Trust the Hand: Lessons from 15 Years of Applied Co-Design for Soft Manipulation

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Abstract A robot's behavior is governed by its body and the controllers that actuate it, making robotics a co-design problem. Until the emergence of soft robotics, the control side dominated robotics. In particular, soft robotic hands shifted the responsibility from complex control strategies to simpler, morphology-driven solutions. Our RBO Lab accumulated 15 years of experience building and applying soft hands for contact-rich manipulation tasks such as grasping and in-hand manipulation. By sharing the lessons we learned along the way, we hope to convince future roboticists that co-design is the right approach for advancing robotics.

1 Introduction

Soft robotics is causing a paradigm shift in robotics [17]. In this shift, the role of the robot's body is changing from a dutiful executor of control policies to an active contributor to robot behavior. The consequences are substantial. Much of our understanding of how to build robotic systems and our intuition about generating behavior has become incomplete.

To advance robotics following this paradigm shift, we must understand how to orchestrate the role of the body and control in generating robot behavior. We must learn how to build robot bodies that complement the capabilities of robot control and vice versa. This is not only new scientific territory; this paradigm shift will require us to overcome some of the well-established wisdom of robotics engineering and science.

Over the past 15 years, our laboratory has grappled with the consequences of this paradigm shift in the context of soft robot manipulation. During this time, we questioned and changed our intuitions time and time again. We had to realize that traditional wisdom was sometimes hindering, not helping. We had to learn many new lessons, some the hard way. In this paper, we have collected the most important of these lessons. We present each lesson as a story.

This format is unusual, but we transmit our transformative experiences most effectively through these stories. We feel justified in taking this unusual approach to transmitting research results by the perspective of Peschl and Fundneider about how drastic innovation takes place in science [33]. In their Emergent Innovation approach, they argue that radically new knowledge emerges via (1) a deep understanding of the innovation object and (2) the letting go of deeply ingrained assumptions. In accordance with this view, our stories explain the insights from co-designing a soft manipulation system and highlight which parts of traditional robotics wisdom we needed "to let go of."

2 Lessons from Co-Designing Soft Manipulation

We continuously and iteratively designed and built a soft, anthropomorphic, pneumatically actuated robot hand (Fig. 1). Each step of this 15-year-long evolution included changes to the hardware and the way we control the hardware. We designed and evaluated the entire system, control and hand together, keeping in mind that improvements could be achieved in either or both [19, 20, 29]. We, therefore, lived through 15 years of practical, comprehensive, applied co-design. By sharing our most insightful stories, we want to provide the reader with a "crash course" in co-design, a fast way of benefiting from our experience. We hope this work lays the foundation for a new generation of roboticists for whom co-design is a natural choice and engineering practice for advancing soft robotics.

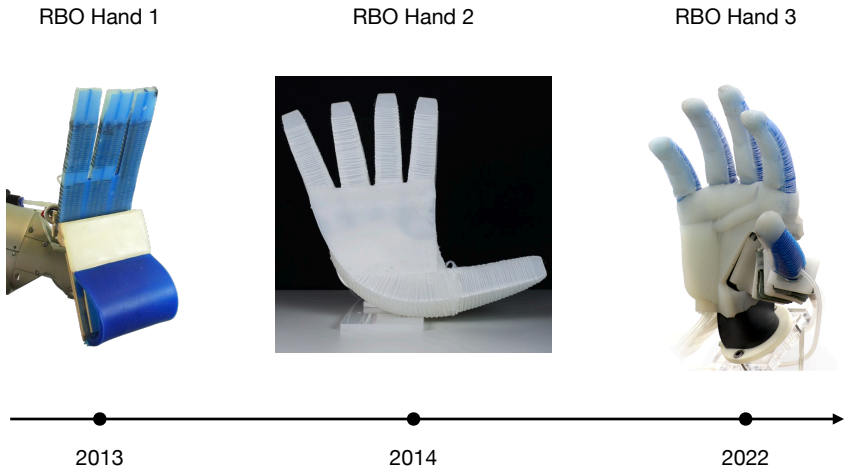

Fig. 1 Three generations of RBO Hands: RBO Hand 1 (photo reprinted from [11] with permission, © 2013 IEEE), RBO Hand 2 (photo reprinted from [12] with permission of the authors), and RBO Hand 3 (photo reprinted from [37], licensed under CC BY 4.0). Anthropomorphism increased over time, driven by improvements in thumb dexterity.

