

A Cross-Embodiment Gripper Benchmark for Rigid-Object Manipulation in Aerial and Industrial Robotics

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Abstract—Robotic grippers are increasingly deployed across industrial, collaborative, and aerial platforms, where each embodiment imposes distinct mechanical, energetic, and operational constraints. Established YCB and NIST benchmarks quantify grasp success, force, or timing on a single platform, but do not evaluate cross-embodiment transferability or energy-aware performance – essential for modern mobile and aerial manipulation. This letter introduces the Cross-Embodiment Gripper Benchmark (CEGB), a reproducible benchmarking suite extending YCB and selected NIST metrics with three additional components: a transfer-time benchmark measuring embodiment exchange effort, an energy-consumption benchmark evaluating grasping and holding efficiency, and an intent-specific ideal payload assessment. Together, these metrics characterize grasp performance and cross-platform suitability. CEGB is validated on two mechanically distinct grippers. The experimental evaluation quantifies embodiment-dependent differences in transfer time, energetic efficiency, and operational capability under unified statistical reporting. CEGB provides a reproducible foundation for cross-platform, energy-aware gripper evaluation.

Index Terms—Gripper benchmarking, cross-embodiment evaluation, energy-aware manipulation, aerial manipulation, robotic grasping.

I. INTRODUCTION

ROBOTIC grasping has been extensively investigated across industrial, collaborative, and aerial domains, leading to numerous gripper designs ranging from simple parallel-jaw and underactuated mechanisms to modern soft, hybrid, and

multifunctional systems [1], [2], [3]. Despite substantial technological progress, grippers deployed across heterogeneous platforms face embodiment-dependent constraints such as mounting geometry, actuation compatibility, and power availability, complicating direct performance comparison. Review papers highlight the lack of a unified, quantitative framework for cross-platform evaluation [4], [5]. Existing benchmarks primarily quantify grasp success or task-specific performance, but seldom address transferability, energy efficiency, or reproducibility across embodiments [6], [7]. To improve reproducibility, standardized object sets and test protocols have been introduced. The YCB Object and Model Set [8] became a reference for grasp success evaluation, while NIST protocols [6] introduced timing, payload, and force-based metrics. Initiatives such as GRASPA [9], OpenGRASP [10], and RGMC [11] advanced transparent benchmarking practices. However, these methods remain largely platform-specific and do not evaluate reuse of a single gripper across heterogeneous systems.

The emergence of soft and hybrid grippers has emphasized the limitations of existing frameworks. Traditional benchmarks such as YCB and NIST were primarily designed for rigid or underactuated mechanisms. Recent developments include multifunctional soft grippers with integrated sensing [12], learning-based hybrid architectures [13], and topology-optimized designs [14]. The SoGraB framework [15] introduced visual deformation analysis for soft grasping, representing a significant step forward. Nevertheless, these approaches focus mainly on shape adaptability and do not systematically consider energy efficiency or cross-platform transferability—factors critical for modern mobile and aerial robots.

Aerial manipulation benchmarks [7] address payload and energy limitations, whereas industrial and collaborative robotics emphasize safety and modularity [16], [17]. Modular and detachable grippers, including the Co-Gripper [18], electromagnetic changers [19] or modular fingertips [20], illustrate the trend toward cross-platform reuse. Nevertheless, quantitative assessment of embodiment transfer and redeployment effort remains largely unexplored. In the literature, transferability refers to operating a gripper across different embodiments, tasks, or environments [7], [18], [21]. Embodiment transfer describes mechanical or control adaptation between robotic platforms, task transfer concerns the reuse of grasp strategies, and environment transfer deployment of the same gripper across aerial and manipulator systems. While these notions are increasingly discussed conceptually, a rigorous benchmarking methodology

Received 2 December 2025; accepted 6 March 2026. Date of publication 25 March 2026; date of current version 7 April 2026. This letter was recommended for publication by Associate Editor M. Todescato and Editor L. Pallottino upon evaluation of the reviewers' comments. This work was supported in part by European Robotics and AI Network (euROBIN) under Grant 101070596, Project funded by European Commission and in part by Slovak Grant Agency under Grant VEGA 1/0337/26 and Grant KEGA 008TUKE-4/2024. (Corresponding author: Marek Vagas.)

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Digital Object Identifier 10.1109/LRA.2026.3677707

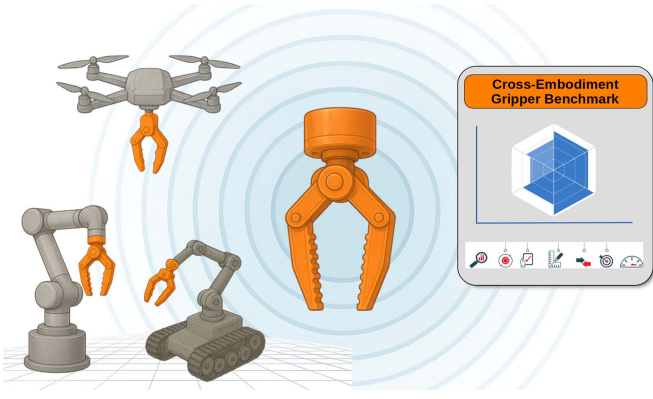


Fig. 1. Overview of the Cross-Embodiment Gripper Benchmark (CEGB). A common reference gripper is mounted on different robotic platforms—a collaborative manipulator, mobile robot with manipulator and Unmanned Aerial Vehicle (UAV)—to evaluate cross-embodiment transfer, mounting compatibility, and performance under different actuation and environmental conditions.

to quantify them is still missing. Existing frameworks remain limited in addressing the three pillars of modern gripper benchmarking — transferability across embodiments, energy-aware operation for resource-constrained platforms, and reproducible cross-platform comparison. In addition, current benchmarks do not provide standardized reporting conventions for transfer-related metrics, making it difficult to compare methods across laboratories or robotic platforms.

