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Soft Hands for Reliable Grasping Strategies

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Summary. Recent insights into human grasping show that humans exploit constraints to reduce uncertainty and reject disturbances during grasping. We propose to transfer this principle to robots and build robust and reliable grasping strategies from interactions with environmental constraints. To make implementation easy, hand hardware has to provide compliance, low inertia, low reaction delays and robustness to collision. Pneumatic continuum actuators such as PneuFlex actuators provide these properties. Additionally they are easy to customize and cheap to manufacture. We present an anthropomorphic hand built with PneuFlex actuators and demonstrate the ease of implementing a robust multi-stage grasping strategy relying on environmental constraints.

Humans are very proficient graspers. In fact, humans grasp so reliably and robustly that experimenters usually assess grasp difficulty by execution speed instead of error rate. For autonomous robots, on the other hand, comparably robust and reliable grasping and manipulation remains an open challenge, despite well established theories for assessing the quality of a grasp [Prattichizzo and Trinkle, 2008, Gabiccini et al., 2013]. Recent studies of human grasping indicate a plausible reason for the difference in human and robot performance. Deimel et al. [2014] and Kazemi et al. [2014] showed that humans interact more with the environment if their vision is impaired (occluded or blurred). To maintain grasp reliability, humans seek contact to counteract uncertainty. We believe that they use available constraints to guide the motion of their hands and fingers to make the execution reliable and robust. The interactions can be terminated by sensing simple events, such as a stop of motion, or sensing contact. By concatenating those interactions, humans can draw from a rich repertoire of reliable grasping strategies for each situation. Our hypothesis shares many ideas with sensorless manipulation proposed by Mason [1985] and Erdmann and Mason [1988], in fact our hypothesis can be seen as a continuation of this work.

To be able to transfer the principle of exploiting constraints successfully to robots, the hardware needs to facilitate easy implementation. Accurately enacting joints torques or angles is less important than making collisions simple, stable, fast and safe. While classical hand designs (see Controzzi et al. [2014] for an overview) can provide the required behavior to some degree, hands such as the Pisa/IIT Soft Hand [Catalano et al., 2014], or the iHY hand [Odhner et al., 2014] are suited much better to this task. These hands provide desirable features with elastomer based or dislocatable joints, but are otherwise based on rigid links. The earliest gripper design with a large number of compliant joints is the soft gripper by Hirose and Umetani [1978], which was able to grasp prismatic objects with widely varying shapes. With the RBO Hand [Deimel and Brock, 2013] and its successor RBO Hand 2 [Deimel and Brock, 2014], we go one step further and investigate the opportunities and limits of a literally soft hand. To explore the design space, we developed a method for creating customizable, soft continuum actuators, inspired by the work of Ilievski et al. [2011]. The positive pressure gripper [Amend et al., 2012] uses a balloon filled with granular material to provide ultimate adaptability to object shape, but its homogeneous structure limits the availability of diverse grasping strategies.

In the following section we will present a selection of interactions that can be used as building blocks for constraint exploiting grasping strategies. From those interactions we will extract desired hardware features that simplify their implementation and present the PneuFlex actuators and the RBO Hand 2 that realizes these features. We will demonstrate the feasibility of our approach by implementing an example grasping strategy using the RBO Hand 2.

1.1 Exploiting Constraints

Our main hypothesis is that competent grasping and manipulation is enabled by actions that exploit the ability of environmental constraints to reduce uncertainty about certain state variables, specifically those that are relevant for the success of subsequent manipulation actions. For example, contact with a surface can reduce uncertainty about distances and orientations between two or more objects. This enables us to execute sequences of actions with a reliable outcome. In many typical situations, the table surface provides such a constraint.

The actions that exploit constraints relate to interactions between hand, object and environmental constraints. Hand morphology and end effector control also determine which interactions are possible. Therefore, hand design should be guided by a description of desirable actions on commonly encountered constraints and should facilitate easy implementation of control. We will now present three examples of interactions between hand, constraint and object to grasp. As we will see in the subsequent sections, implementing control of these interactions is easy with a soft, compliant hand.