2.1 Trust the Hand

In 2019, a new generation of PhD students joined our effort to advance soft in-hand manipulation. The students came from a traditional robotics background and overlooked the role of the hand's embodiment. During their first year, they experimented with standard approaches like simulating the hand, reinforcement learning, and probabilistic movement primitives (against Oliver's advice). However, none of these methods worked. Why? Probably because the underlying assumptions of well-defined kinematics, dynamics, and states simply do not provide the most appropriate framing for soft systems and need to be let go of, as predicted by the Emergent Innovation paradigm [33].

As frustration grew, they began manually exploring the system (and the advice they received). They mapped each actuator to a manual slider and programmed simple open-loop sequences. One of these sequences should rotate a cube. To their surprise, it worked. Not only did it work, it generalized across different object shapes, poses, and even to 80-fold speed-ups despite the hand being sensorless [4][1]. They learned that one can *trust the hand* in taking over substantial control responsibilities.

But which responsibilities can the hand's body take over and why? The soft body of compliant hands can store and release energy via material deformation. This property enables the hand to passively conform to the object's shape and to reject disturbances automatically [1, 42][2]. This self-stabilizing effect [23] simplifies control because the hand's soft body handles large parts of disturbance rejection [40, 28], which typically requires active control [26]. In summary, our soft hand has desirable *morphological computation* abilities, which can be accessed and "programmed" via appropriate digital computation of controllers by changing the overall shape of the hand [20, 35]. Distributing sub-tasks and their solutions across these different types of computation (here: morphological and digital) is at the core of co-design.

2.2 Help the Hand Help You

How can one access the helpful morphological computation of soft hands? In the early days of our work on robotic grasping, we focused heavily on perception. The idea was simple: sense the object accurately, plan exact contact points, and optimize for performance metrics like force closure. In this view, any additional contact with the environment is treated as a problem, not an opportunity. It was necessary and productive to let go of this view, again confirming the ideas expressed in Emergent Innovation [33]. Instead, we now consider extensive physical contact essential to competent grasping.

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[1] View the surprising robustness of open-loop soft manipulation in this playlist: `https://youtube.com/playlist?list=PLb-CNILz7vmt6Ae_yD9i15TrCw0S8bKCn`

[2] The RBO hand passively rejects disturbances: `https://youtu.be/U6KgnqitfvY&t=100`

We reached a turning point when we compared robotic grasping strategies to how humans grasp and manipulate objects [15]. We realized that grasping is not a single moment of perfect contact. Rather, it is a process full of interaction and adjustment. With bewilderment, we watched a chef cutting potatoes[3]: almost none of the hand/environment interactions, except for the grasp on the knife, could be explained by classical grasping concepts. Instead, the chef used her fingers, the counter, and the knife to guide the cutting motion of the potato. We observed that humans deliberately leverage environmental constraints (ECs), such as table surfaces, which enable simple and robust grasping [15, 30]. The same principle of leveraging ECs applies to in-hand manipulation. The entire hand, not just the fingertips, provides ECs to constrain an object [6]. ECs like gravity and inertia can also be leveraged for simplified manipulation [10, 32].

Our soft actuator's compliant properties allow us to safely drive them "into" the environment without risking damage. As shown in Fig. 2, the hand passively conforms to ECs such as table surfaces, enabling guided finger motion without the need for accurate control or perception [5, 15]. We realized that the hand's helpful morphological computation abilities are accessed by bringing the hand into contact and leveraging these ECs. In essence, we *make contact* instead of avoiding contact, and by making contact, we *help the hand help us*. The ability to exploit ECs can be considered an inductive bias for co-design.