These limitations motivate a comprehensive yet and reproducible framework that integrates mechanical, energetic, and functional evaluation across platforms, see Fig. 1. Rather than replacing YCB and NIST, the proposed approach extends them with complementary metrics that address embodiment transfer and energy efficiency.

The main contributions of this letter are as follows: (1) We introduce the Cross-Embodiment Gripper Benchmark (CEGB), a compact benchmarking suite extending YCB and selected NIST metrics with additional evaluations focusing on cross-platform transfer and energy-aware performance; (2) We experimentally validate the proposed benchmark on two distinct gripper implementations: a self-locking reference gripper prototype (RGP) and a commercially available industrial gripper, demonstrating the benchmark’s ability to capture differences in grasp execution, energy consumption, and transfer performance across gripper designs. (3) We provide open-source data, CAD models, and scripts to support reproducible cross-platform comparison of grippers.

CEGB provides a structured foundation for discussing and evaluating gripper performance across heterogeneous embodiments.

The remainder of the paper is organized as follows: Section II introduces the proposed benchmark and evaluation metrics, Section III presents the experimental setup and results, and Section IV concludes the paper.

II. CROSS-EMBODIMENT GRIPPER BENCHMARK

CEGB extends established object-based evaluation protocols with additional metrics targeting embodiment transferability and energy-aware performance. The framework integrates standardized YCB and selected NIST procedures with three

complementary components: Transfer Time Benchmark, Energy Consumption Benchmark, and Ideal Payload Benchmark (IIPB). A unified statistical reporting convention ensures consistent cross-platform comparison.

While CEGB primarily targets fingered grippers employing wrap and pinch grasping, it is also applicable to adhesion-based designs (magnetic, electrostatic, suction). For such grippers, applicable benchmarks use a standardized adhesion sample (AS): a flat 10 mm plate made of PVC or 1.4006 steel with surface roughness not exceeding Ra 1.8, ensuring reproducible cross-family evaluation.

A. YCB Grasp Success and Metrics Benchmark

The YCB Object and Model Set [8] provides a standardized collection of objects for evaluating grasp success across different robotic systems. We follow established YCB evaluation practices [22], [23] using a subset of objects S and testing each object o in k canonical poses, with a repeated attempts per pose. The choice of S , k , and a is driven by a trade-off between experimental time and statistical reliability, and can be adapted by other users of CEGB as long as the configuration is reported together with the results.

For each object o and pose j , the grasp success proportion is

$$s_{o,j} = \frac{g_{o,j}}{a}, \quad j = 1, \dots, k \quad (1)$$

where $g_{o,j}$ is the number of successful attempts. The per-object success rate is

$$s_o = \frac{1}{k} \sum_{j=1}^k s_{o,j} \quad (2)$$

Dataset-level summaries are reported as micro- and macro-averages:

$$\bar{s}_{\text{micro}} = \frac{\sum_{o \in S} \sum_j g_{o,j}}{\sum_{o \in S} \sum_j a}, \quad \bar{s}_{\text{macro}} = \frac{1}{|S|} \sum_{o \in S} s_o \quad (3)$$

Here, $\bar{s}_{\text{micro}}$ emphasizes the overall success rate weighted by the number of trials, while $\bar{s}_{\text{macro}}$ assigns equal weight to each object, which is useful when comparing grippers with different object preferences or failure modes.

To quantify uncertainty in these binomial success proportions, we report Wilson score confidence intervals, which offer well-behaved coverage even for small sample sizes and proportions near 0 or 1, and represent the recommended practice in manipulation benchmarking [6].

A grasp is considered successful if the object is lifted at least 5 cm within 3 s and held for 3 s without slip (10 s timeout), consistent with prior YCB-based evaluations.

This benchmark is not suitable for purely magnetic adhesion grippers, as the majority of objects in the YCB set are non-ferromagnetic and therefore cannot be reliably grasped using magnetic adhesion.

B. NIST Benchmark

To complement the YCB grasp-success evaluation, we adopt a compact subset of NIST end-effector metrics [6], covering timing, force output, slip resistance, and payload capacity. These quantities provide platform-agnostic, time- and force-based descriptors that capture aspects not addressed by the YCB pass/fail

criterion. Within CEGB, the NIST-derived metrics serve as a common reference layer that allows different grippers and embodiments to be compared in terms of fundamental mechanical capability, independently of the specific object set or task.

a) *Grasp Cycle Time*: The grasp cycle time is defined as

$$T_{\text{cycle}} = T_{\text{stop}} - T_{\text{start}} \quad (4)$$

corresponding to the duration of a complete grasp–hold–release sequence. To ensure comparability, either standardized gauge objects or identical commanded stroke lengths are used across trials [24]. Results follow the unified statistical convention of mean values and 95% bootstrap confidence intervals, see Section II.

