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BaRiFlex: A Robotic Gripper with Versatility and Collision Robustness for Robot Learning

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***Abstract*— We present a new approach to robot hand design specifically suited to enable robot learning methods and daily tasks in human environments. We introduce BaRiFlex, an innovative gripper design that alleviates the issues caused by unexpected contact and collisions during robot learning, offering collision mitigation, grasping versatility, task versatility, and simplicity to the learning processes. This achievement is enabled by the incorporation of low-inertia actuators, providing high Back-drivability, and the strategic combination of Rigid and Flexible materials which enhances versatility and the gripper's resilience against unpredicted collisions. Furthermore, the integration of flexible Fin-Ray and rigid linkages allows the gripper to execute compliant grasping and precise pinching. We conducted rigorous performance tests to characterize the novel gripper's compliance, durability, grasping and task versatility, and precision. We also integrated the BaRiFlex with a 7 Degree of Freedom (DoF) Franka Emika's Panda robotic arm to evaluate its capacity to support a trial-and-error (reinforcement learning) training procedure. The results of our experimental study are then compared to those obtained using the original rigid Franka Hand and a reference Fin-Ray soft gripper, demonstrating the superior capabilities and advantages of our developed gripper system. More information and videos at `https://robin-lab.cs.utexas.edu/bariflex`**

I. Introduction

Robots manipulating in unstructured environments must deal with the environment's inherent uncertainty and a large variability of objects and tasks. For example, a service robot performing an everyday activity such as *preparing a cup of instant coffee* will face a different kitchen in every home and have to manipulate multiple objects in different ways: picking and placing them, opening/closing their articulation, pressing their buttons... This required generalization and versatility are challenges that have impeded the development of household robots for decades.

In recent years, the use of robot learning techniques such as reinforcement learning [1], or imitation learning [2, 3] provided more capable and versatile solutions for robots to manipulate unstructured environments [4, 5]. However, robot learning comes with costs including extensive trial and error, initial inaccuracies during training, and frequent collisions with the environment [6, 7]. These costs can result in irreversible damage to the robot, especially when it interacts with traditional rigid hands, which pose further challenges for learning due to their high complexity and large number of active degrees of freedom [8, 9].

To deal with these challenges in robot learning, the community has resorted to embodiments that can handle

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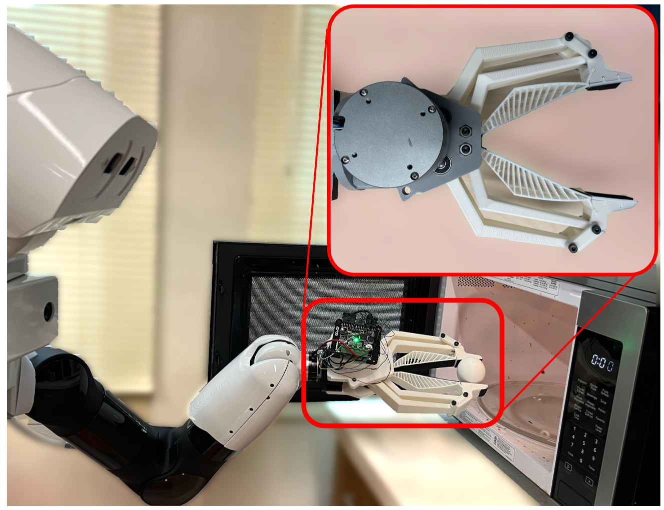

Fig. 1: BaRiFlex mounted on a robot arm and holding a delicate object (an egg). The novel combination of design features in BaRiFlex – high Back-drivable actuator and hybrid Rigid-Flexible structure – provides durability through compliance against contact interactions, adaptability and versatility for grasping, precision for pinch grasps, and support to manipulate heavy objects, enabling a variety of manipulation tasks in unstructured environments. All with a low cost and simple actuation, characteristics that facilitate robot learning.

unexpected contact through compliance and simplify actuation, for example through underactuated [10, 11] or flexible hands [12, 13]. However, these previous hand designs led to a narrower grasp and task versatility, as the trade-off for improved compliance and adaptability often results in reduced control and precision [14], making some tasks and object grasping unfeasible in unstructured environments.

In this work, we present a novel hand, BaRiFlex (Fig. 1), designed to support the requirements of robot learning for manipulation in unstructured environments, namely the collision mitigation to resist frequent and unexpected contacts, and the versatility to grasp and execute the different tasks involved in activities such as household chores. These essential characteristics are achieved through a combination of 1) high back-drivability facilitated by a low-inertia actuator, and 2) high adaptation through a hybrid design structure that synergistically combines both rigid and flexible components. Our approach not only absorbs collisions protecting the robot arm from high contact forces, but also provides the necessary flexibility to enable delicate and fine-grained manipulation of small objects (pinch grasp) while maintaining the ability to apply large forces to grasp and/or interact with heavy objects, and to move extremely fast to react to dynamic events. All with a low budget ($<$ 500 USD), and simple 3D printed elements ($<$ 38 printing hours) and assembly ($<$ 1 hour).

