Multi-Level Reasoning for Delicate Assembly using Dual Arms

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***Abstract*— Robotic assembly is a critical category of tasks in contemporary manufacturing. Despite being a well-known toy brand, LEGO assembly is actually challenging for robots due to the various user-imposed requirements, physical constraints, and specialized expertise in the components involved. We developed a multi-level reasoning approach, from physical reasoning and assembly planning, to dual arm task planning and action planning. To our knowledge, ours is the first robotic system capable of performing customized LEGO assembly using commercial LEGO bricks.**

I. Introduction

Creating assembly product is challenging and time-consuming both in planning and construction itself. LEGO is a diverse, flexible, replicable, and low-cost platform, making it an ideal choice for benchmarking. Assembling LEGO is a non-trival problem due to its customizability, tiny sizes, and most importantly, the passive connections, i.e., connections between bricks are not rigid and could break throughout the assembly process. Thus, achieving LEGO assembly requires that the system and the planning algorithms have a comprehensive understanding of the underlying physics and dexterous manipulation skills.

As shown in Fig. 1 our end-to-end pipeline spans from assembly sequence planning, to robot task and motion planning, as well as robust execution frameworks and manipulation policies. Our contributions include 1) a physics simulation tool to estimate the stability of Lego connections 2) physics-aware assembly sequence planning and 3) a multi-robot task and motion planning framework for safe, efficient, and asynchronous multi-robot execution. Experimentally, our generative design and planning framework can automatically perform robotic assembly of LEGO structures with 30+ commercial LEGO bricks. Below we will discuss our pipeline and highlight our contributions individually.

II. Physics Reasoning: StableLego [1]

Understanding the physical properties of LEGO assemblies is crucial for both designing LEGO structures and constructing LEGO products. Conventional approaches rely on physics engines to simulate assembly properties and provide cost-effective feedback. However, existing simulations often fail to accurately model the physical interactions between components in a LEGO assembly. To address the challenge, we develop computational tools that can reliably and efficiently capture the physical dynamics of LEGO assemblies.

Our proposed method formulates a new optimization that optimizes over force-balancing equations, to infer the structural stability of block stacking assembly. In addition, we provide StableLego: a comprehensive LEGO assembly dataset, which includes a wide variety of LEGO assembly designs for real-world objects. The dataset includes more than 50k LEGO structures built using standardized LEGO bricks with different dimensions along with their stability inferences generated by the proposed algorithm. The physics-based stability estimator is crucial to determine the feasiblity of assembly sequences, selection of grasp pose, and the need for a support arm for collaborative assembly, as seen in the center of Fig. 1.

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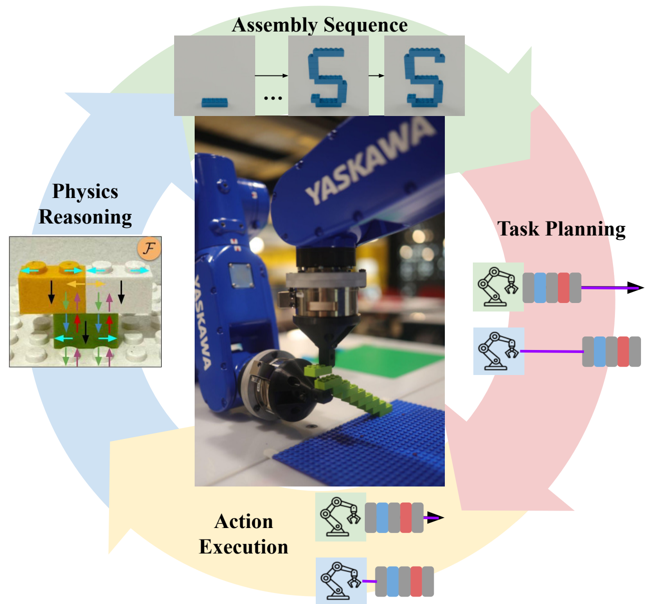


Fig. 1: Illustration of multi-level reasoning for Delicate Bimanual Assembly.

III. Physics-aware Assembly Sequence Planning

Assembly sequence planning (ASP) for LEGO is combinatorial in nature because the obejcts are built with large numbers of a few standardized unit primitives that satisfy user specifications. Given the shape of the desired object, our goal is to find a sequence of actions for placing unit primitives to build the target object. In particular, we aim to ensure the planned assembly sequence is physically executable. However, ASP for combinatorial assembly is particularly challenging due to its combinatorial nature. To address the challenge, we integrate the structural analysis into an assembly-by-disassembly depth-first search algorithm (similar to [2]) and develop an assembly sequence planning method. Given a LEGO structure, the method generates a

