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1 Executive summary

This deliverable defines the key performance indicators dealing with robotic operations and processes that are needed to dismantle electronic devices, taking into account the latest relevant standards. For instance, ISO 22400 for Key Performance Indicators (KPIs) in manufacturing operations management and MRED (MultiRelationship Evaluation Design) developed by NIST (National Institute of Standards and Technology) are used and adapted to the recycling domain. From these standards, we derive the specific KPIs for the different use cases and their target values.

2 Introduction and Background

The diversity and model variety of electronic waste requires more flexible methods for recycling. This leads to an intensified demand for new automation concepts. Despite these facts, electronic waste recycling still has not been automated due to high set-up costs, long set-up times, and lack of adaptive flexibility. The main goal of the ReconCycle project is to introduce this type of flexibility into the existing (and affordable) robot workcell concept that will now enable the application of automated robotic disassembly of different devices.

Performance benchmarks are usually built as a modular set of task-based tests. For example, the NIST task boards are designed for assembly operations (e.g., simple insertions, threading, snap-fitting, meshing, routing) as shown in Fig. 1 and Fig. 2. The process was begun with an analysis of assembly tasks through the lens of measurement science to uncover key metrics and potential test methods [1]. These reconfigurable tests incorporate small part insertions and fastening methods such as threading, snap fits, and gear meshing using standard components including screws, nuts, washers, gears, and electrical connectors. The test methods leverage factors identified by Boothroyd-Dewhurst (B-D) design for assembly (DFA) studies. These studies have already identified and tabulated various important factors based on manual human performance in assembly tasks. For instance, size and symmetry of parts, tool usage, fixturing, mechanical resistance, mechanical fastening processes, visual occlusion, and physical obstruction are all influential towards time-based human performance. The specification of benchmarking tasks that efficiently sample this design space greatly aids the assessment of a robotic system and quickly identify its strengths and weaknesses.

Another important aspect of performance measurement is to provide confidence in the measured results. Consequently, multiple repetitions of a task are required to generate enough data for benchmarking comparisons. Moreover, the use of various statistical tests including a test for correlation, distribution, variance, and mean helps identify significant comparative differences in performance data. Conducting these tests also helps reducing the number of false claims that may be issued regarding a robot's level of performance [1], [3].

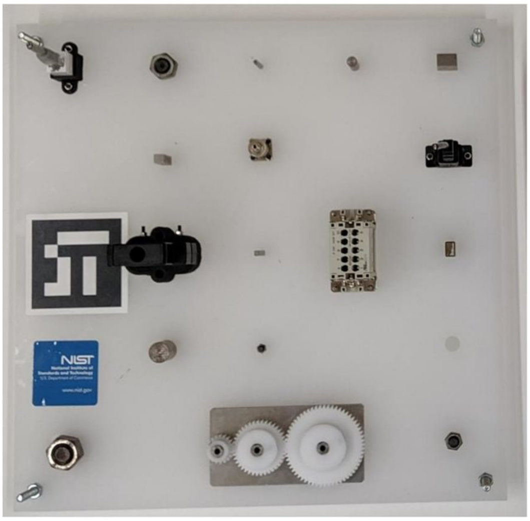

Figure 1: NIST assembly task board.

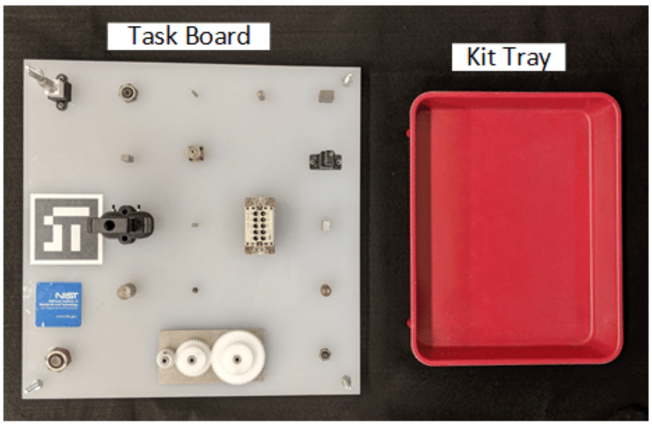

Figure 2: An example of disassembly task board proposed in [3].