We perform an extensive experimental evaluation to characterize physically and functionally our new BaRiFlex hand design. Our experiments indicate that the high compliance, durability, adaptation, and precision of BaRiFlex facilitate grasping a large variety of everyday objects, and support performing tasks extending beyond simple object grasping such as pressing buttons and opening door handles. Moreover, BaRiFlex also enables learning through continuous trial-and-error in a real-world reinforcement learning loop, all without damaging the mechanism despite several collisions.

The foremost takeaway from this paper is the crucial role played by the novel BaRiFlex gripper in overcoming the hardware constraints that have previously limited the applicability of robot learning. The design of the gripper is motivated by our analysis of the requirements for hands to enable robot learning in human daily environments that we also contribute here (Sec. II). The result is the fusion of collision mitigation, and versatility in a single gripper, that empowers robotic agents to successfully perform an array of tasks beyond what other grippers achieve.

II. Requirements in a Robot Hand for Learning

The human hand is a remarkable manipulation apparatus, not just due to its ability to handle both heavy and small objects but also because of its diverse range of functional capabilities and its robustness in adapting to contact and absorbing impact [22, 23]. In contrast, most robot hands are hard and rigid, possibly inherited from the design of robots in structured factory domains, which lead to brittle and dangerous interactions when facing unexpected contact [21, 24]. Humans, supported by the versatility and durability of their hands, learn and demonstrate superior manipulation abilities by leveraging the same contact that robots with rigid hands try to avoid. For instance, in a single household activity like preparing coffee, human hands proficiently manage a range of actions from handling heavy items like a water bottle to manipulating small ones like utensils, and even executing complex tasks such as operating and opening a microwave [25, 26]. These skills are acquired through trial-and-error, beginning in infancy. Research with infants shows that they extensively utilize contact interactions to learn how to interact with the world [27, 28]. Prior work in robotics evidenced the benefits of enabling similar rich interactions in robots [29, 30].

Based on these observations, we would like to equip our robots with a hand that possesses the specific attributes that seem to support learning and manipulation tasks in humans in unstructured environments: 1) an innate capability to mitigate collisions and resist wear and tear through adaptation to contact, 2) generalization in grasping objects of diverse materials, shapes, and sizes, and 3) the potential to support a wide range of tasks beyond simple grasping motions. All with 4) the simplicity in actuation to empower current learning algorithms and facilitate its production. In the following, we provide a working definition of these attributes. In the next section, we will analyze previous hand designs based on them.

*1) **Collision Mitigation**:* Collision mitigation refers to *designing a robotic hand to absorb impact and resist damage when interacting with the environment without breaking or losing functionalities* [31]. This is attained through *compliance*, utilizing soft materials, elastic mechanisms [32], and back-drivable actuators [18] with low inertia and viscous friction, enabling absorption and dissipation of forces to protect the hand and connected arm.

*2) **Grasping Versatility**:* Hands and grippers with high grasping versatility have the *potential to grasp a wide range of objects* of different sizes, shapes, masses, surface materials, and other physical properties, even based on partial or noisy information. This is frequently attained by hands that can perform multiple types of grasps [33] such as power and pinch grasps, and/or by hands that can conform to the shape of the objects, and succeed even when the assumed object pose is inaccurate. Grasping versatility is linked to the robot's application domain: being able to grasp all objects involved in the application domain (e.g., household activities) is a prerequisite for its success.

*3) **Task Versatility**:* Robots in unstructured environments need to perform multiple manipulation tasks: picking, pushing, opening, turning, catching... Task versatility is the *capability of a hand to support a wide range of operations beyond grasping*. This capability is backed by various properties of hands such as actuation speed, morphology, transmission of force, or accuracy in its movement. For example, button pressing requires compact, strong fingertips, catching objects demands quick actuation, door opening necessitates enough force transmission, and delicate tasks need precise movements. As with grasping versatility, task versatility is scoped by the robot's application domain: a robot hand intended to enable household activities should demonstrate that it is capable of performing all tasks related to that domain.

*4) **Simplicity**:* Simplicity in a robotic hand relates to a *clean mechanism with few active degrees of freedom and straightforward construction, providing a simple action space for effective learning* [34, 35]. While in the future, more dexterity may be enabled by more complex hands like the human hand, multi-finger end-effectors currently do not seem suitable for performing multiple tasks or grasping different types of objects due to their higher mechatronic and control complexity [36]. The current state of robot learning demands simplicity in hand designs, as indicated by some of the most successful recent solutions to manipulation [5]. Simplicity also reduces costs and facilitates repairs and maintenance, making simple designs more practical for current robot application.

In the next section, we will use the hand attributes defined above to analyze previously proposed hand designs.