For adhesion-based grippers, the grasp cycle time is defined as the interval between gripper activation and de-energization, with each trial starting at direct contact between the gripper and the object.

b) *Grasp Strength*: Grasp strength is the total normal force exerted by all fingers pressing a rigid reference object. Let F_{N_i} denote the normal force at finger i ; then

$$F_{\text{total}} = \sum_{i=1}^n F_{N_i} \quad (5)$$

Peak and plateau values are recorded for each trial and low-pass filtered to suppress measurement spikes. This metric refines earlier NIST terminology and ensures unambiguous definition of normal-force summation [6].

This benchmark is not applicable to adhesion-based grippers, as grasp strength is defined based on force closure generated by articulated contacts.

c) *Slip Resistance*: Slip resistance quantifies the tangential load that induces object motion. The effective friction coefficient is

$$\mu_{\text{eff}} = \frac{F_{\text{slip}}}{\sum_i N_i} \quad (6)$$

where F_{slip} is the tangential force at slip onset. For designs where an external torque T_a is applied along a finger of length L , we additionally report the dimensionless holding-quality factor

$$Q_{\text{hold}} = \frac{F_{\text{slip}} L}{T_a} \quad (7)$$

supporting different loading modes and test fixtures [25]. Each condition is repeated multiple times, including worst-case pull directions. In CEGB, μ_{eff} and Q_{hold} together capture how the contact design, surface materials, and finger geometry influence robustness to external disturbances.

C. Transfer Time Benchmark

Transferability refers to the ability of a gripper to operate across different robotic embodiments without mechanical redesign or control recalibration, as emphasized in prior modular and cross-platform end-effector work [18], [19], [21]. While transferability is often discussed qualitatively in the literature, no quantitative metric currently exists to measure the operational effort required to reuse the same gripper across heterogeneous platforms.

To address this gap, the *Transfer Time Benchmark* measures the duration required to detach the gripper from one platform and reattach it to another. The metric captures practical factors such

as connector accessibility, alignment tolerance, mechanical keying, safety interlocks, and human operator interaction, elements that strongly affect deployability in real-world applications, especially in mobile or aerial manipulation where downtime is critical. Within CEGB, this benchmark explicitly links hardware design choices (e.g., quick-release interfaces, connector placement) to measurable differences in transfer performance.

The average transfer duration is defined as

$$T_{\text{transfer}} = \frac{1}{N} \sum_{i=1}^N T_i \quad (8)$$

where T_i is the duration of the i -th attach/detach cycle. Robustness is quantified by the success rate

$$S_{\text{transfer}} = \frac{N_{\text{success}}}{N} \quad (9)$$

in which N_{success} counts transfers completed without mechanical misalignment, electrical-connector faults, or software/communication errors.

a) *Experimental Protocol*: Transfer trials are performed between two representative robotic platforms. To isolate the end-effector exchange process from platform motion, both platforms are placed in a neutral pose, powered off, and mechanically locked. Each trial starts when the operator touches the gripper and ends when the gripper is fully reattached and electrically available to the host platform. Multiple repetitions are conducted across participant groups (novices, intermediate users, trained operators) to capture human-related variability, which is known to influence repeatability in modular tool-changing systems.

b) *Relevance*: The Transfer Time Benchmark quantifies the practical overhead of reusing the same gripper across heterogeneous embodiments. This is particularly important in aerial manipulation, where minimizing downtime directly affects mission endurance, and in industrial, where rapid tool changes are required. Unlike existing benchmarks, which evaluate gripper performance on a single platform, this metric captures the effort and reliability of embodiment transfer, complementing YCB and NIST by linking gripper modularity to system-level deployability.

D. Energy Consumption Benchmark

Energy consumption is a critical dimension of gripper performance, particularly for aerial and mobile manipulation platforms where onboard power is limited. Existing benchmarks rarely quantify energy usage in a standardized manner, despite its direct impact on endurance and system efficiency. We therefore introduce an *Energy Consumption Benchmark* that evaluates the energy required across the main phases of a grasp cycle. The definition is actuation-agnostic and applicable to electrically, pneumatically, or hydraulically actuated grippers. By reporting phase-specific energy, CEGB distinguishes between designs that are efficient during motion, during holding, or in both regimes.

The total cycle energy is defined as

$$E_{\text{cycle}} = E_{\text{grasp}} + E_{\text{hold}} + E_{\text{release}} \quad (10)$$

where each component corresponds to a distinct phase of the grasping process.

a) *Energy Components*: E_{grasp} denotes the energy consumed from the commanded closing motion until the object is securely lifted. E_{hold} represents the energy used during a prescribed

holding interval t_{hold} , and E_{release} covers the energy required from the opening command until the gripper fully opens.

Each energy quantity is computed by integrating the instantaneous input power,

$$E = \int P(t) dt \quad (11)$$

where $P(t)$ denotes the instantaneous power supplied to the gripper actuation system. For electrically actuated grippers, this reduces to $P(t) = U(t) I(t)$ using measured voltage $U(t)$ and current $I(t)$, whereas pneumatic or hydraulic systems may compute $P(t)$ from their corresponding pressure and flow variables. Thus, the benchmark remains general while allowing platform-specific implementations.