The first interaction we consider is to collide with a surface (see Figure 1.1). The collision path can e.g. be guided by visual servoing. This interaction makes the distance between the two colliding objects very certain. To be able to implement this interaction easily, the hand must limit impact forces and be able to react to disturbances quickly.

In a special case, the object to grasp itself provides the constraining surface. Compliant actuation of each joint then makes it easy to establish many contact points on the object and to balance contact forces to achieve a grasp [Dollar and Howe, 2010, Deimel and Brock, 2013, 2014].

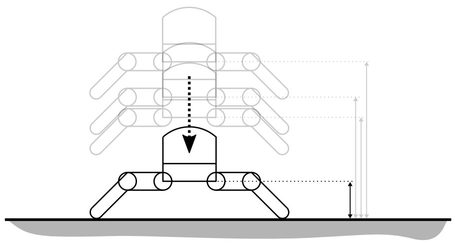

Fig. 1.1. Two objects can be positioned relative to each other by using compliant collision.

The second interaction we consider is to slide fingers and object along a surface and is shown in Figure 1.2. This interaction fixates motion along the surface normal and rotation out of plane, which in turn simplifies the control of finger position and hence object position. For most reliable execution, the fingers should always stay in contact with the constraint during the sliding motion.

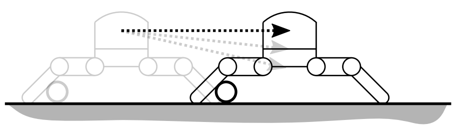

Fig. 1.2. Staying in contact simplifies motion control.

The third interaction we consider is closing a cage around an object that was previously formed with the hand and a surface (see Figure 1.3). By sliding the contacts between surface and fingertips, the cage gets smaller while at the same time an enclosed object cannot escape the cage. That effectively reduces the uncertainty about object location. For maintaining the cage, the fingers should continuously stay in contact with the surface. Additionally, the cage itself can also reject disturbances that concurrent manipulation, such as sliding, may introduce otherwise. This makes caging a very useful interaction in a grasping strategy.

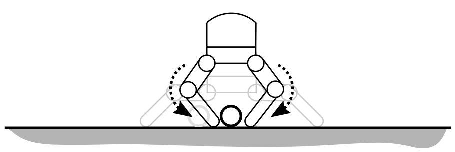

Fig. 1.3. Reducing uncertainty by closing a cage.

The list of possible constraint exploiting interactions here is not comprehensive. Grasping strategies may also include intermittent servoing to be able to concatenate interactions, but should be avoided as they lower reliability of execution.

1.2 Requirements to Hardware

Guidance by constraints – which was explained in the previous section – can be used to reject uncertainties from perception and reject anticipated disturbances arising from actuation. In the best case, this results in a fixed sequence of interactions that yields a predictable outcome in many situations. While better perception reduces uncertainty about the state of the world too, using constraints also simplifies planning. A planner that constructs these strategies will greatly benefit from a large and diverse set of interactions to choose from, therefore manipulator hardware should facilitate as many different interactions as possible. Additionally, this approach frees up perceptual resources for other tasks. From this problem description, we can extract a set of goals for hand design:

Low Inertia

Movable parts of the robot should exhibit a low apparent inertia. It enables reaction to fast changes in contact location and limits the energy transferred upon impact. The former makes it easy to maintain contact, while the latter limits the increase of uncertainty to position and orientation of the contacted object.

No Reaction Delay

Actuation should provide a very low time delay for reactive motion to stay compliant during fast disturbances. This requirement is especially difficult to achieve when actively controlling compliance, e.g. with geared electric motors.

Robustness to Arbitrary Collisions

The hardware has to be robust against arbitrary collisions. The robot needs to contact objects of unknown shape and position frequently and quickly, without having full or accurate knowledge of the world. Errors will happen, and therefore unexpected collisions will occur. A suitable hardware will tolerate these collisions and not break. Robustness can be accomplished by providing compliance in every direction and about many rotation axes.

Safe for the Environment

To a lesser extent, it is also desirable for the manipulator to generally not break or injure objects. If safety to the environment can be ensured by passive, mechanical means, more actions can be tried without risking catastrophic damage. This requirement also facilitates autonomous learning.

