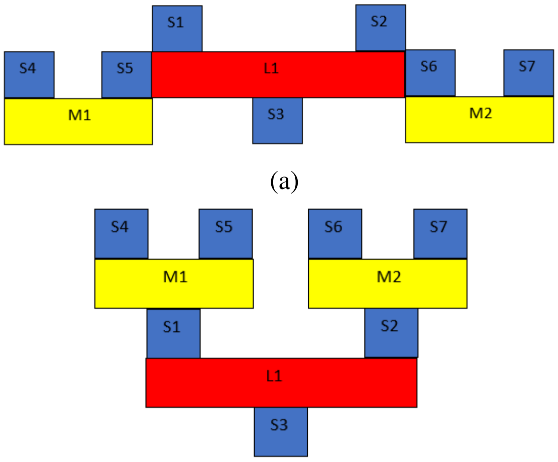
Revisiting Robot Construction Problems as Benchmarks for Task and Motion Planning

Faseeh Ahmad, Esra Erdem and Volkan Patoglu
Faculty of Engineering and Natural Sciences, Sabanci University, Istanbul, Turkey
Email: {faseehahmad,esraerdem,vpatoglu}@sabanciuniv.edu

We consider the robot construction planning problems introduced by Scott Elliott Fahlman in his seminal article [2], where the aim is for a robot to build specified structures out of simple rectangular blocks of different sizes. These problems are challenging from the perspective of task planning since they need incorporation of preexisting structure into the final design, pre-assembly of movable substructures on the table, and the use of extra blocks as temporary supports or counterweights during construction. They are challenging from the perspective of geometric reasoning as well since they need feasibility checks, like reachability of a block, collisions of blocks, and stability of complex structures. Let us illustrate these challenges by some examples.

Scenario 1: (Fig. 1) This construction problem involves incorporation of the existing structures into the final design. For instance, a plan for a bimanual robot, like Baxter, to achieve the goal configuration from the initial state involves the following actions: 1) pick the block $M1$ with the left gripper, while picking the block $M2$ with the right gripper, 2) place $M1$ on $S1$, while placing $M2$ on $S2$.

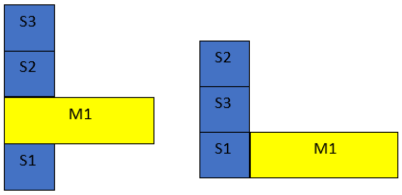


(a)

(b)

Fig. 1. (Fig. 1.8 of [2]): (a) initial state and (b) goal state.

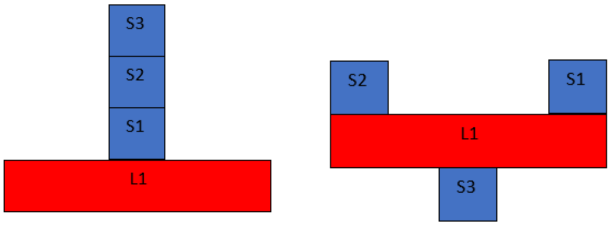
Scenario 2: (Fig. 2) This construction problem cannot be solved by moving one block at a time as in the Blocks World, since the stability of the overall structure needs to be preserved while executing the plan. It requires first moving the block $M1$ and the blocks above it: 1) pick the block $M1$ with the left gripper, 2) place the block $M1$ on the table, 3) pick the block $S3$ with the right gripper, 4) place $S3$ on $S1$, while picking $S2$ with the left gripper, 5) place $S2$ on $S3$.



(a) (b)

Fig. 2. (Fig. 1.9 of [2]): (a) initial state and (b) goal state.

Scenario 3: (Fig. 3) This problem requires first the pre-assembly of a movable stable substructure on the table: 1) pick $S3$ with the left gripper, 2) pick $S2$ with the right gripper, while placing $S3$ on the table, 3) pick $S1$ with the left arm, while placing $S2$ on l_1, 4) place $S1$ on l_1, 5) pick l_1 with the left arm, 6) place l_1 on $S3$. Note that special attention needs to be paid as to where blocks are placed on l_1 to ensure stability.

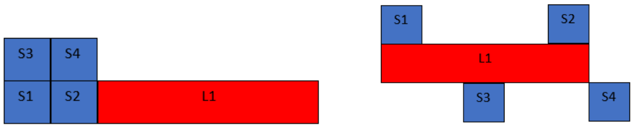


(a) (b)

Fig. 3. (Fig. 1.4 of [2]): (a) initial state and (b) goal state.

Scenario 4: (Fig. 4) For this problem, consider the following plan: 1) pick $S3$ with the left arm, 2) pick l_1 with the right arm, while placing $S3$ on the table towards the right part, 3) pick $S4$ with the left arm, while placing l_1 onto $S3$, 4) pick $S1$ with the right arm, while placing $S4$ on the table to serve as a temporary external support for l_1, 5) pick $S2$ with the left arm, while placing $S1$ onto l_1, 6) pick $S4$ with the right arm, while placing $S2$ onto l_1, 7) place $S4$ on the table towards the right part.

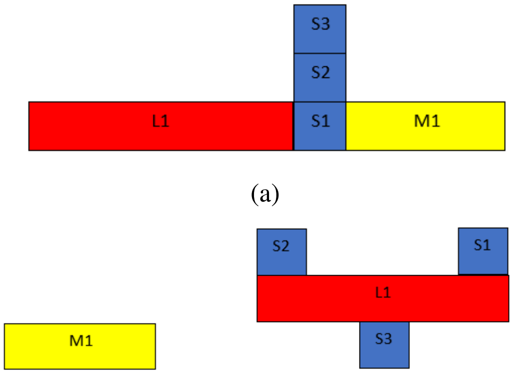
Scenario 5: (Fig. 5) For this problem, consider the following plan: 1) pick $S3$ with the left arm, 2) pick l_1 with the right arm, while placing $S3$ on the table towards the right part, 3) pick $M1$ with the left arm, while placing l_1 onto $S3$,



(a) (b)

Fig. 4. A construction problem: (a) initial state and (b) goal state.