Because holding energy scales with holding duration, we report a standardized 10-second equivalent:

$$E_{\text{hold10}} = 10 \bar{P}_{\text{hold}} \quad (12)$$

where $\bar{P}_{\text{hold}}$ is the average input power during the stable hold phase. This normalization facilitates comparison across grippers and use cases with different holding durations and duty cycles.

b) Experimental Protocol: Measurements are performed under controlled conditions using representative object weights. To ensure comparability across grippers with different kinematics and stroke ranges, additional constraints on object geometry, contact surfaces, and effective gripper travel are imposed. For pinch or wrap grippers, the object dimension is approximately half of the nominal stroke to avoid extreme joint configurations. Cylindrical, spherical, or box-shaped objects with PVC-coated contact surfaces are used. During holding, a static load along the z -direction equal to half of the nominal secure holding force is applied.

For adhesion-based grippers, the standardized AS is used. Tests begin with direct contact, measuring energy during energization, holding, and de-energization.

For each object, the grasp cycles are repeated in statistically reasonable count, and the three components E_{grasp} , E_{hold10} , and E_{release} are recorded under identical approach conditions and reported using the unified statistical convention (mean values and 95% bootstrap confidence intervals). Fixed-rate sampling enables reconstruction of instantaneous power profiles $P(t)$ for diagnostic comparison.

E. Intent-Specific Ideal Payload Benchmark

General-purpose benchmarks often do not reflect the conditions for which a gripper is primarily designed. Since performance depends on grasp type, object geometry, and structural compliance, we introduce the Intent-Specific Ideal Payload Benchmark (IIPB), evaluating the maximum sustainable load in the gripper's intended configuration. Within CEGB, IIPB links mechanical capability to application-specific use cases.

Four standardized artifacts are used to represent typical grasping scenarios: (i) a NIST test cylinder, (ii) a rectangular box with PVC-coated contact surfaces, (iii) a rigid PVC-coated sphere, and (iv) a standardized AS. Each artifact is labeled (C, B, S, A) to enable concise comparison across gripper designs, see Table I. The ideal test artifact for the gripper under evaluation should be chosen.

To account for structural compliance, grippers are classified as rigid (R- rigid) or compliant in one (1S- semicompliant in one axis), two (2S- semicompliant in two axis), or all three

TABLE I
GRIPPER CLASSIFICATION CODES USED FOR IIPB COMPARISON

Parameter	Option	Code
Compliance Type	Rigid / 1-axis / 2-axis / 3-axis	R / 1S / 2S / F
Preferred Grip Type	Wrap / Pinch / Adhesion	W / P / A
Ideal Object Shape	Cylinder / Box / Sphere / AS	C / B / S / A

(F- fully compliant) principal axes. While compliant fingers enhance adaptability to irregular or fragile objects, they typically reduce the achievable payload; thus, compliance is reported jointly with the ideal payload capacity. This joint reporting encourages designers to explicitly state the trade-offs between adaptability and load capacity, rather than optimizing one at the expense of the other without documentation.

The measurement procedure follows the slip-resistance protocol described in Section II-B. The artifact is grasped in the preferred configuration, and an external pulling force is gradually increased until slippage occurs or a predefined safety limit is reached. The ideal payload is defined as

$$F_{\text{ideal}} = \max(F_{\text{pull}}) \quad (13)$$

where F_{pull} is the externally applied tangential force. Each test is repeated statistically reasonable times for each artifact size, and results are reported using the unified statistical convention. When combined with the compliance and grip-type codes in Table I, these values enable concise cataloguing of grippers in terms of both their preferred operating regime and their achievable intent-specific payload.

III. EXPERIMENTAL RESULTS

The proposed CEGB was evaluated using two representative grippers: the RGP and a commercially available industrial gripper, the SCHUNK Co-act EGP-C (SCHUNK), equipped with custom fingers providing a 42–54 mm effective travel based on the official gripper geometry. All experiments followed identical protocols and metrics, enabling direct comparison between a lightweight research prototype and an industrial solution.

All experimental evaluations were conducted using an industrial robotic setup. A MELFA ASSISTA RV-5AS-D robotic manipulator was used to execute the benchmark procedures, while interaction forces were measured using two EMSYST EMS21-U force sensors (100 N range). Electrical signals were recorded using a Rohde & Schwarz HMO1002 oscilloscope. This setup was kept consistent across all experiments to ensure repeatability and fair comparison between evaluated grippers.

A. YCB Evaluation

To quantify the baseline grasping ability, we applied the YCB Grasp Success approach using a constant approach trajectory and fixed grasping speed. For each object–pose combination, $a = 5$ attempts were performed, and per-object success rates were computed according to Eqs. 1–3. The RGP and the SCHUNK achieved micro-average success rates of 39.5%(95%CI[37.35, 41.55]) and 4.7%(95%CI[3.90, 5.71]), and macro-average success rates of 38.7%(95%CI[22.6, 57.66]) and 4.81%(95%CI[1.0, 20.26]), respectively. Spherical and cylindrical objects exceeded 63.75% micro-average success rate for the RGP and 15.63% for the SCHUNK, while thin and flat objects remained below 1.7% for the RGP and 0.0% for the SCHUNK, and articulated objects