1.3 PneuFlex Actuators

To build literally soft hands, we developed a process to create customizable, mechanically compliant, and pneumatically actuated continuum actuators. An example actuator is shown in Fig. 1.4. These so called PneuFlex actuators bend with an

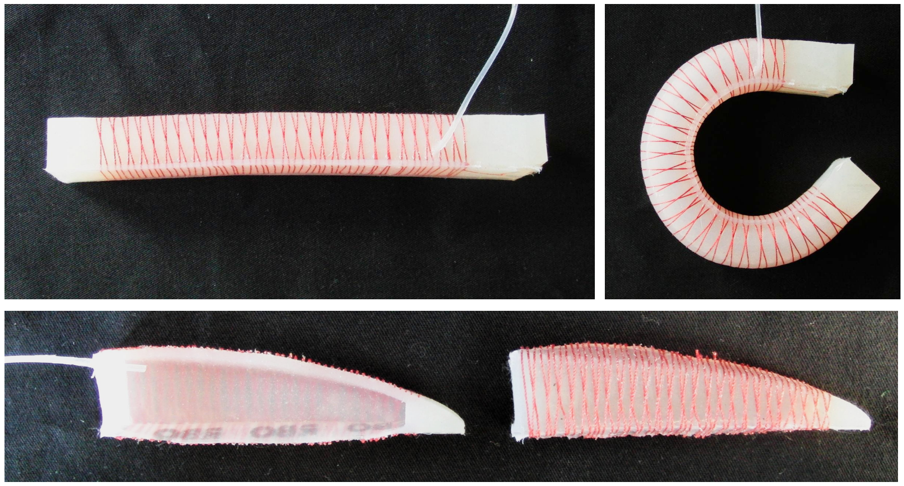

Fig. 1.4. A PneuFlex actuator in deflated and inflated state, and a cross cut of an actuator used as a finger, revealing its inner structure

approximately constant ratio of curvature per pressure [Deimel and Brock, 2013], and have a fixed stiffness.

The actuator is made of silicone rubber and forms a closed air chamber. A thin silicone tube is inserted into the actuator at a convenient position to inflate and deflate the actuator. The actuator is restricted from expanding radially by the thread wound helically around it. Additionally, the bottom side of the actuator embeds a flexible mesh, making it inextensible. Polyester (PET) is used as the fiber material throughout, as it is readily available and easy to handle. The manufacturing method is openly documented[1] to facilitate reuse and application by independent research.

The actuation ratio (curvature w.r.t. applied pressure) and actuator stiffness (change of curvature w.r.t. change of moment) can be customized with the cross section geometry. PneuFlex actuators are manufactured using printed molds, which greatly simplifies customizing and replicating actuators. The required materials are cheap, encouraging a Rapid Prototyping work flow for exploring design space.

The PneuFlex actuators enables us to build hands that have the properties we require for exploiting constraints. The actuation method ensures very low inertia, which is complemented by local deformation of the rubber body. The fingers provide high quality compliant actuation, and are able to comply to collision forces from any direction. The rubber used (SmoothOn DragonSkin brand) offers high tear strength and large strains, making it very robust. The attainable contact pressures are limited, which makes the hand passively safe for direct interaction with humans.

[1] `http://www.robotics.tu-berlin.de/index.php?id=pneuflex_tutorial`

1.4 Anthropomorphic Soft Hand Prototype

The RBO Hand 2 (see Figure 1.5) is the latest in a series of experimental prototypes and the first anthropomorphic soft hand. Its capability for diverse grasp postures is detailed in Deimel and Brock [2014]. The hand is built from seven actuators, five for each finger including thumb, and two forming the palm and providing a dexterous thumb. The compliance and robustness of its PneuFlex actuators is complemented by the flexible polyamide scaffold (see Figure 1.6). The design avoids stiff structures where collisions are probable while providing a rigid connection to the wrist of a conventional robot arm. The individual struts are stabilized by a flexible palmar sheet connecting the fingers and palm actuators. As the scaffold is manufactured with selective laser sintering, we can also easily integrate other function such as structures to distribute air from control channels to individual actuators. The pervasive compliance, robustness to collision and limited contact pressures of the RBO Hand 2 make contact with constraints easy to control.