4) pick $S2$ with the right arm, while placing $M1$ on l_1 to serve as a temporary counterweight, 5) pick $S1$ with the left arm, while placing $S2$ onto l_1, 6) pick $M1$ with the right arm, while placing $S1$ onto l_1, 7) place $M1$ on the table towards the left part. It is interesting that the block $M1$ is moved onto l_1 as a counterweight, so that the blocks $S2$ and $S1$ can be moved onto l_1.



(a)

(b)

Fig. 5. A construction problem: (a) initial state and (b) goal state.

Note that the robot construction planning problems above cannot be solved (i) using physics simulators or motion planners only, due to planning of pick and place actions, and (ii) using task planners or automated reasoners only, due to reachability and stability checks. In that sense, Fahlman's robot construction problems provide more challenging benchmarks compared to the Blocks World.

As Fahlman notes, these robot construction problems can be considered a descendant of the Blocks World portion of Winograd's language system [7], since both types of problems are about reconfiguration of blocks. However, "since Winograd's main interest was in language rather than in construction problems, his models were so restricted that the type of problems discussed above could not even be represented, let alone solved."

Fahlman implemented a planning system, called BUILD, in the programming language CONNIVER [4] to solve these problems to some extent. The initial state is given to BUILD in the form of a 3D model that specifies the size and position of each block in the scene; it is assumed that they are obtained, e.g., by perception. A goal state is presented to BUILD in a similar way but the 3D model may be incomplete.

Fahlman's robot construction problems have not been investigated with a formal approach since then. We study Fahlman's robot construction problems and its variations, and present a solution by formalizing the robots actuation actions and the change in the world using Answer Set Programming [1], and by embedding feasibility checks into the domain description.

We describe the initial and goal states by a set of facts. For instance, in Scenario 2, the initial state is described as follows:

$$\begin{aligned}&\mathit{init\_on}(S1, Table, 1, 1).\\&\mathit{init\_on}(M1, S1, 1, 1).\\&\mathit{init\_on}(S2, M1, 1, 1).\\&\mathit{init\_on}(S3, S2, 1, 1).\end{aligned}$$

Here, $\mathit{init\_on}(x, y, u, v)$ expresses that, initially, the unit u of box x is on the unit v of location y; we consider the leftmost overlapping units with respect to the table. The goal state is described by a set of facts as well:

$$\begin{aligned}&\mathit{goal}(S1, Table).\\&\mathit{goal}(M1, Table).\\&\mathit{goal}(S3, S1).\\&\mathit{goal}(S2, S3).\end{aligned}$$

where $\mathit{goal}(x, y)$ expresses that, in a goal state, the box x is on location y. Note that Fahlman's robot construction problems can be described easily by a set of such facts in other planning formalisms and to other planners; the challenge is to describe the hybrid robotic domain (i.e., hybrid actuation actions, constraints, ramifications).

We have embedded reachability checks and stability checks in the formal descriptions of the robotic actions and change. For reachability checks, we have used the RRT* motion planner [3] from the OMPL library [6]. For stability checks, we have used the physics-based simulator Pybullet. If these feasibility checks are verified in a reasonable amount of time, then the robotic actuation actions are considered feasible; otherwise, we increase the time threshold and/or the number of samples as suggested by the completeness results of hybrid planning in [5].

We show applications of our method by dynamic simulations with Baxter robot. [1]

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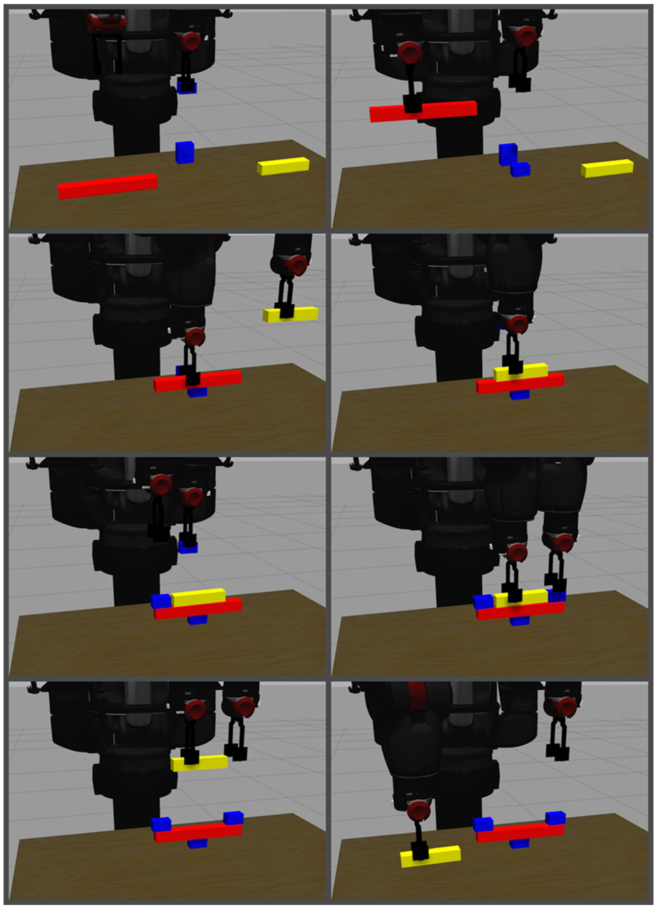

Fig. 6. Snapshots present dynamic simulation of a sample construction problem with a Baxter robot.

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