3 Reconcycle KPIs and use-cases

The robotic workcell for dismantling the electronic devices, which is being developed in the ReconCycle project, will be benchmarked by measuring:

- The success rates of action choices and parameterizations made by the ReconCycle system in specific numbers of different exemplars from different device types and available actions as arising from the use-cases.
- The number of suitable actions planned and executed by the system to recover from specific types of failures.
- The number of suitable actions generated and executed for situations distinct, in specific ways, from those the system had encountered during the creation of the archetypical solution.
- The execution times of the individual steps required to address the use cases. Here we quantify especially the performance of the workcell relative to human performance.

Furthermore, we grouped our KPIs based on the work packages in the project.

3.1 KPIs in WP1

Cycle times and robustness of dismantling processes:

- Robustness and reliability of inserting electronic devices into the vise: over 95%.
- Robustness and reliability of battery extraction from different electronic devices: over 90%.
- Cycle time of the dismantling process of simple devices (no tool change necessary): less than 50 seconds.
- Cycle time of the dismantling process of a complex device, involving change of tools: less than 90 seconds.

Adaptation and reconfiguration times:

- Time of hardware reconfiguration and software changes when switching the dismantling process from one known device to another known device within the same family of devices: less than 2 minutes.
- Time of hardware reconfiguration and software policy adaptation when switching the dismantling process from a known device to an unknown device within the same family of devices, provided that the same sequence of operations can be applied (albeit with changed parameters): less than 15 minutes.
- Time of hardware reconfiguration and software changes when switching the dismantling process from a known device of one family, to a known device of another family: less than 5 minutes.

- Time of hardware reconfiguration and software policy adaptation when switching the dismantling process from a known device of one family, to an unknown device of another family, provided that the device falls within the reconfiguration range of the existing hardware elements: 1 day.

Indices:

- Reconfigurability/adaptation index (RAI): the percentage of devices from a device family that can be dismantled without manual intervention when switching from one device to another: over 33%.
- Exception detection index (EDI): the percentage of detected workpieces that can't be dismantled but are correctly classified as such: over 70%.

3.2 KPIs in WP2

Recognition accuracy:

- The complete device should be detected from the background 99% of the time.
- The complete device should be labeled correctly 95% of the time.
- The device battery should be detected from the background 99% of the time.
- The device battery should be labeled correctly 95% of the time.
- The remaining device internal components should be detected from the background 99% of the time.
- The remaining device internal components should be labeled correctly 90% of the time
- Transparent objects may cause issues and further testing is required.

Pose accuracy:

- The pose of an object is the rotation of the object as seen from above, together with its location. For the complete device, the side that is facing upwards is also detected, giving a second discrete dimension for orientation: To an accuracy of +/- 20 degrees.
- The orientation of the complete device should be correctly detected to an error 99% of the time.
- The orientation of the battery should be correctly detected 99% of the time.
- The orientation of the remaining components should be correctly detected 99% of the time.
- The location of the objects should be accurate to ± 5 mm in the x and y-direction.
- The recognition should work under varying lighting conditions, from a dimly lit room to a fully lit room.

System speed:

- The system should be able to process an image in under 500ms when running on modern computer hardware coupled with an Nvidia 1080Ti graphics card or better.

3.3 KPIs in WP3

- Number of developed disassembly tactile skills: > 5 skills
- Success rate for implementation of tactile skills under various conditions: > 90%
- Force and displacement error from motion generator and unified force-impedance control: Under discussion, but something around < 3 N, < 4mm
- Improvement of controller efficiency by adaption and learning parameters: > 30%
- Handling faults due to unforeseen external wrench: > 90%
- Stability of the controller: 100%
- Optimization of trajectory generation to reduce the required energy in the virtual tank: > 10%

3.4 KPIs in WP4

- Pinch and power grasp: standard dynamo-meters can be used to measure the force of grasp of the hand. This value is deemed as the main performance indicator for a gripper. Pinch Grasp: [1 N –5N], Power Grasp: [1N –50N].
- Capability of the hand to hold objects with different shapes and orientations. Pinch Grasp: [> 0,2 kg], Power Grasp: [> 2 kg], Hanging : [> 5 kg]
- Opening and closing time: Since the opening and closing commands are executed many times in a given task, their running time has a strong impact on the whole duration of the dismounting process. Closing time: [1,5 sec]
- If available the possibility to reconfigure the EE. EE Reconfiguration time: [<20 sec]
- Quick engage and disconnect wrist would as well contribute to speed up the disassembly task. EE Change time: [<60 sec]
- Electromagnetic compatibility for the final robotic EE integrated into the cell measured according to EN ISO 6100-6-2 / 6-4
- Estimated price of EE for the final robotic cell. Two Fingers: [< 3 k€], Five Fingers: [< 10k€]
- Successful grasp repeatability for different orientations of objects relevant for the ReconCycle Project. Parallelepiped shape: >90%, Disk shape: >90%, Cylindrical shape: >90%