III. Related Work

The literature on hand designs is vast and rich. In the following, we present our metrics, and analyze the most relevant families of gripper designs and their relationship

TABLE I: Comparison of grippers and hands in terms of Structure, Features, and Attributes

Gripper	Structure			Features			Attributes			
	Actuation	Transmission	Material	Grip Force(N) or Payload(kg)	Speed	Compliance	Collision Mitigation	GV	TV	Simplicity
BLT Gripper [15]	Geared (125:1)	Linkage & Lead Screw	Rigid&Soft	10N	↑	Me	↑	⇑	⇑	↑
Robotiq [16]	Geared (NM)	Linkage	Rigid	10-125N	↑	Me	↑	⇑	⇑	⇑
Magripper [17]	Direct-Drive	Linkage	Rigid	NM	⇑	BD	⇑	↓	↓	⇑
Open Hand [10]	Geared (193:1)	Tendon	Rigid	9.6N	↑	Ma	⇑	↑	↑	⇑
DD Hand [18]	Direct-Drive	Linkage	Rigid	6N	⇑	BD	⇑	↓	↑	↑
Allegro Hand [19]	Geared (369:1)	Linkage	Rigid	5kg	⇑	-	↓	⇑	⇑	↓
RBO Hand3 [12]	Pneumatic	Tube	Soft	8.3N	⇑	Ma	⇑	⇑	↑	↓
Fin-Ray® [20] in Franka Hand	Geared (NM)	NM	Soft	NM	↑	Ma	⇑	↑	↓	⇑
Franka Hand [21]	Geared (NM)	NM	Rigid	70-140N	↑	-	↓	↓	↓	⇑
BaRiFlex	Direct-Drive	Linkage	Rigid&Soft	11N	⇑	Me, Ma, BD	⇑	⇑	⇑	⇑

NM=Not Mentioned, Me=Mechanical Compliance, Ma=Material Compliance, BD=Back-Drivable
GV=Grasping Versatility, TV=Task Versatility, ⇑=high, ↑=medium, ↓=low

to the attributes discussed above, with Table I presenting a more detailed comparison of some of the most-used robotic hands.

We consider high, medium, and low grasping speed depending on the time it takes to close the hand, $t < 0.5\,\mathrm{s}$, $t \in (0.5\,\mathrm{s}, 1.5\,\mathrm{s})$, or $t > 1.5\,\mathrm{s}$, and observe three types of hardware hand compliance: 1) mechanical compliance (e.g., obtained by an underactuated mechanism with spring), 2) material compliance (provided by soft materials such as silicon), and 3) back-drivable actuators that present low resistance to input forces in their output. Compliance is highly correlated with the capacity of the hand to mitigate collision forces: hands with high compliance in multiple collision directions provide high mitigation, with compliance in one specific joint or linkage provide medium mitigation, and without compliance do not provide mitigation.

Grasping and task versatility are defined wrt. the operational domain, in our case, human households, where Feix et al. [33] found that 96% of human contact points distanced less than 7 cm to each other, and 92% of objects grasped are lighter than 500 g. The larger the contact surface between hand and object, the higher the grasping success. Based on the above, we consider grasping versatility to be high if the grasping range is above 7 cm in all dimensions, applies a grasping force over 8 N (necessary to create enough tangential force to lift a 0.5 kg object with the friction of a human hand [37]), and the shape of the hand adapts to have more than three contact points. If a hand provides only two of the above we consider it medium versatile for grasping, and low versatile if it presents one or none. We will measure it empirically with different objects and locations.

Task versatility in household environments demands a hand that strikes a balance between adequate speed and force capacity while achieving precision. High task versatility is considered when the hand exhibits both high speed and ability to execute precise grasps, as well as apply strong forces (hard to achieve with soft hands. We will evaluate this using BaRiFlex to perform a comprehensive range of household tasks. Finally, we assess simplicity based on the number of actuators in the hand and the number of linkages in the entire finger [35]. High simplicity is attributed to designs with < 2 actuators and < 10 linkages for fingers, medium if only one of these conditions is met, and low if none. We will test BaRiFlex's simplicity by using it to learn to grasp an object.