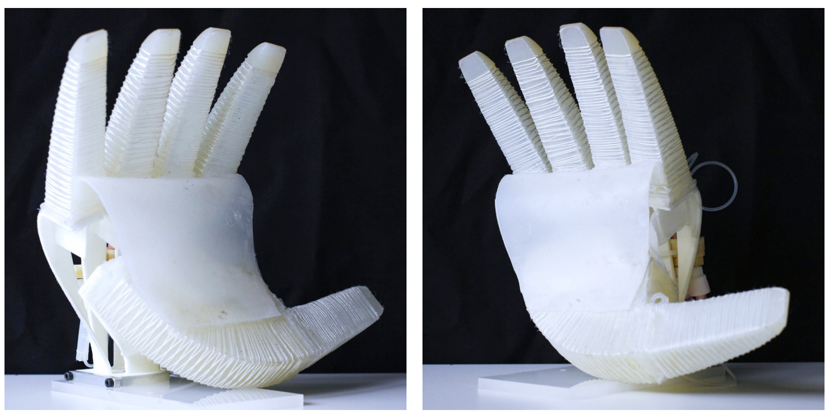

Fig. 1.5. First prototype of a soft, anthropomorphic hand for exploring the capabilities of soft hands.

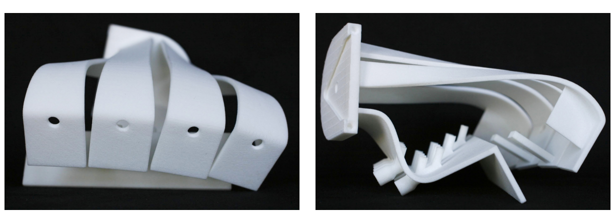

Fig. 1.6. Top and side view of the printed polyamide scaffold.

1.5 Example Implementation of a Grasping Strategy

To demonstrate the simplicity of implementing interactions with constraints using the RBO Hand 2, we explain the creation of an example grasping strategy. Figure 1.7 shows the execution of a strategy we will refer to as slide-to-wall-grasp. The implementation uses an RBO Hand 2 and a Meka robot arm. The environment provides a horizontal surface and a wall whose inclination can be modified. First, the robot moves the hand until the fingertips contact the table surface. It then slides the fingers across the horizontal surface towards the corner. In the corner, the robot rotates the fingers around their tips and slides them under the object to grasp. After that, the hand again is rotated around the fingertips while slightly flexing the fingers to cage the object against the wall, and to bring the fingers into the position for the final step: The object is grasped by flexing the fingers while dragging them upwards along the wall.

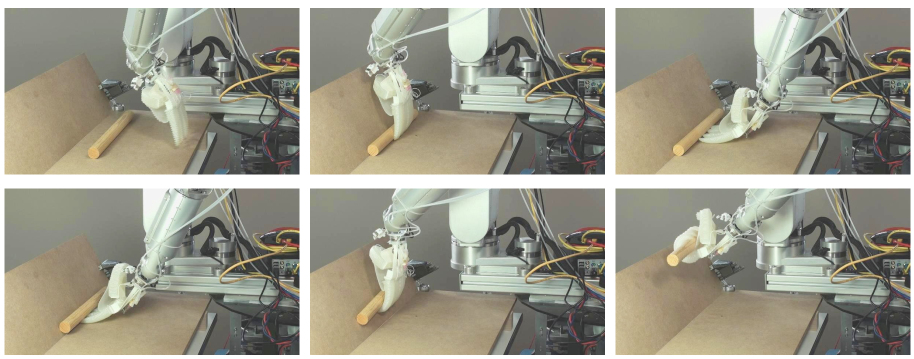

Fig. 1.7. Slide-to-wall grasping strategy.

Figure 1.8 shows the probability of success when picking a cylinder with 22 mm diameter. The experiment tested at $40°, 45°, 50°, 60°, 70°, 80°, 85°$, and $90°$ wall inclination. The grasp reliably works at $60°$, but the strategy still succeeds when deviating up to $15°$. This result indicates a robustness against variation in the environment, which is a stated goal of the grasping strategy.

