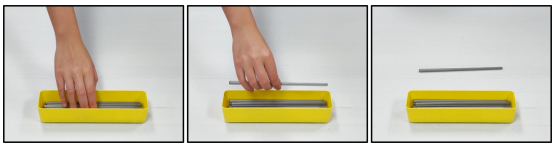
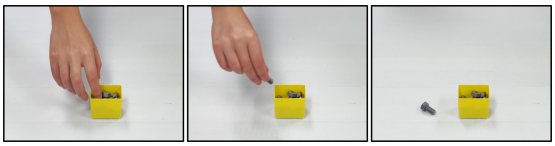
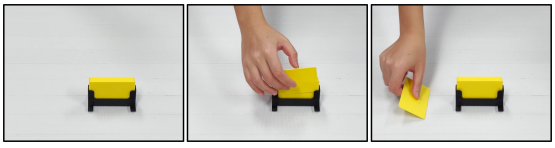
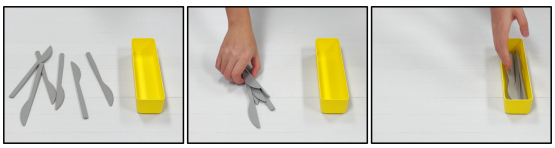
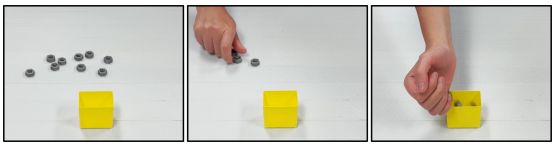
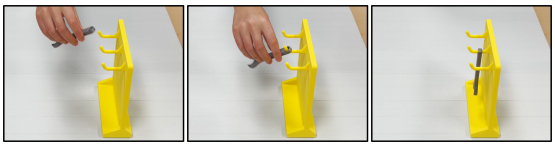
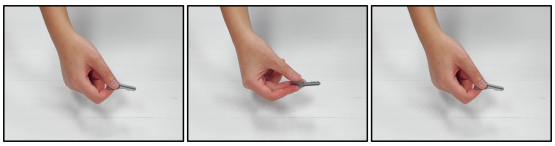
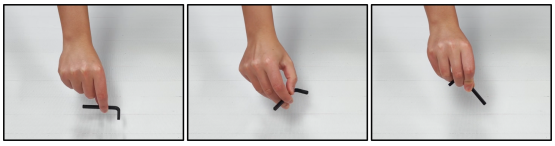
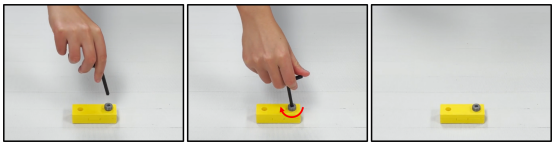
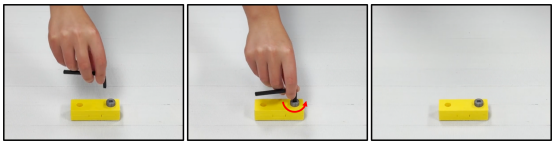
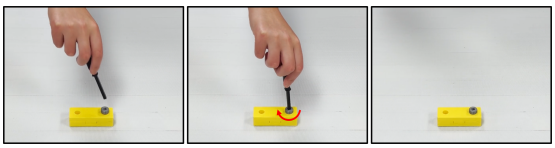
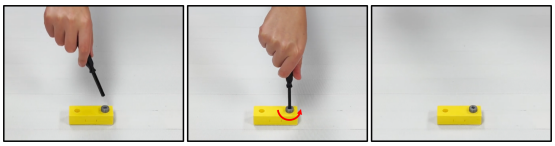
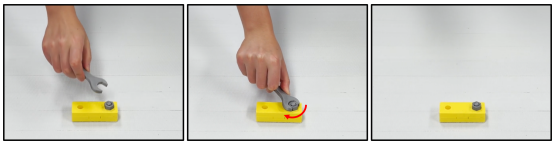
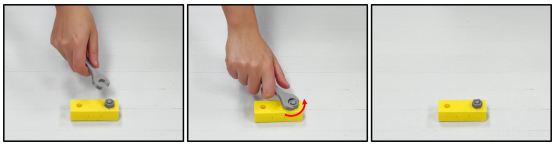
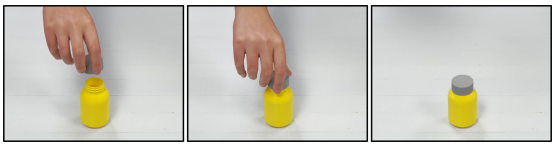
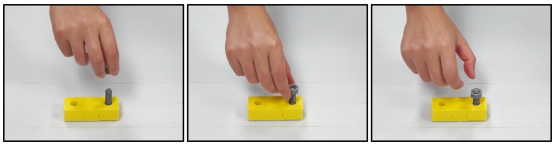
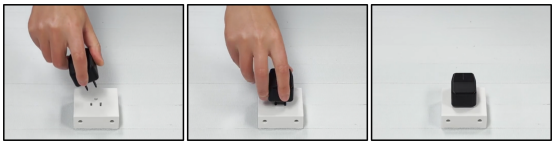
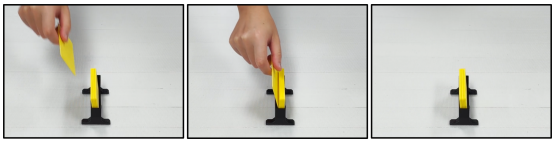
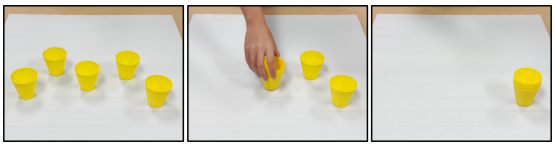
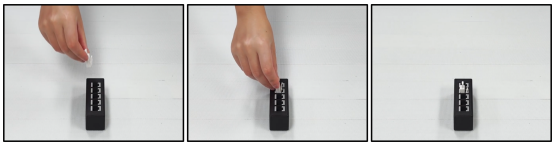
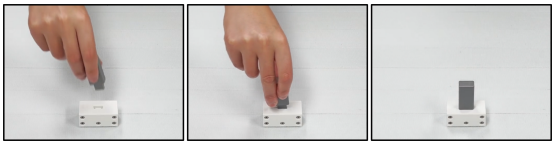
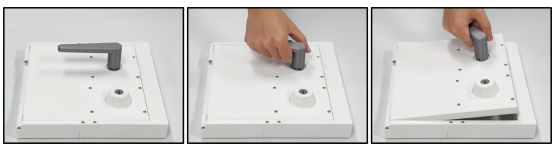
APPENDIX C
DETAILED BENCHMARK TASK DESCRIPTIONS

TABLE C1: Base benchmark tasks

Task Execution Sequence	Task Specs
	**Task:** Grasp target key from keychain **Skills:** Grasping from clutter, grasping thin or small objects **Description:** For a keychain in the workspace with multiple keys, find and singulate the specified target key among all keys on the keychain. **Success criteria:** The robot movement stops with only the specified target key stably grasped within the robot end-effector.
	**Task:** Retrieve single utensil from bin **Skills:** Grasping from clutter, grasping thin or small objects **Description:** A utensil storage bin is placed in the workspace. The target utensil is placed in the bin alongside multiple other utensils. Pick up a single copy of the target utensil from the cluttered storage bin and place it on the table without removing other objects from the bin. **Success criteria:** The robot movement stops after separating a single copy of the target utensil and placing it on the table. Other utensils should remain in the storage bin. The robot should not remain in contact with the task objects.