Most designs for robotic hands follow the same type of construction as robot arms –a series of rigid links connected by actively controlled joints [19, 21]– providing full controllability, high precision, and potentially high versatility, but being usually expensive, brittle, and highly complex. To overcome these challenges, researchers have explored semi-rigid underactuated [15, 16] and soft hand designs [12, 13] that improve collision mitigation but tend to be complex and with difficult manufacturing processes, and with restrictions on the tasks they can perform (e.g., no precision/pinch grasps or high force). The BLT Gripper [15] presents high grasping versatility with its mix of active compliant belts and rigid linkages, enhanced by a torsional spring at the fingertip for collision absorption. However, its lead-screw transmission with a high-geared ratio makes the gripper brittle and easy to damage due to unexpected collision at the other linkages. The Direct Drive (DD) hand [18] improves collision durability with its two direct drive actuators per finger but lacks grasping and task versatility as it only enables pinch motion with a small grasping aperture. The Allegro Hand [19] is one of the most used fully actuated robotic hands with 16 DoF joints, offering enhanced task and grasping versatility at the high cost of high complexity and low collision mitigation due to its high-gear, non-back-drivable motors. On the contrary, the soft materials of the RBO Hand [12] provide high collision durability and grasping versatility but the softness makes the hand less precise than rigid ones and limits the transmission of forces. Due to the widespread of the arm, the included Franka Hand [21] is well-known in the field of robot learning. It is a simple parallel jaw gripper, with a high gear ratio that allows for strong grasps but makes it less durable in unexpected collisions that are fully transmitted without mitigation to the arm. Its short fingers lead to low grasping versatility (Sec. V-B).

In BaRiFlex, we achieve high collision mitigation, grasping, and task versatility by combining a highly back-drivable system with compliant elements: soft materials and mechanical torsion springs. This solution results in a highly compliant grasping/interacting behavior while keeping costs low by using readily available components, ultimately enhancing the gripper's collision mitigation and durability. Our combination of rigidity and flexibility through mechanics and materials enables BaRiFlex to perform both pinch grasps that soft or flexible fingers cannot achieve (e.g., scooping fine grains with a thin spoon) and adaptable grasps that rigid grippers cannot provide (e.g., grasping easily deformed objects), significantly increasing the range of objects that hand can grip and manipulate. In the next section, we provide a detailed description of the design of BaRiFlex.

IV. BaRiFlex Design Concept

Our design decisions for BaRiFlex are made to satisfy the requirements for robot learning, namely, collision mitigation, versatility (in grasping and task), and simplicity (Section II). BaRiFlex design is simple with only one actuator, 10 linkages for fingers and weight under 750 g. Collision mitigation and versatility are accomplished by a rigid-flexible hybrid mechanism and a highly back-drivable mechanism.

A. Rigid-Flexible Hybrid Mechanism

To enable BaRiFlex to grasp diverse objects and perform a wide range of tasks while also maintaining durability, we designed a combination of rigid and flexible mechanisms.

The rigid portion comprises high-quality 3D-printed quadrilateral mechanisms on each side, with low-friction bearings at the joints and gears with low backlash, enabling the gripper to achieve efficient power transmission and precise pinch grasping by orienting the fingertips to face each other during motion. The actuator's pinion is connected to one side of the outer linkage via main gear with 1.54 gear ratio(37T-24T), which subsequently rotates to engage the opposite-side finger linkage (Fig. 2a). The lengths of all linkages have been carefully selected to grasp various everyday objects, such as a water bottle, mustard container, and cereal box. As a result, we are able to pinch objects with a width of 200 mm at the fingertip and grasp objects with a depth of 70 mm using the inner flexible linkage. The quadrilateral mechanism also ensures that the fingertip link has no more than 10 degrees of movement while the gripper is in operation and can generate 11N at the fingertip. The fingertip joint possesses a torsion spring (2.57Nmm/deg) that couples the fingertip to the coupler (Section view in Fig. 2a), allowing for compliant flexion and disturbance rejection. A mechanical stopper on the coupler not only prevents excessive fingertip extension but also transmits disturbance forces to the actuator. The wide grasping area and strong force contribute to the high grasping versatility of BaRiFlex, while the compliant fingertips enhance its collision mitigation capabilities.

As depicted in Fig. 2d, the flexible Fin-Ray effect mechanism is employed to achieve compliant grasping motion. Unlike prior Fin-Ray grippers, which increase the thickness of the side support for added strength and rigidity [38] (which reduces flexibility), our gripper incorporates a thin side support structure to facilitate retraction. We selected thermoplastic polyurethane with a Shore-A hardness of 95 (TPU-95A) due to its flexibility and its ability to effectively transfer support forces from the rocker linkage to the object.