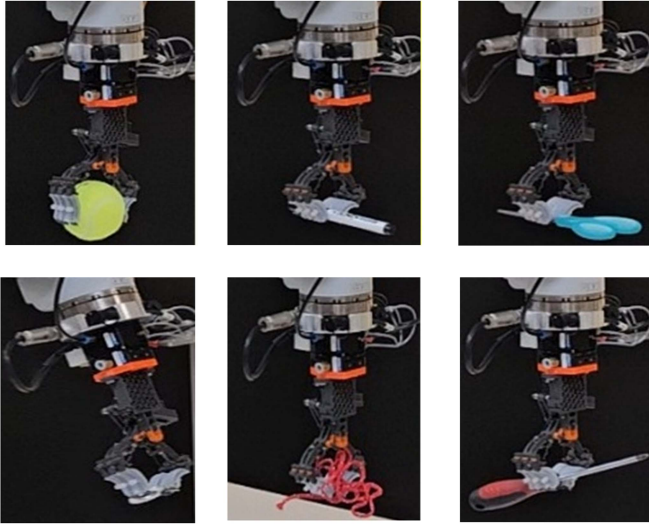


Fig. 2. Reference gripper prototype performance metric results based on the YCB benchmark.

reached above 80.25% for the RGP and 0.0% for the SCHUNK in terms of micro-average success rate.

These outcomes are consistent with the RGP gripper's mechanical structure: high-friction pads and passive finger compliance support adaptation to curved and irregular geometries, whereas planar artifacts remain challenging due to the fixed fingernail geometry and the absence of a universal picking motion. Fig. 2 illustrates representative examples, including successful grasps of articulated objects by our RGP.

Large or unevenly distributed masses also reduced performance. The main contributors were (i) local pad deformation leading to slippage and (ii) torsional stresses in the compliant joints causing suboptimal finger alignment. These observations suggest that future iterations may benefit from semi-flexible fingernails to improve ground-level picking.

Across repeated trials, the RGP exhibited consistent temporal behavior.

Overall, the YCB evaluation demonstrates robust and reproducible grasping performance of the RGP across diverse object classes, while highlighting limitations for thin and heavy items. The lower performance of the SCHUNK gripper is primarily attributed to its limited effective finger travel, restricting adaptability to object geometry.

B. NIST Evaluation

The NIST-based evaluation complements the YCB results by quantifying grasp timing, force output, and slip resistance according to Section II-B. Three metrics were evaluated: grasp cycle time, grasp strength, and slip resistance. Each experiment was repeated at least $N = 10$ times under identical conditions, and results are reported as mean values with 95% bootstrap confidence intervals.

The grasp cycle time was evaluated using standard cylindrical artifacts of 50 mm and 80 mm diameter. Each cycle started at the commanded approach (T_{start}) and ended once the gripper returned to its fully open state (T_{stop}), yielding $T_{\text{cycle}} = T_{\text{stop}} - T_{\text{start}}$.

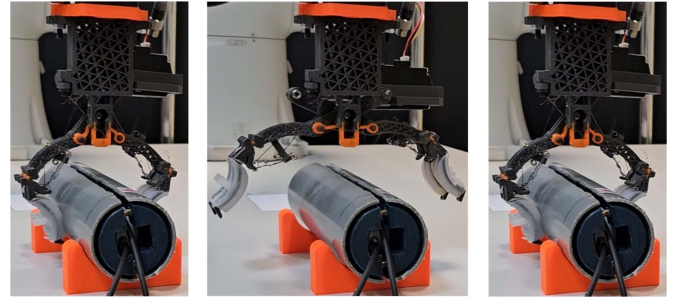


Fig. 3. Determination of the reference gripper prototype grasp cycle time following the NIST procedure.

TABLE II
EVALUATION OF GRASP CYCLE TIME FOR DIFFERENT GRIPPERS

Gripper	Artifact [mm]	Type	Orientation [°]	Cycle time [s]
RGP	50	pinch	0	3.91 [3.88, 3.94]
RGP	80	pinch	0	3.23 [3.20, 3.60]
SCHUNK	50	pinch	0	1.34 [1.33, 1.35]
SCHUNK	80	pinch	0	–

TABLE III
EVALUATION OF GRASPING STRENGTH FOR DIFFERENT GRIPPERS

Gripper	Artifact	Grasp Type	Mean [N]	95% CI [N]
RGP	50 mm	pinch	9.79	[9.76, 9.82]
RGP	80 mm	pinch	8.18	[8.15, 8.20]
SCHUNK	50 mm	pinch	90.4	[90.25, 90.54]
SCHUNK	80 mm	pinch	–	–

Each measurement was repeated 32 times under identical conditions to ensure reproducibility. The grasping sequence is shown in Fig. 3.

The mean cycle times and 95% confidence intervals are summarized in Table II. For the 50 mm artifact, the RGP and the SCHUNK achieved mean cycle durations of 3.91 s and 1.34 s, respectively. For the 80 mm artifact, the RGP achieved a mean cycle duration of 3.23 s, whereas the SCHUNK was unable to grasp the object due to its limited opening–closing range. The shorter cycle time for the larger artifact reflects reduced finger travel during power grasping.

Grasp strength was evaluated with 50 mm and 80 mm cylindrical artifacts using the NIST force-measurement protocol, defined in Section II-B. For each trial, the normal forces exerted by all contacting fingers (N_i) were summed to obtain the total grasp force $F_{\text{total}} = \sum_i N_i$.