	**Task:** Retrieve single fastener from bin **Skills:** Grasping from clutter, grasping thin or small objects **Description:** A fastener storage bin is placed in the workspace. The target fastener is placed in the bin alongside multiple other fasteners. Pick up a single copy of the target fastener from the cluttered storage bin and place it on the table without removing other objects from the bin. **Success criteria:** The robot movement stops after separating a single copy of the target fastener and placing it on the table. Other fasteners should remain in the storage bin. The robot should not remain in contact with the task objects.
	**Task:** Retrieve top cup from stack **Skills:** Grasping from clutter **Description:** A neatly organized stack of cups is placed in the workspace. Pick up the top cup from the stack and place it on the table without disturbing the rest of the stack. **Success criteria:** The robot movement stops after separating the top cup from the stack and placing it on the table. The remaining cups should remain in a neat stack. The robot should not remain in contact with the task objects.
	**Task:** Retrieve single card from deck **Skills:** Grasping from clutter, grasping thin or small objects **Description:** A neatly organized deck of cards is placed in a cardholder in the workspace. Pick up a single card and place it on the table without disrupting the rest of the card deck. **Success criteria:** The robot movement stops after separating a single card from the deck and placing it on the table. The remaining cards should remain a neat deck in the cardholder. The robot should not remain in contact with the task objects.