3.5 KPIs in WP5

- Throughput time: at least 100 pieces per hour.
- Sorting purity (battery, circuit board, others): 100%.
- Labour costs: 0.53 EUR per kilogram.
- Start-up time (boot time): less than 1 minute.

- Set-up of a known workcell on a new location: 90 minutes.
- Set-up of a new workcell for new devices (includes hardware design and manual programming): no more than 2 weeks.

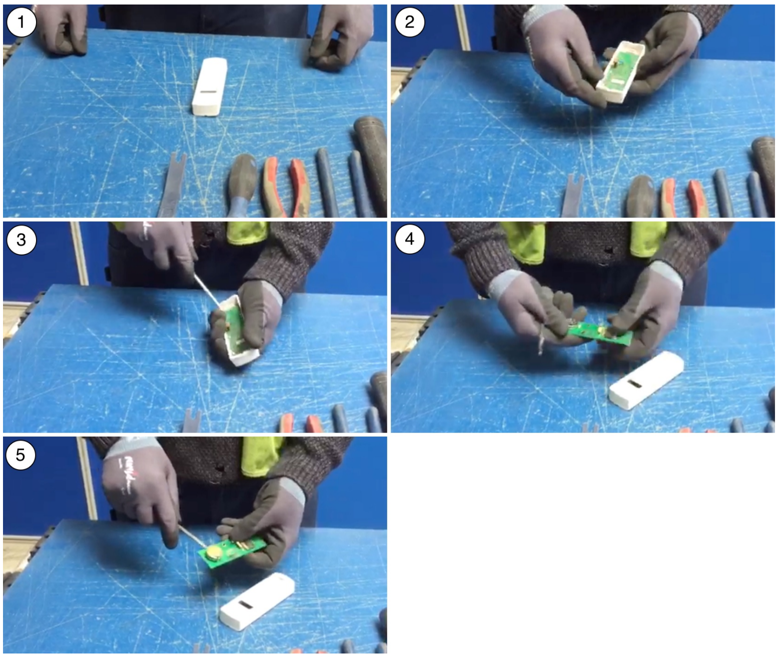

Figure 3: Manual disassembly of a heat cost allocator, Kalo 1.5.

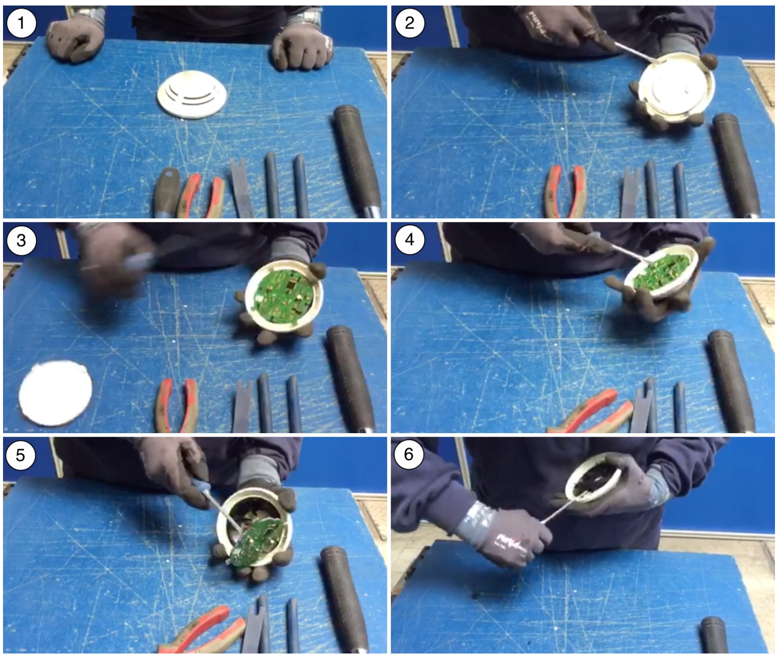

Figure 4: Manual disassembly of a smoke detector.