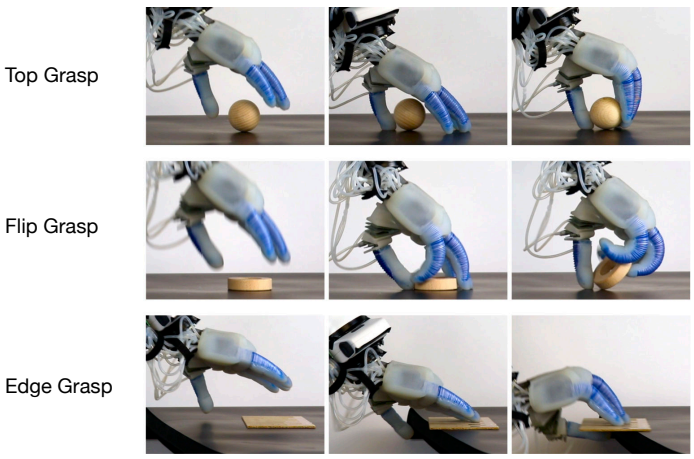

Fig. 2 Our soft actuators can safely make contact with the environment. Therefore, our hand can replicate human grasping strategies that exploit the environment, such as table surfaces, without risking damage. These robust grasping strategies leverage the hand's morphological computation, reducing the need for accurate sensing and control [15] (figure adapted from [37], licensed under CC BY 4.0). View our videos of the top grasp `https://youtu.be/ENbrUOmDsSI`, the edge grasp `https://youtu.be/0LnvVSEINH4`, and more EC-exploiting grasps `https://youtu.be/WuSbj64F4N0`.

[3] Julia Child, "The Potato Show", see: `https://youtu.be/Vjq5P24AkwM`

2.3 Do not Always Trust the Hand

When we designed the RBO Hand 1 [11] and 2 [12], our main goal was to maximize compliance, as we were enthusiastic about our early results on grasping.

However, we quickly observed that not all compliance is helpful [18]. In the RBO Hand 2, the actuators were sometimes too soft. They struggled to lift heavy objects and often buckled when coming into contact with the environment. Their compliance made their behavior unpredictable and limited what the hand could do, as shown in Fig. 3. To fix this, we made the actuators of the RBO Hand 3 stiffer, giving them more strength and significantly reducing the risk of buckling.

Realizing that not all compliance is good highlights the importance of adjusting the hand's compliance for a given task. Our actuators' compliance is tunable by changing their inflation level: high inflation means lower compliance. Our RBO Hand 3 has more degrees of actuation per finger than its predecessors and can, therefore, more accurately tune its compliant response [37]. Furthermore, variable stiffness actuators can improve the versatility of hands by selectively stiffening their body [47, 27]. In summary, the degree of material compliance and the actuation abilities of a soft hand are key factors that must be considered in a co-design process.

Fig. 3 Examples of bad morphological computation. Left: soft fingers yield while pulling on a heavy door handle. Middle: fingers buckle while sliding along a wall. Right: fingers buckle while lifting a heavy bottle (photos reprinted from [48] with permission, © 2017 IEEE).

2.4 The Human Hand Inspires

After successfully using soft hands for grasping through environmental constraint exploitation, where the hand simply closes upon force feedback triggered by contact, we began considering how to control the hand for more fine-grained tasks, like in-hand manipulation. These tasks posed a challenge because common control, planning, and learning methods [34, 25, 45, 3, 9, 36], which rely on precise models, are unsuitable for soft hands. Again, we had to question

our deeply ingrained assumptions from traditional robotics approaches to these problems [33].

Motivated by a programming error in a class exercise, we experimented with random Jacobians to control an object's position tracked using an AprilTag marker. Each entry was randomly set to 1 or -1, and if we could not reduce the error, we flipped the signs. Surprisingly, this naive approach worked far better than expected. This revealed that the hand's natural compliance and self-stabilizing properties could compensate for the lack of precise models. Around this time, we came across a paper on human motor control, suggesting that forceful tasks could be performed using "sloppy" models rather than precise ones [2], which aligned with our findings. Inspired, we developed a robust feedback control algorithm using coarse, inaccurate models [41]. These models were not inaccurate for the sake of inaccuracy. But making them more accurate was very costly and did not lead to any improvements in performance—something that deeply seems to contradict standard engineering intuitions.

Our soft, anthropomorphic hands look like human hands and behave surprisingly similarly. Their shape and compliance naturally aid in guiding and stabilizing interactions, even without complex control. This insight allowed us to investigate bio-inspired control strategies for grasping and in-hand manipulation [2, 14, 15, 16, 22]. As the human hand is already the product of co-design through evolution, human control strategies can serve as inductive biases for control in our co-design efforts.