	**Task:** Pick up object from platform **Skills:** Grasping thin or small objects **Description:** Pick up the thin and/or small object placed on the flat platform. **Success criteria:** The target object is stably grasped by the robot and lifted off the platform.
	**Task:** Collect utensils **Skills:** Grasping multiple objects, placing under environmental constraints **Description:** Collect all utensils scattered across the workspace and place them into the storage bin. Being able to hold multiple utensils simultaneously will greatly increase task completion efficiency. **Success criteria:** The robot movement stops after placing all utensils inside the storage bin. The robot should not remain in contact with the task objects.

Task Execution Sequence	Task Specs
	**Task:** Collect fasteners **Skills:** Grasping multiple objects, placing under environmental constraints **Description:** Collect all fasteners scattered across the workspace and place them into the storage bin. Being able to hold multiple fasteners simultaneously will greatly increase task completion efficiency. **Success criteria:** The robot movement stops after placing all fasteners inside the storage bin. The robot should not remain in contact with the task objects.
	**Task:** Hang object **Skills:** Placing under environmental constraints **Description:** Hang the object in-hand onto an empty hanging board hook. **Success criteria:** The robot movement stops after placing the target object onto a hanging hook. The robot should not remain in contact with the task objects.
	**Task:** Place utensil into bin **Skills:** Placing under environmental constraints **Description:** A utensil bin with utensils already stored in it is placed in the workspace. Starting with a utensil held in hand, find an open pocket in the cluttered utensil storage bin and place the held utensil in it. **Success criteria:** The robot movement stops after placing the target object into the storage bin. The robot should not remain in contact with the task objects.
	**Task:** In-hand repose **Skills:** In-hand repositioning **Description:** Manipulate the target object in-hand, such that it ends up in the desired pose relative to the hand. Examples include flipping the orientation of a key or a USB stick to align with the slot. **Success criteria:** The target object pose converges and stabilizes to the desired pose, and remains within the robot end-effector throughout the execution without being dropped.
	**Task:** In-hand grasp transition **Skills:** In-hand repositioning **Description:** Manipulate the target object in-hand, such that it ends up with the desired grasp type (see grasp types defined in the Grasp Taxonomy [39]). **Success criteria:** The target object pose converges and stabilizes with the desired grasp type, and remains within the robot end-effector throughout the execution without being dropped.
	**Task:** Tighten screw with Allen key **Skills:** Extrinsic contact control, insertion and alignment **Description:** A screw is placed into the screw slot of an assembly block in the workspace, but the threads are unengaged. Use the Allen key grasped in hand to tighten the screw. **Success criteria:** The screw is tightened and remains stationary when a small force is applied in an attempt to rotate the screw. The robot movement stops after terminating the tightening motion, moving away from, and breaking contact with the screw.
	**Task:** Loosen screw with Allen key **Skills:** Extrinsic contact control, insertion and alignment **Description:** A screw is placed into the screw slot of an assembly block in the workspace and is fully tightened. Use the Allen key grasped in hand to loosen the screw. **Success criteria:** The screw is loosened and can rotate freely when a small force is applied in an attempt to rotate the screw. The robot movement stops after terminating the loosening motion, moving away from, and breaking contact with the screw.
	**Task:** Tighten screw with screwdriver **Skills:** Extrinsic contact control, insertion and alignment **Description:** A screw is placed into the screw slot of an assembly block in the workspace, but the threads are unengaged. Use the screwdriver grasped in hand to tighten the screw. **Success criteria:** The screw is tightened and remains stationary when a small force is applied in an attempt to rotate the screw. The robot movement stops after terminating the tightening motion, moving away from, and breaking contact with the screw.

Task Execution Sequence	Task Specs
	**Task:** Loosen screw with screwdriver **Skills:** Extrinsic contact control, insertion and alignment **Description:** A screw is placed into the screw slot of an assembly block in the workspace and is fully tightened. Use the screwdriver grasped in hand to loosen the screw. **Success criteria:** The screw is loosened and can rotate freely when a small force is applied in an attempt to rotate the screw. The robot movement stops after terminating the loosening motion, moving away from, and breaking contact with the screw.
	**Task:** Tighten nut with wrench **Skills:** Extrinsic contact control, insertion and alignment **Description:** A nut is threaded onto a screw head in the workspace but is left untightened. Use the wrench grasped in hand to tighten the nut. **Success criteria:** The nut is tightened and remains stationary when a small force is applied in an attempt to rotate the nut. The robot movement stops after terminating the tightening motion, moving away from, and breaking contact with the nut.