As shown in Table III, the RGP generated 9.79 N on the 50 mm artifact and 8.18 N on the 80 mm artifact. The decrease in force for larger diameters is expected, as finger curvature reduces local contact pressure and the gripping force is not constant through its stroke. For the 50 mm artifact, the SCHUNK generated 90.4 N. For the 80 mm artifact, the SCHUNK was unable to grasp the object due to its limited opening–closing range relative to the artifact size.

The slip resistance test quantifies the gripper's ability to withstand externally applied tangential loads without object loss, following the NIST methodology defined in Section II-B. Four cylindrical artifacts with diameters of 32 mm, 50 mm, 75 mm, and 110 mm were used. Each artifact was grasped in a pinch configuration at an orientation of 90°, while the robotic arm applied a constant translational motion along the

TABLE IV
EVALUATION OF SLIP RESISTANCE FOR DIFFERENT GRIPPERS

Gripper	Artifact [mm]	Grasp Type	Mean [N]	95% CI [N]
RGP	32	pinch	6.28	[6.17, 6.40]
RGP	50	pinch	5.78	[5.69, 5.87]
RGP	75	pinch	6.24	[6.06, 6.41]
RGP	110	pinch	3.75	[3.67, 3.83]
SCHUNK	32	pinch	—	—
SCHUNK	50	pinch	34.79	[33.73, 34.84]
SCHUNK	75	pinch	—	—
SCHUNK	110	pinch	—	—

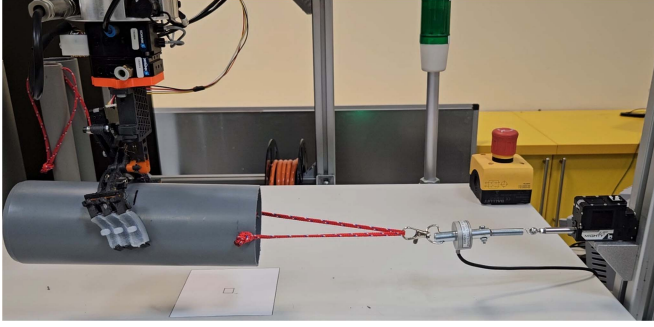


Fig. 4. Experimental setup for the slip-resistance test based on the NIST methodology.

y -axis at a speed of 150 mm/min. A calibrated force sensor recorded the tangential resistance force F_{slip} until the onset of motion. According to Eq. 6, the effective friction coefficient was evaluated. For the RGP, all artifact sizes were successfully evaluated. The SCHUNK was tested only on the 50 mm artifact due to its limited opening-closing range. Ten repetitions were performed for each artifact to ensure statistical reliability, and the mean values with 95% confidence intervals are reported in Table IV.

For the RGP, results were consistent across comparable artifact sizes, with reduced slip resistance at 110 mm due to stroke-dependent force variation and pad deformation at wider openings. Overall, stable contact forces were maintained across the tested range, satisfying the NIST slip-resistance criteria, see Fig. 4.

C. Transfer Time Evaluation

The Transfer Time Benchmark introduced in Section II-C quantified redeployment effort across the platforms. For each trial, the transfer time T_{transfer} was computed as the mean duration of 5 attach/detach cycles (Eq. 8), while robustness was captured by the success rate S_{transfer} (Eq. 9).

Fig. 5 illustrates the detach/attach sequence performed by participants with the RGP. Both platforms were placed in a neutral pose and powered off to isolate the end-effector exchange from any platform. Fig. 6 shows that after transferring the gripper between the two embodiments, it was immediately deployed in representative pick-and-place tasks on both the industrial manipulator and the UAV, demonstrating functional continuity beyond the attach/detach procedure.

The experiment was repeated across four participant groups (40 in total): bachelor students, master students, colleagues without prior explanation, and experienced researchers involved in this work.

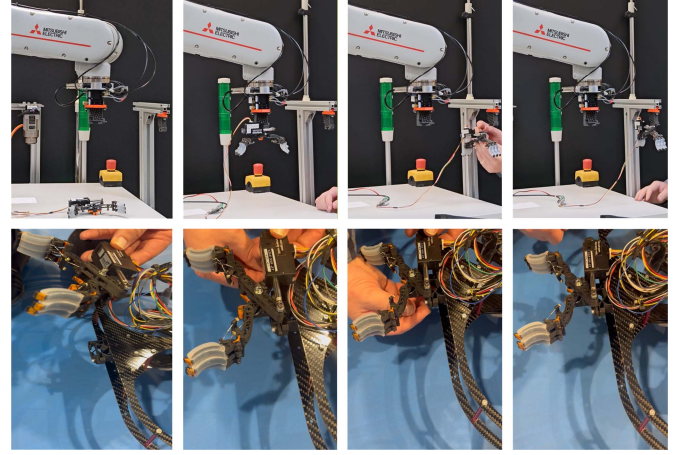


Fig. 5. Experimental sequence for participants to attach and detach the reference gripper prototype.