Interestingly, anthropomorphic design also impacts how the community perceives research. While the grasping performance of the RBO Hand 1 was impressive, it did not manage to capture the community's substantial attention. However, by making the RBO Hand 2 more anthropomorphic (among other things, of course), we were able to win a best student paper award at RSS 2014 [12]. The imbalance in attention is also reflected in the citation counts as of May 2025: the RBO Hand 1 paper [11] has 431 citations while the later RBO Hand 2 paper [12] has 1364 citations.

2.5 Think Beyond the Human Hand

Fig. 1 shows the three generations of hands developed in our lab to make the hand as anthropomorphic as possible. While developing in-hand manipulation skills with the RBO Hand 3, we encountered a surprisingly human problem: clamping an object between two fingers to let the thumb gait along the object. People do this instinctively, but with their high lateral compliance, our soft robotic fingers required precise contact placement, which was far from trivial.

Guided by lesson 2 (Sec. 2.2) encouraging us to exploit contact, we avoided solving this problem with control for the current hand. Instead, we went to hand design again (Fig. 4). We increased the bending range of the actuated palm from 30° to 80° to enable a firmer grip between the fingers. Then, we made an even

larger change by adding a second thumb. This extra thumb offered an additional contact patch, helping to stabilize the grasp while gaiting the other thumb.

Addressing this problem solely at the control level would have required intricate control. But by co-changing the hand's design, we could explore capabilities beyond the human form factor. This iterative co-design aims to identify the fundamental properties required for a general manipulation platform rather than simply copying the human hand. The second thumb simplified the original control problem and enhanced the hand's co-designed abilities.

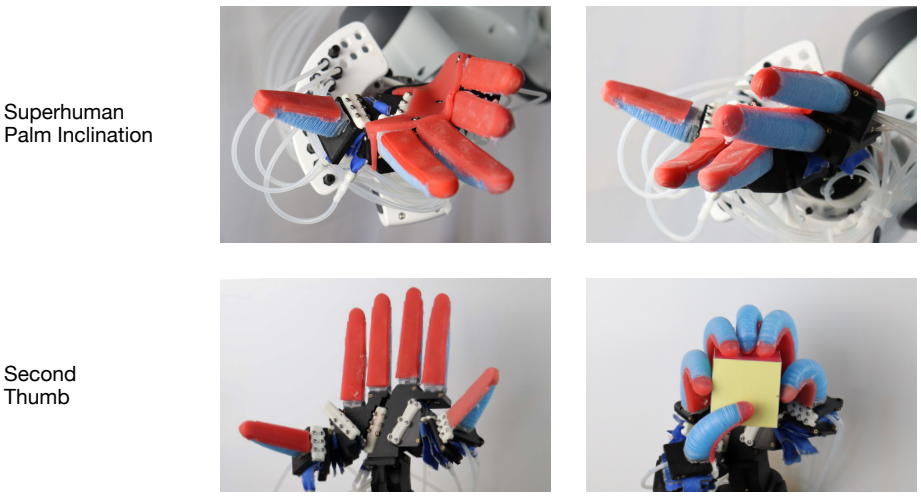

Fig. 4 Bioinspiration is only a starting point. Top row: We equipped the hand with a superhuman palm inclination of up to 80°, increasing the range and dexterity of the ring and little fingers. Bottom row: A second thumb can secure an object from one more side and increases the hand's overall dexterity. View the second thumb in action: `https://www.youtube.com/playlist?list=PLb-CNILz7vmuvzliy-YiXME-ksJyFBwOd`.

2.6 Treat Friction Like an Actuator

New challenges emerged when we started to exploit contact with the environment for grasping. While using the RBO Hand 2 to pick objects from cluttered boxes in the *Soft Manipulation (SOMA)* [39] project, we kept running into a frustrating issue. As the hand slid across the bottom of the box, its soft silicone fingers, made from high-friction *Dragon Skin 10*, would stick, bend awkwardly, and buckle under load.