	**Task:** Loosen nut with wrench **Skills:** Extrinsic contact control, insertion and alignment **Description:** A nut is threaded onto a screw head in the workspace and is fully tightened. Use the wrench grasped in hand to loosen the nut. **Success criteria:** The nut is loosened and can rotate freely when a small force is applied in an attempt to rotate the nut. The robot movement stops after terminating the loosening motion, moving away from, and breaking contact with the nut.
	**Task:** Put bottle cap onto bottle **Skills:** Insertion and alignment, articulated object manipulation **Description:** A bottle without a cap is placed in the workspace. Screw the bottle cap held in hand onto the bottle and tighten it. **Success criteria:** The bottle cap is tightened and remains stationary when a small force is applied in an attempt to rotate the cap. The robot movement stops after terminating the tightening motion, moving away from, and breaking contact with the task objects.
	**Task:** Thread nut onto screw **Skills:** Insertion and alignment, articulated object manipulation **Description:** Screw the nut held in hand onto the screw head placed in the workspace such that their threads fully engage. **Success criteria:** The nut and screw threads engage. The robot movement stops after terminating the rotation motion, moving away from, and breaking contact with the task objects.
	**Task:** Insert key into lock **Skills:** Insertion and alignment **Description:** A lock is placed in the workspace. Insert the key held in hand into the lock. **Success criteria:** The key is inserted into the lock. The robot movement stops after terminating the insertion motion, moving away from, and breaking contact with the task objects.
	**Task:** Plug in charger **Skills:** Insertion and alignment **Description:** An outlet is placed in the workspace. Fully insert the charger held in hand into the outlet. **Success criteria:** The charger is fully inserted into the outlet, such that it does not noticeably move when further pushed toward the outlet. The robot movement stops after terminating the insertion motion, moving away from, and breaking contact with the task objects.

Task Execution Sequence	Task Specs
	**Task:** Place card into holder **Skills:** Placing under environmental constraints **Description:** A card holder that already contains other cards is placed in the workspace. Place the card held in hand into the card holder. **Success criteria:** The robot movement stops after placing the card in the card holder, with existing cards remaining in the card holder. The robot should not remain in contact with the task objects.
	**Task:** Stack cups **Skills:** Placing under environmental constraints **Description:** Multiple cups are scattered around the workspace. Collect the cups and place them inside one another to form a tight stack. **Success criteria:** The robot movement stops after all cups form a tight, upright stack (not knocked over). The robot should not remain in contact with the task objects.
	**Task:** Plug in Ethernet **Skills:** Insertion and alignment **Description:** Fully insert the Ethernet plug held in hand into a socket placed in the workspace. **Success criteria:** The Ethernet plug is fully inserted into the socket with its latch engaged, such that the plug can't be withdrawn by a light pull. The robot movement stops after terminating the insertion motion, moving away from, and breaking contact with the task objects.
	**Task:** Plug in USB **Skills:** Insertion and alignment **Description:** Fully insert the USB stick held in hand into the USB slot placed in the workspace. **Success criteria:** The USB stick is fully inserted into the slot, such that it does not noticeably move when further pushed toward the slot. The robot movement stops after terminating the insertion motion, moving away from, and breaking contact with the task objects.
	**Task:** Turn key to unlock door **Skills:** Articulated object manipulation **Description:** A locked door module is placed in the workspace with a key already inserted into the lock. Turn the key to unlock the door. **Success criteria:** The key is fully turned such that the door can be opened. The robot movement stops after terminating the rotation motion, moving away from, and breaking contact with the task objects.
	**Task:** Turn doorknob to open door **Skills:** Articulated object manipulation **Description:** Turn the doorknob fully to unlock the door, then open the door. **Success criteria:** The door is opened by at least 5 degrees, such that it is visually obvious that the door has been unlocked.
	**Task:** Turn door handle to open door **Skills:** Articulated object manipulation **Description:** Turn the door handle fully to unlock the door, then open the door. **Success criteria:** The door is opened by at least 5 degrees, such that it is visually obvious that the door has been unlocked.
	**Task:** Turn dial to target position **Skills:** Articulated object manipulation **Description:** Operate the dial to turn it to the specified target position. **Success criteria:** The dial is turned to the target position. For dials that can be turned continuously, the final position should be within half a tick interval from the target position. The robot movement stops after terminating the rotation motion, moving away from, and breaking contact with the task objects.