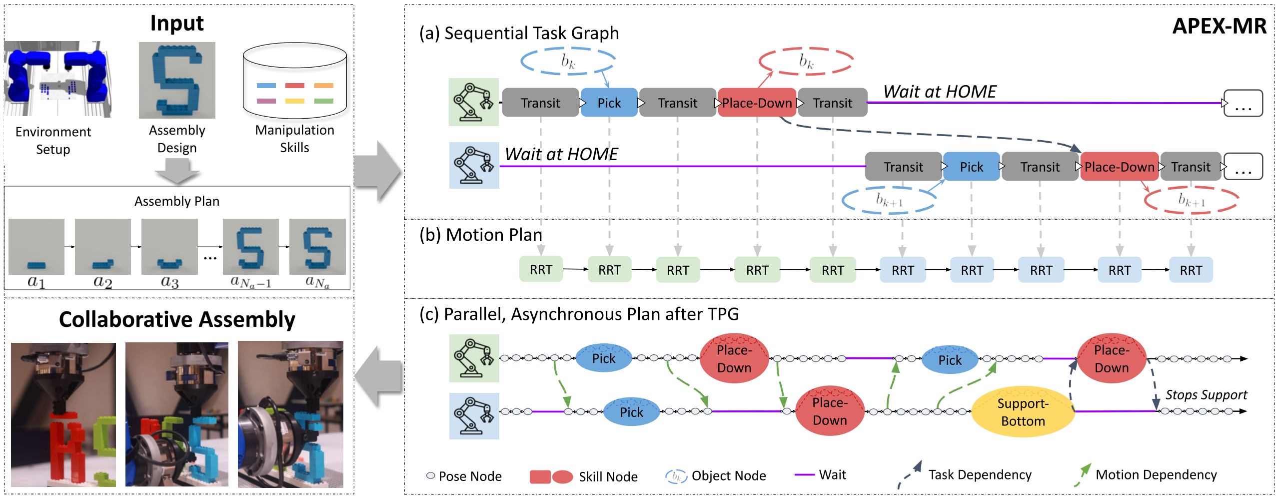


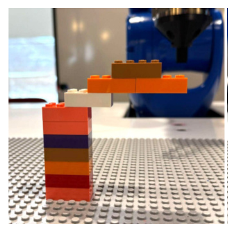
Fig. 2: An overview of APEX-MR. Given inputs (Environment, Assembly Plan, Skills), APEX-MR (a) generates a sequential task plan (task graph), (b) plans corresponding sequential motions (RRT-Connect), and (c) converts this into a parallel, asynchronous execution plan using a multi-modal Temporal Plan Graph (TPG), enabling efficient and robust execution.

step-by-step brick sequence plan that allows the user (either a human or robots) to construct the structure following the order. The search algorithm uses an online physics-aware action mask [3] that filters out invalid actions based on physical stability and robot reachability, which effectively guides the search and ensures violation-free deployment.

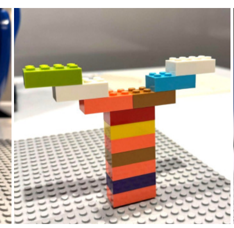
IV. Task and Action Reasoning: Asynchronous Planning and Execution

Given an assembly plan, the next step is to plan the robot assignment, grasp poses, and coordinate the motions of the dual-arm assembly robots. Compared to a single-robot workstation, a multi-robot system offers several advantages: 1) it expands the system's workspace, 2) improves task efficiency, and more importantly, 3) enables robots to achieve significantly more complex and dexterous tasks, such as cooperative assembly. However, coordinating the tasks and motions of multiple robots is challenging due to issues, e.g., system uncertainty, task efficiency, algorithm scalability, and safety concerns. To address these challenges, we propose APEX-MR [4], an asynchronous planning and execution framework designed to safely and efficiently coordinate multiple robots to achieve cooperative assembly. We assume the required skills are pre-learned. A skill can be a learned policy, a parameterized motion, or even a simple trajectory. APEX-MR selects appropriate skills from the library and coordinates the robots to accomplish the task as shown above. Specifically in LEGO assembly, we learn the following robot skills - pick, place, support, and handover - based on the robot EOAT tool and manipulation policy [5].

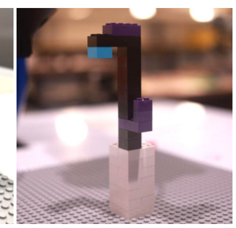
The crux of our proposed method, Multi-Robot Asynchronous Planning and Execution for Cooperative Assembly (APEX-MR), is to efficiently generate a sequential task and motion plan first, then post-process it for safe asynchronous execution. As shown in Fig. 2, APEX-MR solves an integer-linear program (ILP) to generate a sequential task plan, then generates individual task motion plan sequentially. To enable



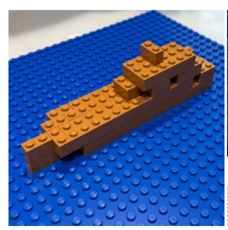
(a) Cliff.



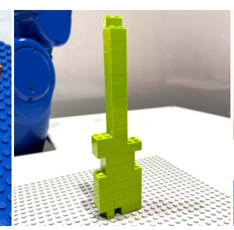
(b) Branched stairs.



(c) Faucet.



(d) Vessel.



(e) Guitar.

(f) RSS.

Fig. 3: Example LEGO structures constructed in real by the dual-arm system.

seamless collaboration, APEX-MR extends the Temporal Plan Graph (TPG) [6] to multiple robot arms and generates an asynchronous execution schedule given the sequential task and motion plan. More importantly, the asynchronous execution plan accommodates execution delays and contingencies to ensure robust and safe bimanual manipulation under uncertainty. Experimental results demonstrate that APEX-MR can significantly speed up the execution time of many long-horizon LEGO assembly tasks by 48% compared to sequential planning and 36% compared to synchronous planning on average. APEX-MR is the first a dual-industrial-arm system that can accomplish customized, delicate assemblies using commercial LEGO in real. Fig. 3 shows some examples of LEGO structures of ours built by our dual arm assembly system following our planned assembly sequences and multi-robot task and motion plan.

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