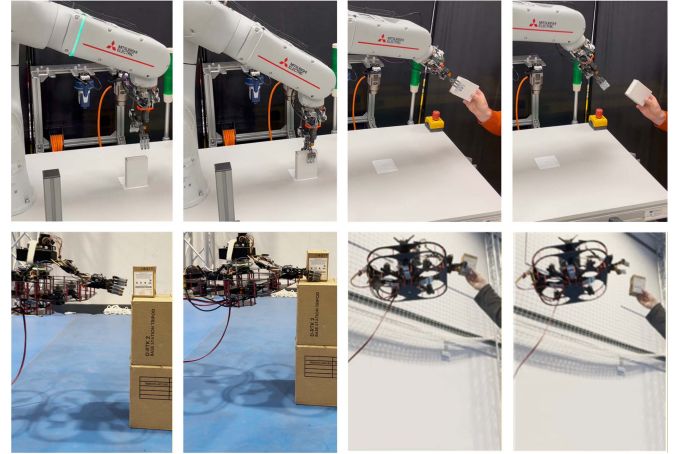


Fig. 6. Transferability to the platforms with parcel delivery task.

The results are summarized in Fig. 7 and reported as mean values and 95% bootstrap confidence intervals. All groups achieved perfect robustness ($S_{\text{transfer}} = 1.0$) for both grippers. For the RGP, untrained participants required the longest time (22.8s), while bachelor and master students achieved 16.1 s and 14.2 s, respectively. Experienced researchers averaged 17.6 s. The SCHUNK exhibited consistently shorter transfer times across groups.

Overall, the detachable designs enabled fast and reliable transfer across embodiments, with comparable performance between inexperienced and trained users.

D. Energy Efficiency Evaluation

Energy efficiency was evaluated according to Section II-D across three grasp phases: grasping (E_{grasp}), holding (E_{hold10}), and release (E_{release}) with 10 repetitions per condition. Instantaneous voltage $U(t)$ and current $I(t)$ were sampled at 0.1 kHz, and electrical energy for each phase was obtained by integrating power over time (Eq. 11). Each grasping/releasing phase lasted approximately 2 s, corresponding to a stable and repeatable motion profile.

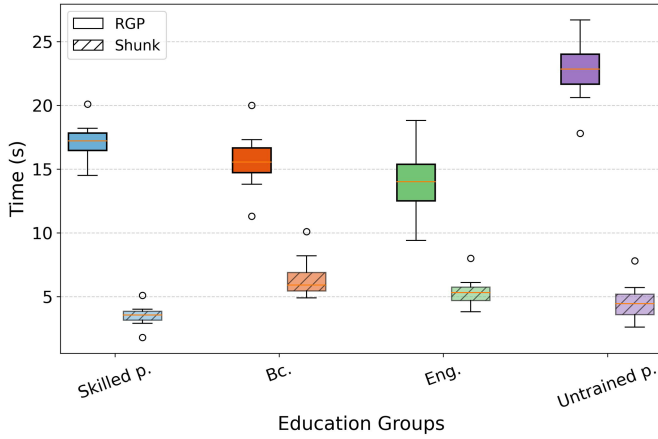


Fig. 7. Transfer times collected from the target participant groups.

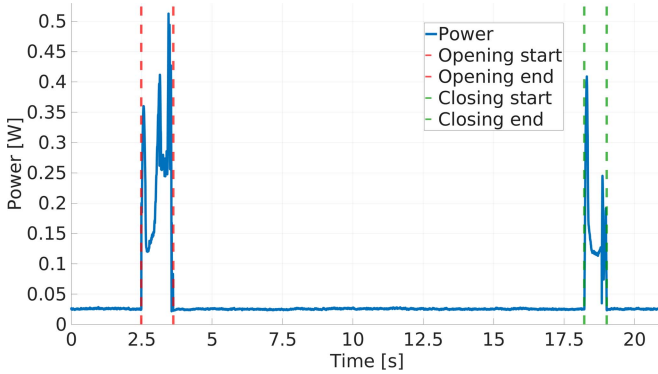


Fig. 8. Instantaneous electrical power $P(t) = U(t)I(t)$ measured during the grasp cycle for the RGP. The plot shows the real-time power profile across the closing, holding, and release phases.

TABLE V
EVALUATION OF ENERGY CONSUMPTION FOR DIFFERENT GRIPPERS

Gripper	Cycle phase	Mean [J]	95% CI [J]
RGP	Grasping	0.35	[0.32, 0.38]
RGP	Holding 10s	0.25	[0.25, 0.25]
RGP	Releasing	0.12	[0.12, 0.12]
SCHUNK	Grasping	0.11	[0.11, 0.11]
SCHUNK	Holding 10s	3.48	[3.47, 3.50]
SCHUNK	Releasing	0.06	[0.06, 0.06]

Fig. 8 illustrates representative power traces, showing transient peaks during closing and object contact, while the holding phase remains energetically minimal due to the self-locking mechanism. For the RGP, this results in a normalized holding energy of $E_{\text{hold}10} \approx 0.25$ J. In contrast, the SCHUNK required $E_{\text{hold}10} \approx 3.48$ J over the same interval, see Table V.