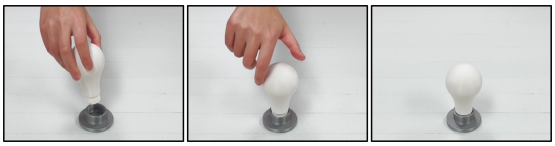
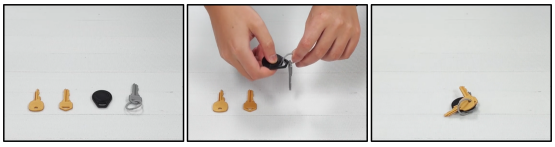
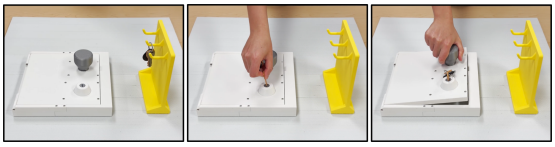
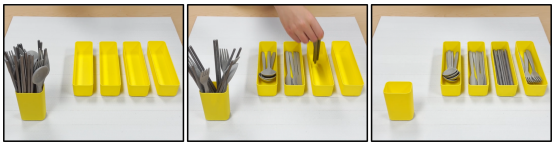
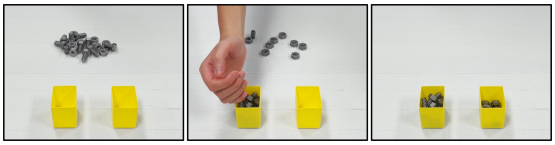
Task Execution Sequence	Task Specs
	**Task:** Install light bulb **Skills:** Insertion and alignment, articulated object manipulation **Description:** A light bulb socket is placed in the workspace. Screw the light bulb held in hand into the socket and tighten it. **Success criteria:** The light bulb is tightened and remains stationary when a small force is applied in an attempt to rotate it. The robot movement stops after terminating the tightening motion, moving away from, and breaking contact with the task objects.

TABLE C2: Longer-horizon benchmark tasks that demand more dexterity and chain several skills together

Task Execution Sequence	Task Specs
	**Task:** Assemble toy block **Skills:** Grasping thin or small objects, grasping from clutter, in-hand repositioning, insertion and alignment, extrinsic contact control **Description:** Components of the block to be assembled, required tools, and bins of screws and nuts are placed in the workspace. Using the tools available, assemble the two halves of the block together with two screws and two nuts. **Success criteria:** The robot movement stops after fully assembling the block with screws tightened and placing the assembled block onto the table. The robot should not remain in contact with the block.
	**Task:** Add keys to keyring **Skills:** Grasping thin or small objects, insertion and alignment **Description:** A keyring and several keys are scattered around the workspace. Add all loose keys onto the keyring. **Success criteria:** The robot movement stops after adding all loose keys to the keyring and placing the chained keys onto the table. The robot should not remain in contact with the task objects.
	**Task:** Unlock and open door **Skills:** Grasping thin or small objects, grasping from clutter, in-hand repositioning, insertion and alignment, articulated object manipulation **Description:** A set of keys on a hanging board and a locked door are placed in the workspace. Retrieve the keys from the hanging board, use the correct key to unlock the door, then turn the doorknob to open the door. **Success criteria:** The door is opened by at least 5 degrees, such that it is visually obvious that the door has been unlocked.
	**Task:** Sort utensils **Skills:** Grasping thin or small objects, grasping multiple objects, grasping from clutter, placing under environmental constraints **Description:** A tight pile of mixed utensils is placed in the workspace or a storage bin in the workspace. Sort the utensils and place different types of utensils into their corresponding storage bins. Being able to hold multiple utensils simultaneously will greatly increase task completion efficiency. **Success criteria:** The robot movement stops after sorting every utensil in the pile into its corresponding bin. Only utensils of the same type should be in the same bin. The robot should not remain in contact with the task objects.
	**Task:** Sort fasteners **Skills:** Grasping thin or small objects, grasping multiple objects, grasping from clutter, placing under environmental constraints **Description:** A tight pile of mixed fasteners is placed in the workspace or a storage bin in the workspace. Sort the fasteners and place different types of fasteners into their corresponding storage bins. Being able to hold multiple fasteners simultaneously will greatly increase task completion efficiency. **Success criteria:** The robot movement stops after sorting every fastener in the pile into its corresponding bin. Only fasteners of the same type should be in the same bin. The robot should not remain in contact with the task objects.