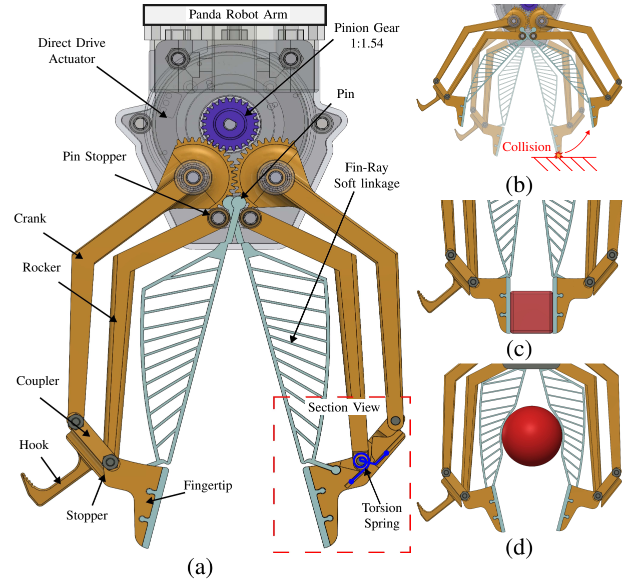

Fig. 2: Design structure of the BaRiFlex gripper. (a) The rigid quadrilateral linkage mechanism transmits the torques from the direct-drive actuator and the collision forces back to it, enabling (b) smooth back-drive motion, and facilitating (c) parallel precise grasping when combined with the underactuated fingertips. The torsional springs at the fingertips further enhance durability by absorbing collision forces. The inner linkage is constructed with a Fin-Ray structure of soft 3D printed material that yields (d) compliant grasping with adaption to the objects' shape, increasing BaRiFlex's grasp versatility. The design is simple, with only one actuated DoF and no gearbox, cost is under 500 USD, and is manufacturable in one day with two 3D printers.

The TPU Fin-Ray flexible linkage is equipped with a pin at one end that moves freely up and down to prevent any overconstraining by the quadrilateral linkage. Additionally, the inner joint of the rocker linkage serves as a stopper and guide for this TPU pin, ensuring that the pins remain within their intended range. These flexible Fin-Ray linkages facilitate adaptive grasping with enhanced contact region between the gripper and unknown objects, leading to the application of uniformly distributed force with only one actuator, thereby contributing to grasping versatility.

B. Highly Back-drivabable Mechanism

The utilization of a low-friction rigid linkage mechanism ensures that unexpected collision forces can be transferred to the low-inertia actuator. This actuator, characterized by its high back-drivability, plays a crucial role in absorbing and mitigating the impact forces generated during collisions. The T-Motor GL60 brushless DC (BLDC) gimbal motor was chosen due to its ability to provide precise and stable control, along with its compact size and lightweight design. To accurately sense the motor's position, an 14-bit absolute encoder was mounted on the motor. The collision force transfers to the actuator through the rigid linkage mechanism, and the low inertia actuator retracts based on the transferred torque direction. High speed is an additional feature achieved by the direct drive actuator, allowing for an open-to-close motion in just 0.18 seconds. The high precision and speed of BaRiFlex enable it to perform various tasks, such as pinching

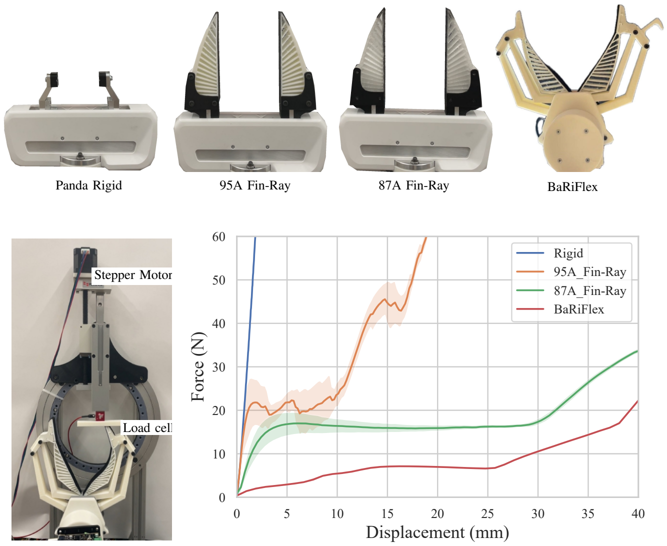

Fig. 3: Experimental evaluation for compliance regarding four grippers (top). An accurate linear stepper motor presses on the tested hand (bottom-left). The reactive forces corresponding to different collision distances are recorded (bottom-right). BaRiFlex exhibits the highest compliance, being able to absorb more impact forces, which facilitates interactions and learning in unstructured environments.

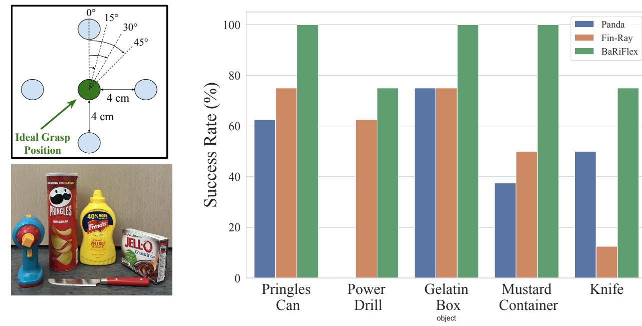

Fig. 4: Experimental evaluation for grasp tolerance. (Top-left) target objects are placed at five locations and with four orientations to evaluate the tolerance of the grippers to inaccuracies in poses. (Bottom-left) We test multiple objects with different shapes, sizes, surfaces, and weights. (Right) Results: BaRiFlex demonstrates a superior grasp versatility in all cases, especially with objects that require pinch grasps or conformity, thanks to its rigid-flexible design.

thin objects, grasping delicate items, or snatching objects swiftly, thereby enhancing its task versatility.