Then came an unexpectedly simple fix. One PhD student, watching the hand struggle with the surface, grabbed a bottle of baby powder and lightly dusted the back of the actuators. Suddenly, the fingers stopped catching. They slid cleanly, and the buckling problem disappeared. It worked so well that we started using baby powder even during in-hand manipulation, as the actuators had been designed for grasping and had too much friction.

The key lesson here is that selecting the appropriate level of friction is crucial for performance. To address this, we designed a special pulp layer that we attach to the soft actuators, allowing us to tune both the stiffness and friction at the contact. Eventually, we turned away from using baby powder. Now, we adjust the stiffness using different silicones. We also modify friction by adding a *Slide STD/1 Surface Tension Diffuser* into the silicone during manufacturing. Specific compliance structures in the pulp can further enhance grasping performance [38]. In the future, we hope to build soft actuators that can adjust their friction through control, allowing even greater adaptability [44]. Similar to compliance, friction is an important variable in a co-design process.

2.7 Material Compliance Simplifies Exhibiting Compliance

In 2020, our PhD students set out to better understand the unique contributions of soft bodies in robotic manipulation. In a simple but revealing experiment (Fig. 5), they clamped a wooden annulus between the index and the thumb of a soft robotic hand. Then, they actuated only the thumb for just half a second.

What happened next was unexpected. The annulus kept rotating in a coordinated motion with the thumb, even though the thumb was not actuated at all. The students realized that this behavior is not just acceptable—it is desirable! The body itself is manipulating, reducing the burden on control. It is a feature, not a bug! And again, this violated our intuitions.

What makes this passive, continued motion possible? The answer lies in the omnidirectional compliance of soft actuators (Fig. 6). Thanks to its compliance, the index finger automatically stays opposed to the thumb. The thumb essentially actuates the *passive workspace* of the index. The thumb's brief actuation initiated a cascade of energy storage and release, naturally moving the system into a new energy minimum—without extra control. Rigid hands would require intricate joints and complex control schemes to achieve similar results. Mean-

while, the soft hand achieves it effortlessly. Enabled by the soft body, we could let go of the typical assumption that fine manipulation, such as rotating the annulus, requires accurate sensing and control, further supporting the Emergent Innovation paradigm [33].

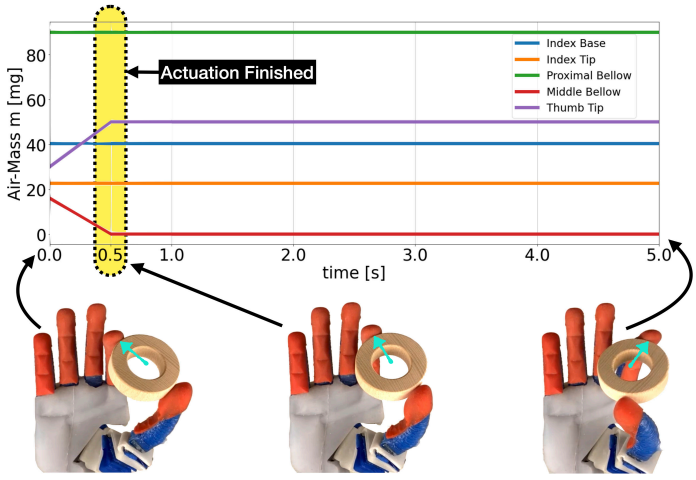

Fig. 5 Embodied intelligence at work: a brief thumb actuation introduced energy into the system, rotating the annulus. After the actuation stops at 0.5 seconds, the hand continues rotating the annulus as it progresses into a new energy minimum. The turquoise arrow indicates annulus rotation. Watch the video here: `https://youtu.be/Nor2QEtM4W8` (figure adapted from [4] with permission of the authors).

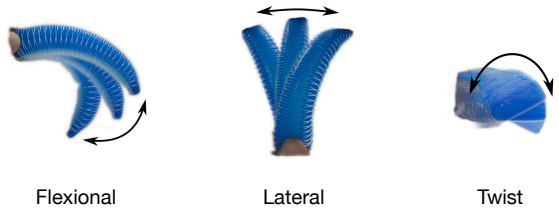

Fig. 6 The omnidirectional compliance of our fingers is a key enabler for its morphological computation, as demonstrated in Fig. 5. Exhibiting a similar level of compliance on a rigid hand would require complex articulation and control. A hand that is compliant in more directions is more self-stabilizing because its body can compensate for disturbances in more directions (photos reprinted from [48] with permission, © 2017 IEEE).