The total energy per grasp cycle reached approximately $E_{\text{cycle}} \approx 0.72$ J for the RGP and 3.66 J for SCHUNK for a 600 g object, yielding an energy-to-weight ratio of 0.0012 J/g for RGP and 0.1833 J/g for the SCHUNK for the full cycle and 0.583×10^{-3} J/g for the grasping phase alone. Overall, the results confirm that the RGP consumes energy primarily during active finger motion, with negligible energy required to maintain a grasp. This validates the assumptions of Section II-D and demonstrates the suitability of the self-locking design for

TABLE VI
REFERENCE GRIPPER PROTOTYPE PARAMETERS AND OPTIONS

Gripper Parameter	Option (RGP)	Option (SCHUNK)
Compliance Type	Compliant in 2 axes (2S)	Compliant in 2 axes (R)
Preferred Grip Type	Pinch (P)	Pinch (P)
Ideal Object Shape	Box-type artifacts (B)	Box-type artifacts (B)
Gripping Range	40–100 mm	42–54 mm

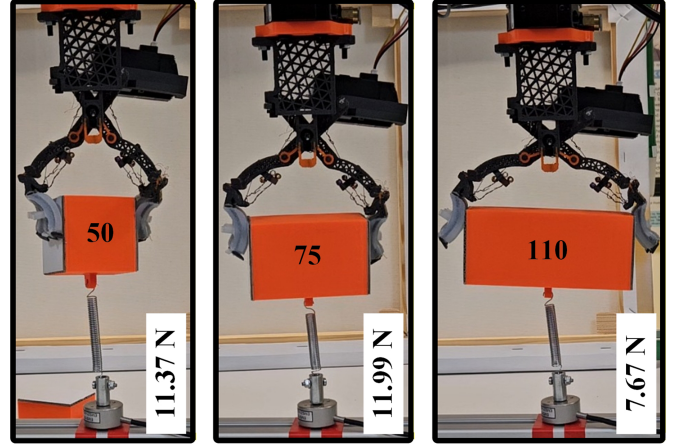


Fig. 9. Experimental setup for the Ideal Payload Benchmark.

energy-limited platforms such as UAVs and other mobile manipulators. Such energy characteristics are particularly advantageous for UAV-based manipulation, where even small reductions in holding power can translate into measurable gains in flight endurance.

E. Intent-Specific Ideal Payload Benchmark

The IIPB introduced in Section II-E was applied to evaluate both grippers under their intended operational conditions. As the proposed design is optimized for lightweight, energy-efficient aerial manipulation, this benchmark quantifies its maximum sustainable load in the preferred grasp configuration.

The RGP gripper exhibits compliance primarily in the x - and y -axes of the gripping plane, with limited compliance in the z -axis. It predominantly operates in a power-pinch configuration with a reliable grasping range of 40–100 mm, while wrap grasps are used only in rare situations. The SCHUNK is rigid, utilizing a power-pinch grasp with a grasping range of 42–54 mm. The key parameters and compliance classification are summarized in Table VI.

The measurement procedure follows the slip-resistance protocol in Section II-B, adapted for payload evaluation. Three box-type artifacts with gripping surface distances of 50 mm, 75 mm, and 110 mm were tested. One side of the artifact was grasped by the RGP, while the opposite side was attached to a calibrated 100 N force sensor. During each trial, the robotic arm moved vertically upward at 150 mm/min until slip or detachment occurred. The maximum recorded pulling force corresponds to the ideal payload as defined in Eq. 13, where F_{pull} denotes the externally applied tangential force.

Each measurement was repeated 10 times for each artifact size, and the resulting ideal payload distributions are shown in Fig. 9 and summarised in Table VII using the unified statistical

TABLE VII
EVALUATION OF IDEAL MAXIMUM LOAD FOR DIFFERENT GRIPPERS

Gripper	Artifact [mm]	Ideal Max Load [N]	95% CI [N]
RGP	50	11.37	[11.06, 11.69]
RGP	75	11.99	[11.59, 12.38]
RGP	110	7.67	[7.22, 8.11]
SCHUNK	50	22.8	[22.2, 23.4]
SCHUNK	75	—	—
SCHUNK	110	—	—

convention (mean values and 95% bootstrap confidence intervals). The highest payload for the RGP was achieved for the mid-range artifact (75 mm), while the reduced load capacity for the 110 mm artifact is consistent with lower normal pressure, increased pad deformation at wide openings and non-constant force output throughout the stroke. For the SCHUNK, payload measurements were feasible only for the 50 mm artifact due to limitations in the opening–closing range relative to the larger artifact sizes.

The IIPB results demonstrate reliable grasping across the RGP’s operational range, confirming its suitability for aerial and mobile tasks that prioritise robustness, energy efficiency, and moderate payload capacity. The IIPB benchmark therefore provides a concise descriptor of a gripper’s intended capability, complementing platform-agnostic metrics such as YCB and NIST with task-specific operational insight.

IV. CONCLUSION AND FUTURE WORK

This letter presented the Cross-Embodiment Gripper Benchmark, a reproducible framework that extends YCB and NIST protocols with embodiment-transfer, energy-aware, and intent-specific payload metrics. Using a self-locking reference gripper prototype and a commercial industrial gripper, we experimentally validated the benchmark and demonstrated its ability to capture differences in grasp execution, energy consumption, and transfer performance across embodiments.

The results confirm that CEGB supports standardized cross-platform comparison while maintaining comparable initial conditions across grippers with different kinematics and actuation principles. As with any modular benchmark, the applicability of individual metrics depends on the underlying grasping principle: while most CEGB components are compatible with both contact-based and adhesion-based grippers, a small subset of metrics relies on explicit contact interactions and is therefore evaluated only for applicable gripper types.

Future work will address these limitations by refining metric applicability across gripper families, extending the benchmark to dynamic and mobile manipulation scenarios, and further supporting community adoption through automation and open benchmarking resources.

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