V. Experimental Evaluation and Result

Our experiments aim to assess how our gripper design decisions impact its performance within a robot learning context. In particular, we designed the experiments to answer the following three questions: 1) Is the gripper robust enough to tolerate multiple collisions? 2) How versatile is the gripper to grasp different shapes, sizes, and variations in poses of objects? 3) How versatile is the gripper in terms of the tasks that it can enable to perform? Finally, we perform an integrated experiment where we learn with real-world reinforcement learning to grasp an object using the BaRiFlex gripper, evaluating its capabilities to enable robot learning.

A. Evaluating Collision Mitigation

In BaRiFlex, collision mitigation is obtained through compliance, the ability to absorb impact with an elastic deformation, attained through a combination of high back-drivability and rigid-flexible hybrid mechanism design (see Sec. IV). Therefore, we evaluate the capacity of our gripper to mitigate collisions by measuring its compliance characteristics: its ability to flexibly and smoothly absorb mechanical force when compressed. In our evaluation, we tested four different grippers: BaRiFlex, Franka Panda with original fingers, and Franka Panda with Fin-Ray fingers printed with 87A TPU and 95A TPU materials(Fig. 3 top). The hands are placed in a device with a linear actuator that repeatedly presses them at the fingertips, measuring the resulting reactive force from the hands as a function of the applied displacement (Fig. 3). Each test was conducted six times, pushing up to 40 mm into the resting surface of the fingertip or until a maximum reactive force of 60 N was reached. Due to the high back-drivability of our hand, the fingers absorb some of the impact by changing its configuration: for a fair comparison, we command the gripper to return to the initial position after each collision.

Fig. 3 (right), depicts the result of our experiment. The original Franka hand, popularly used by the robot learning community, exhibited the lowest compliance because of the rigid nature of all the components of the mechanism. The Franka hand with Fin-Ray fingers improves compliance and therefore, durability, with the 95A TPU exhibiting lower compliance than the 87A due to the stiffer material. BaRiFlex achieves the highest compliance, reacting with only 22 N to the maximum collision at 40 mm. The combination of rigid-flexible linkages and high back-drivability provides superior compliance leading to better collision robustness. Finally, the robustness-durability of BaRiFlex was tested by applying repeatable 40 mm pushing collisions to the fingertips 200 times before using it to grasp. The gripper did not show any signs of wear or tear, and operated without changes. This demonstrates that BaRiFlex is highly robust and can be used in robot learning procedures involving hundreds of repetitive contact interactions (see Sec. V-D).

B. Evaluating Grasping Versatility

We evaluate the grasping versatility of the robotic hand based on two key aspects: First, its ability to successfully grasp objects when the information regarding the object's location is either insufficient or inaccurate, i.e., its tolerance. This assesses the hand's adaptability and success under uncertain conditions. Second, we assess BaRiFlex's capability to grasp diverse objects commonly found in a household setting, evaluating its versatility across different sizes, shapes and textures.

1) Grasping Tolerance: To test BaRiFlex's tolerance to grasp objects we used a subset of YCB objects [39] – pringles can, mustard bottle, power drill, knife and gelatin box (Fig. 4)– covering a wide range of sizes, shapes, weights and surface materials. We assessed the tolerance of BaRiFlex

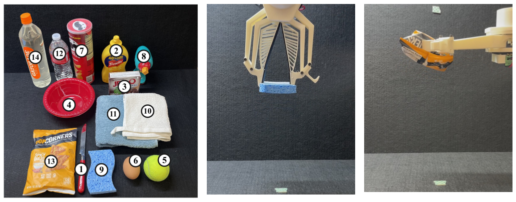

Fig. 5: Experimental evaluation for grasping various objects. 14 objects representing various categories concerning size, shape, material, and daily objects are selected to validate grasp versatility performance (left). BaRiFlex, rigid, and Fin-Ray grippers conducted the grasping object tasks in vertical (middle) and lateral (right) directions.