3.6 Use-cases

To illustrate the type of tasks that need to be performed by the ReconCycle system, we present here two of our use cases. We focus on the extraction of batteries from different device types. The first use case is about disassembling heat cost allocators and the second shows how to take apart smoke detectors. These operations are currently performed manually at Electorcycling as shown in Fig. 3 and Fig. 4. We expect that some changes will be needed when automating these disassembly processes. For example, for a robot it is easier to just cut through the heat cost allocator above the battery instead of breaking and levering the circuit board off. Note that all of these devices exist in many model variants and our goal is to enable generalization across different variants. Moreover, the devices arrive at the recycling company in various states of damage. Consequently, the dismantling processes have to include innovative tools and steps included in our system.

The use cases among smoke alarms and heat-cost allocators were decided by the partner Electrocycling: Kalo 1.2, Kalo 1.4, Kalo 1.5, Kundo, AS, Qundis, Siemens, Caloric, Qventis, Ista Vitera, Techem.

4 Design philosophy

4.1 Task Board Design

All the components are assembled on the task board as shown in Fig. 5. Robots must disassemble all the components from the board and place them in a predefined tray.

The current elements on this disassembly task board are as follows:

- AA Battery and its stationary housing: to show the performance of levering, grasping, and computer vision.
- CR2032 battery: to show the performance of computer vision and pushing under spring housing.

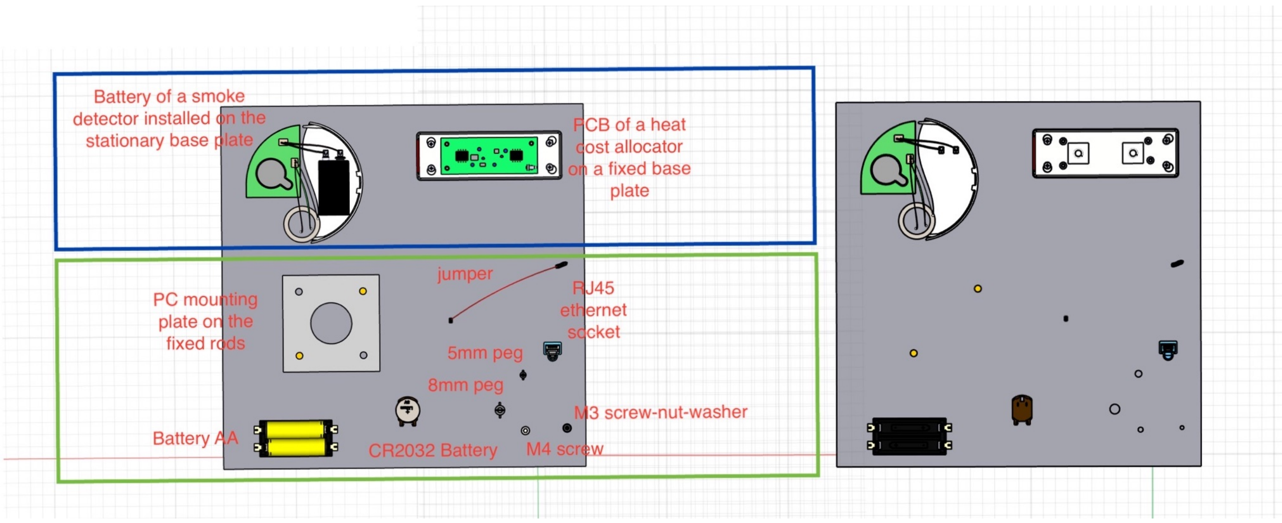

Figure 5: The proposed disassembly task board with its assembled and disassembled elements (top view). The upper part in the assembled board is to benchmark our use-cases in the ReconCycle project, whereas the lower part is inspired from the NIST task board.

- A plate on the fixed rods: to show the performance of levering, grasping, and computer vision.
- Jumper: to show the cutting and vision performances.
- 5mm and 8mm pegs: to show the peg-in-hole and vision performances.
- M4 and M3 screw: to show the unscrewing, grasping, and vision performances.
- RJ45 Ethernet socket: to show the push-pull and vision performances.
- Standard battery installed on the base plate of a smoke detector: to show the levering and vision performances.
- PCB installed on the base plate of a heat-cost-allocator: to show the levering, grasping, and vision performances.