2.8 The Body Is the Sensor

Although soft hands enable robust manipulation in a sensorless, i.e. open-loop, fashion [1, 4, 32], we need sensorization to avoid, detect, and recover from failures, as well as for learning manipulation behaviors. With this in mind, we began building sensors specifically tailored to soft hands, i.e., sensors that preserve the compliance of the hand [21]. Oliver voiced an unconventional idea—embedding a speaker and a microphone into the squishy fingers to listen to their deformations. Everyone was skeptical. It sounded too strange, too different. Nobody wanted to take on such a risky project. However, Gabriel Zöller, a Master's student at the time, decided (in alternative accounts: was coerced) to give it a try during a project course we were offering at the time.

To everyone's—even Oliver's—surprise, the soft fingers had much to say. The internal sounds, captured by the microphone, revealed rich information like contact position, force, and even temperature, all decoded using simple machine learning models. The results were so unexpectedly accurate and general that Gabriel did not initially trust them. Something must have gone wrong. But he could not find the mistake. He wiped the slate clean, rebuilt the entire setup from scratch, and collected an entirely new dataset. But again, the soft fingers told the same astonishing story.

Acoustic sensing [49], together with other sensing technologies we explored (Fig. 7), gave rise to the idea of *morphological sensing* [46]: The entire morphology of the body serves as a powerful sensor. Fig. 8 illustrates this approach. Morphological sensing is based on the observation that all interactions between hand and environment manifest themselves in changes to the *morphology*. Sound propagating through these changed morphologies is modulated to capture these changes. The desired sensor information can then be reconstructed from the recorded, modulated sound signal via computation [43], reconstructing the relevant *measurement* from the sound. Computation can use the morphological sensor to emulate several different "classical" sensor types (Fig. 7). Therefore, it is essential to recognize that sensing naturally becomes part of the co-design process and should not be considered a separate problem.

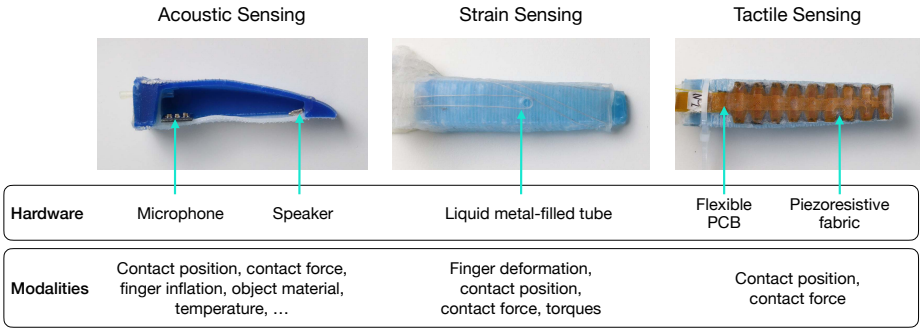

Fig. 7 Our three sensor types for soft fingers: The sensors preserve compliance because they are either flexible or their rigid components are placed in a way that preserves actuator compliance. The acoustic sensor is placed inside the finger [49]. Flexible strain sensors are glued onto the finger [48]. Stretchable tactile arrays are mounted on the non-stretchable inside of the fingers [31]. The table lists the physical properties that can be sensed by the respective sensor.

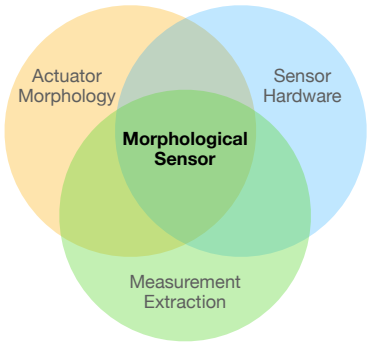

Fig. 8 The morphological sensing paradigm: the interactions between hand and environment influence the actuator morphology, a sensor captures a raw signal from this morphology, and a digital process extracts the measurement that caused the change in actuator morphology (figure reproduced from [46], licensed under CC BY 4.0).