TABLE II: Object grasping versatility task results

	Properties					Success rate %					
No.	Object	Type	Dims. (mm)	Size	Weight (g)	BaRiFlex		Panda		Fin-Ray	
						Top-down.	Lat.	Top-down.	Lat.	Top-down.	Lat.
1	Knife	Squared	2x14x215	Sm.	35.9	**100**	**100**	**100**	**100**	33	0
2	Mustard bottle	Irregular	58x95x190	Med.	50	**100**	**100**	**100**	**100**	**100**	**100**
3	Gelatin box	Squared	35x110x89	Med.	14	**100**	**100**	**100**	**100**	**100**	**100**
4	Plastic bowl	Circular	ϕ170x50	Lg.	12	**100**	**100**	0	0	0	0
5	Tennis ball	Circular	ϕ65	Med.	60	**100**	**100**	**100**	**100**	**100**	**100**
6	Egg	Circular.	ϕ50	Sm.	60	**100**	**100**	**100**	**100**	**100**	**100**
7	Pringles Can	Circular	ϕ75x250	Med.	50	**100**	**100**	0	**100**	**100**	**100**
8	Toy Power Drill	Irregular	60x130x145	Med.	140	**100**	**100**	**100**	**100**	**100**	**100**
9	Sponge	Delicate	65x120x20	Sm.	13	**100**	**100**	**100**	33	**100**	**100**
10	Linen	Fabric	265x265x1	-	50	**100**	**100**	**100**	**100**	**100**	**100**
11	Bath towel	Fabric	406x752x2	-	170	**100**	**100**	**100**	**100**	**100**	**100**
12	500ml Bottle	Circular	ϕ50x200	Med.	513	**100**	**100**	66	**100**	**100**	**100**
13	Snack	Delicate	185x130x15	Lg.	34	**100**	**100**	66	66	**100**	66
14	1L Bottle	Circular	ϕ75x295	Med.	1050	66	0	**100**	**100**	33	**100**
Average						98	93	81	86	83	83

and other hands (Franka, and Franka with Fin-Ray fingers) to grasp when the objects are misplaced wrt. the predicted grasping location. To that end, we designed an experiment with five distinct positions, each located 4 cm away from the expected position (see Fig. 4 top-left), and four different orientations at 0, 15, 30, and 45 degrees from the easiest grasping orientation, i.e., the orientation that offers the thinner object side to the gripper aperture. The gripper is mounted on a Panda robot arm that moves it along a predefined trajectory until it brings it to a predefined pose where the gripper closes and then the hand moves up. If the object is lifted without dropping, the grasp is successful.

Fig. 4 (right) summarizes the results of our experiments. We observe that BaRiFlex outperforms the other grippers for all objects. In particular, comparing the power drill and knife reveals intriguing insights. The panda gripper performs well with the knife, owing to its pinch grasp capability, while the Fin-Ray gripper handles the power drill effectively due to its conforming ability. In contrast, BaRiFlex stands out as the top performer, combining conformity to various shapes through its rigid-flexible construction and precise pinch grasp. Analyzing successes per location and orientation, we also observe a superior performance of BaRiFlex. In particular, the Panda Gripper faces difficulties with orientation deviations due to its small fingers and lack of flexible material, while the Fin-Ray gripper encounters issues with distant positions because its fingertips can't exert sufficient force to maintain the grasp. Conversely, The morphology of BaRiFlex with larger fingers and caging area increases its tolerance to variations in position and orientation.

2) Grasping Various Objects: The performance of the hands when grasping various objects is assessed on 14 household items that cover the sizes, shapes, weights, and materials commonly found in houses (Fig. 5, left). As in Phodapol et al. [40], in each test, the object is centrally placed and the gripper is adjusted to the ideal position for grasping. The grippers attempt to grasp and lift each object three times in both top-down and lateral directions. Any inability to maintain grip or drop the object during lifting, caused by deformation or excessive weight, is recorded as a failure.

Table. II shows the success rates for three different grippers(BaRiFlex, Panda Rigid gripper, and Fin-Ray gripper). BaRiFlex demonstrates the highest success rates (98% in top-down and 93% in lateral directions), only struggling with a 1L bottle in lateral lifts because of its heavy weight (1 kg), over the 500 g that most objects in houses weight [33]. The Panda rigid gripper cannot grasp large objects (e.g., the large plastic bowl and the Pringles can) due to its limited grasping width, and fails to lift a sponge because the space between the sponge and the ground causes further deformation, leading the gripper to lose its hold on the object. The Fin-Ray gripper fails to grasp large objects (the large plastic bowl), objects that deform (the snack bag) and small objects due to low precision (the knife). The high grasping tolerance and success in grasping different objects indicate that BaRiFlex is a highly versatile hand to grasp in household domains.

C. Evaluating Task Versatility

We perform a qualitative evaluation of BaRiFlex's ability to enable performing a wide range of tasks in household domains. For this evaluation, BaRiFlex is mounted on a handheld portable device and is operated by a human. Fig. 6 summarizes some of the tasks tested that BaRiFlex is able to open cabinets and heavy doors, grasp thin objects such as spoons, open the cap of a coffee bottle, and press buttons on a microwave.