4.2 Replication

The board was designed in SolidWorks and is available in STL files. CAD models for all components are provided. The 3-D view of the task board is illustrated in Fig. 6.

The smoke alarm (Siemens) and heat cost allocator (Kalo 1.5) are the standard parts of our use cases and are placed in the same housings as in the Reconcycle robotic workcell. This way, the housing can be dismantled from the task board as done in our robotic disassembly procedures in the ReconCycle project.

5 Test Method

For the standard parts we use the same test method as in the NIST board [1]. To test the robot's disassembly capabilities, we randomly place both the fully assembled task board and kit tray (for parts) within the dexterous workspace of the robot. Once configured, there should be no human intervention (e.g., lead-through programming) and the robot system should remain autonomous. Thus, the robotic system should move, grasp, disassemble, and transport all the target components from the task board to the kit tray. Components may be dismantled in any order. Any type of manual interference, e.g., physical, teleoperation, or via remote input, by a human operator is not acceptable and the trial is considered void and the test must be reset to the starting conditions. The task board and the kit tray are fixed in place possibly with different poses. The following procedures in the subsections 5.1, 5.2, and 5.3 are adapted from the study described in [1].

5.1 Steps

1. Record the start time, T_{start}.
2. The robot system disassembles parts from the task board.
3. The robot system places the removed part into the associated kit tray.
4. Repeat 2) and 3) for all parts (recording end times, T_{finish}).