2.9 Do not Control Compliance "Away"

In the early days of designing our soft hands, we needed a way to inflate and deflate the actuators. The obvious choice was to control the internal pressure since pressure sensors are inexpensive and reliable. So, we followed the conventional approach and built a pneumatic controller based on pressure.

As we worked with this setup, problems started to emerge. The issue was that soft actuators change shape when they contact something, altering their internal volume. As a result, the controller kept trying to regulate pressure even during contact. When the hand grasped an object, the pressure increased, and the controller would deflate it, almost as if the hand was "scared" of the contact, controlling its natural compliance "away". To circumvent this behavior, we tried

something different. We opened the valve for a fixed amount of time to let air in, then shut it. That was it. With no controller constantly adjusting the pressure, the hand was free to respond naturally to contact, just as we intended.

Closing the valve locks in a fixed amount of air mass, which sets the shape the actuator returns to when no external forces are applied—like a stretched spring returning to its original position [4]. This makes air mass a more suitable control variable than pressure [13]. Air mass control effectively turns soft pneumatic actuators into programmable springs, helpful in sensing actuator deformation [41] and modeling the hand's free-motion kinematics, which is useful for in-hand manipulation tasks [42]. This perspective on control lets us disambiguate the contributions of software and hardware. Knowing these contributions can inform the design of an objective function of a co-design algorithm [18].

2.10 Pneumatics and Silicone Are Good for Prototyping

Building a robotic hand is traditionally a complex task. Therefore, only a few are built, making it costly to break one. As a result, contact—something a hand is meant to handle—becomes something to avoid, which is counterintuitive.

In 2011, we discovered the universal jamming gripper [8] and the starfish gripper [24]. Suddenly, a whole new way of thinking about hands opened up. Pneumatic actuation was a game-changer. It allows us to decouple the control system (valves and compressors) from the actuators, enabling quick replacement of broken actuators. In addition, silicone actuators are easy to manufacture. All we do is 3D-print a new mold, and we can change its design at will.

With this newfound flexibility, we began building. Over the past 15 years, we've created around 70 hands, sharing them with research groups and showcasing them at exhibitions. Each time we built a new hand, the hardware continuously improved. Every student joining the lab gets their own hand (and most often builds it), which has shifted our mindset. We no longer fear breaking the hand. Instead, we embrace hardware failure as an opportunity to improve the system. In the language of Emergent Innovation [33]: By building pneumatically actuated hands out of silicone, we can quickly prototype and, therefore, efficiently obtain a deeper understanding of our soft manipulation system.

2.11 Dare to Change Everything

When the new PhD cohort joined the RBO lab in 2019, the outgoing group, which had been working on soft manipulation, was beginning to hand over their projects. At first, they assumed they would simply inherit the existing version of the robotic hand and develop software solutions for manipulation tasks. They were afraid to change the hand design because they were unfamiliar with hardware development and were trained in machine learning and control.

But that assumption did not last long. As the students started working with the hand, it became clear that real progress could not come from treating the hardware as fixed. They quickly found themselves getting hands-on with every part of the stack—improving the low-level pneumatic control, making the manufacturing of actuators more reproducible, enhancing the design of the hand for easy and quick assembly, and even changing the kinematics of the hand. The hand is far from perfect, and there was and still is much room for improvement.

Daring to change everything is essential for a successful co-design project, where every part of the system must be open to change. While this might seem daunting initially, it pays off in the long run by providing the deep understanding of every aspect of the hand needed to truly engage in an Emergent Innovation process [33]. Otherwise, you risk being limited by artificially imposed, unnecessary constraints, like those of traditional robotics that focus narrowly on the control aspect and disregard the body's capabilities.

3 Conclusion

We have shared our experiences with orchestrating the role of the body and control through a real-world co-design process in the context of robotic in-hand manipulation and grasping. Our findings demonstrate that simple control can lead to remarkably general behaviors when making appropriate hardware choices, which starkly contrasts with how current deep learning approaches achieve generalization [3, 9, 36]. This new paradigm calls for us to be generalists. While this perspective is not new—robotics was interdisciplinary in its early days [7]—it had become more compartmentalized over time. We encourage future roboticists to embrace co-design, thoughtfully distributing responsibilities between a robot's body and its controls to unlock simple, general, and robust robots.

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