We also perform a dedicated test to evaluate the grasp precision of BaRiFlex particularly for delicate objects. The test involves the gripper's fingertip pressing a dial indicator with a resolution of 0.001 inches, 25 times. We measure the pressing displacement. The results indicate that the average pressing displacement is 3.7597 mm with a standard deviation of 0.0253 mm and a maximum deviation of just 0.0889 mm. This exceptional precision is attributed to the gripper's utilization of a rigid, low-friction quadrilateral linkage mechanism and a high-precision Direct-Drive actuator, which collectively enable the precise and consistent motion required for accurate object manipulation and grasping of delicate objects. The utility of BaRiFlex's high precision is evaluated qualitatively through tasks such as grasping an egg (Fig. 6 bottom-left). Lastly, the direct-drive actuator of BaRiFlex enables high-speed actuation that can be critical for reactive tasks in unstructured environments (e.g., grasping a falling object). We evaluate this ability with an experiment where a ball slides along a slope and is grasped by the gripper (Fig. 6 bottom-centre). The large variability

Fig. 6: Experimental evaluation for task versatility. BaRiFlex is mounted on a portable device and used by a human to perform multiple household tasks including a full long horizon activity, *prepare a cup of instant coffee* that involves tasks such as (top row, left-to-right): opening cabinets, opening jars, pinch-grasping utensils, pressing buttons, grasping delicate plastic cups. We also evaluated other tasks such as grasping an egg, catching a fast-moving object, and opening heavy doors (Bottom row). Through this human-controlled manipulation, we empirically evidence the high task-variability enabled by BaRiFlex, which covers a significant fraction of possible tasks in household domains.

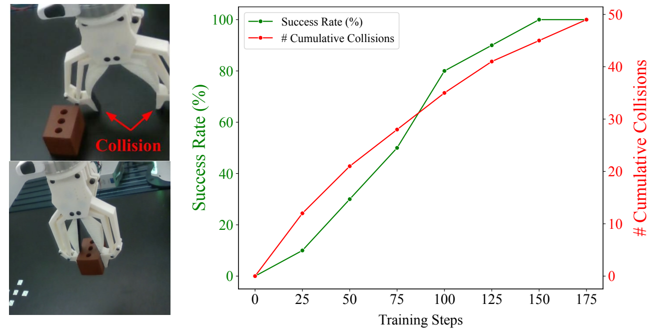

Fig. 7: Experimental evaluation for BaRiFlex supporting real-world reinforcement learning. The hand is used to learn to pick up a cube from trial and error. The gripper collides with the surface a total of 49 times without any damage eventually achieving a 100% success rate at the task. (top-left) shows an example of collision and (bottom-left) shows an example of a successful grasp. The robustness and versatility of BaRiFlex enable the multiple unexpected collisions involved in learning manipulation tasks in unstructured environments.

of tasks supported by BaRiFlex is a significant departure from specialized grippers; while only controlled manually, our experiments evidence that BaRiFlex supports general manipulation in unstructured environments for household application domains.

D. BaRiFlex for Robot Learning

Our ultimate goal in developing BaRiFlex is to enable safe and efficient robot learning in the real world. We designed a final experiment where we evaluated the capabilities of BaRiFlex to operate under repeated collisions during the training process of a task using reinforcement learning. The task is to learn to grasp a cube placed on a table. We use Upper Confidence Bound [41] as the algorithm to learn this task with each epoch consisting of 15 train steps and 8 evaluation steps. The algorithm consists of actions with varying levels of contact with the tabletop surface. Fig. 7 depicts the results of the training process and the number of collisions withstood by our hand. BaRiFlex absorbs up to 49 collisions without any damage or abrupt halting of the robot, enabling learning. The final policy after 175 steps reaches a 100% success rate. Thanks to the novel design in BaRiFlex that combines a highly back-drivable actuator and a hybrid rigid-flexible construction, real-world reinforcement learning is safe and successful for our robot without any interruptions due to the numerous collisions.

VI. Conclusions and Limitations

We have presented a new approach for designing robotic grippers tailored for robot learning with an ability to manipulate in daily unstructured environments and we designed a novel gripper BaRiFlex based on these principles. Using a highly back-drivable actuator and a hybrid rigid-flexible mechanism we are able to achieve high collision mitigation, grasping and task versatility while maintaining simplicity. Our extensive experiments, including a real-world reinforcement learning task, demonstrated BaRiFlex's effectiveness, with impressive compliance, reacting with only 22 N of force to maximum collision at 40mm and a high success rate of over 93% for grasping household objects. The gripper's outstanding features such as a fast grasping speed of 0.13 s, high precision with an error deviation of just 0.0889 mm, and a robust grasping force of 11 N enable the gripper to conduct multiple household tasks. The high simplicity of BaRiFlex, featuring 10 linkages for the fingers and a lightweight design under 750 g, enhances ease of maintenance and allows for grasping heavier objects within the given manipulator's payload capacity. Some limitations of our gripper include its low in-hand dexterity due to having only two fingers since we primed simplicity over dexterity. BaRiFlex may also struggle to absorb collision forces effectively when impact occurs in the palmar/dorsal direction. Integrating a flexible wrist between the gripper and the robot arm would alleviate this problem.

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