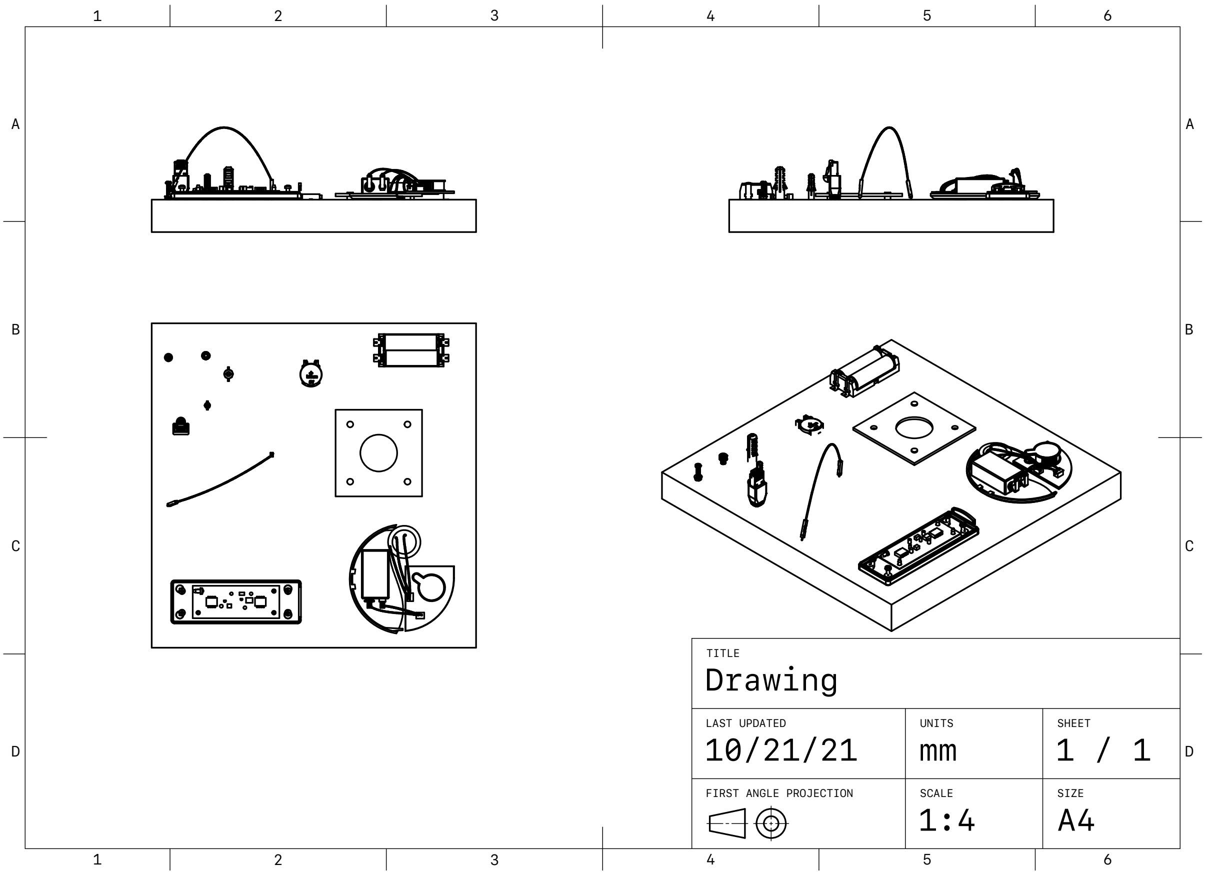

Figure 6: Technical drawing of the disassembly board.

5.2 Scoring

1. Two points for each part removed from the board (plus 2 points for an unscrewed screw and cutting the wire).
2. One point for each part placed into the kit tray.

5.3 Rules

1. Time bonus points are only available if all removable parts are successfully disassembled into the kit tray (maximum points achieved).
2. Any part is considered removed from the task board even if it is dropped by the robot system.
3. No points for placement in the kit tray if part touches the table surface.
4. No manual or teleoperated intervention by a human operator (e.g., no manual tool changes).
5. No restriction on the number of arms, grippers, and sensors used.
6. Use of hand tools (e.g., wrenches, electric drivers) is allowed provided the robot acquires these tools without human assistance.

7. Perception system markers (e.g., reflectors, AR tags, QR codes) may not be placed on the individual parts to be disassembled.
8. Perception system markers can be placed on the task board and kit.
9. Working area is the area within which the end-effector of the robot can move. The maximum size of the working area is the tabletop which is estimated to be 150 cm x 75 cm.
10. A reset is allowed to make program changes or repair/secure a task board. During a reset, one must reassemble all parts on the task board. All accumulated points are reset to zero. The clock continues to run throughout the reset.

6 Performance Metrics

Speed and reliability are primarily the main performance indices of any robot system for the assigned tasks. For our proposed task board, speed is reflected by the completion time for disassembly of the entire task board. Reliability is reflected by the probability of successfully grasping an object and completing a disassembly operation, and the degree to which a task board was completely disassembled. We acknowledge that there are other good tertiary metrics as well, e.g., exerted forces and torques; however, these come with a significant additional cost of test equipment and, in many applications, are only significant once speed and reliability requirements are met.

The performance metrics chosen to evaluate robotic disassembly systems thus include speed and reliability. Speed is measured as the completion time of a task or sub-task as $T_{taskboard} = T_{finish} - T_{start}$. Reliability is captured as the probability of completing a task or sub-task.

7 Data Analysis and Benchmarking

The overall disassembly performance of the board should be evaluated over 32 trials. For each set of trials, one must compute the mean, standard deviation, and 95% confidence interval of the completion time.

The theoretical upper bound probability for successfully dismantling a component (PS) is calculated given a confidence level (CL), the number of successes (m), and the number of independent trials ($n = 32$). The binomial cumulative distribution function [2], [4] is used:

$$CL \leq \sum_{i=0}^{m-1} \binom{n}{i} PS^i (1 - PS)^{n-i} = F(m-1; n, PS) \quad (1)$$

We use only the binomial cumulative distribution function above, as our data is not continuous but rather discrete (pass or fail).

8 Conclusion

In this deliverable, we specified the KPIs for each work packages in the ReconCycle project. The performance benchmarking metrics (speed and reliability) were quantified and evaluated based on the KPIs, considering certain disassembly operations such as detecting, localizing, levering, cutting, unscrewing, pushing-pulling, and grasping. Additionally, we adapted the NIST assembly board to evaluate our KPIs for robotic disassembly and, thereby, to benchmark the disassembly performance of the ReconCycle robotic workcell. The organized way of presenting different disassembly operations on the task board, together with the performance benchmarking metrics, serves as a way to guide and structure the development of the performance benchmarking framework.

In the next stages of the project, we will study how the combination of performances of various tasks can be composed to predict the performance of higher-level tasks.

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