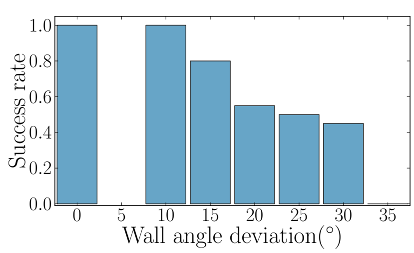

Fig. 1.8. Data indicating the robustness of the grasping strategy with respect to changes of the environment. Angles were first tested in $10°$ increments, intermediate angles where success changes rapidly were tested additionally to increase resolution. The wall inclination was varied from the initial configuration of $60°$, each angle was tested 10 times.

1.5.1 Used Interactions

The grasping strategy uses several interactions at various phases to reduce uncertainty or reject disturbances. Here, we will restrict ourselves to analyzing an example for each of the interactions explained in Section 1.1.

Figure 1.9 shows the hand sliding along the table surface. In the first phase (first two images), the compliant fingertips are used to contact the horizontal table surface. As the fingertips are compliant, the arm does not need to stop in an accurate position. Also, approach direction is not critical, as long as it is well within the friction cone of the finger contact. The collision can be done relatively quick too, as the arm's inertia is decoupled from the contact by the compliant, soft fingers. This makes implementation of this interaction simple.

For reliably sliding small objects across the table, as illustrated by third and fourth image in Figure 1.9, we have to ensure that the fingertips move as low as possible, which can be done by keeping them in contact with the table. This is accomplished by the compliant fingers and greatly reduces the accuracy requirements for the wrist trajectory compared to a hand with few or stiff joints.

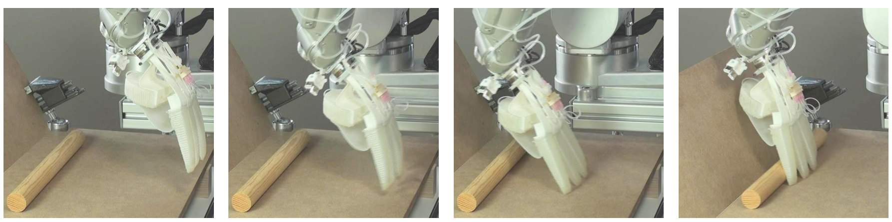

Fig. 1.9. Using the flat surface to vertically align fingertips prior to and during sliding a cylinder into the corner.

Closing of a cage is done in the final stage of the grasp, where the object is first caged against the wall (see Figure 1.10). The cage ensures that the cylinder reliably ends up between palm and closing fingers, while at the same time it also rejects disturbances in the cylinder's orientation that are caused by not grasping it at exactly its center of mass. The compliance of the fingers – and the palm – is enough to handle a deviation of wall inclination of at least 15° as shown in the experimental results in Figure 1.8. Accurate knowledge of wall orientation is therefore not necessary for reliable execution.

The example in this section shows that constraints can be used for creating robust, multi-stage grasping strategies, and that the interactions can readily be implemented with simple joint controllers of limited accuracy when errors are compensated by the compliant end effector.

1.6 Limitations

Soft Robotics turns out to be a well suited technology to implement grasping strategies that utilize the environment. It is difficult today though, to create soft mecha-

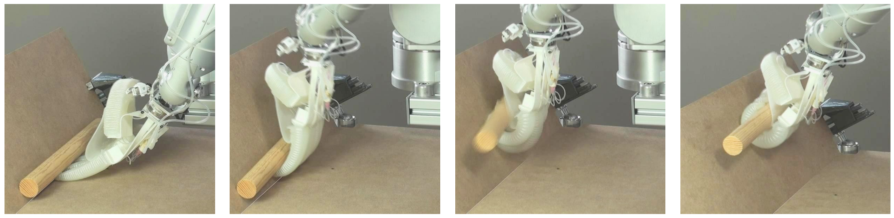

Fig. 1.10. Caging during of the slide-to-wall grasp strategy.

nisms that are as sophisticated as conventional rigid-bodied robots. This is due to the lack of established best practices for integration and off-the-shelf solutions for sensing, actuation, control, and modeling. The missing integration of sensing and actuation is especially unfortunate because soft structures may provide several of these function at once and this size and cost advantage is currently is not exploited to its full potential. Pneumatics are also more difficult to use for controlling forces than electromechanical systems. This is a severe restriction for many applications, but we believe that the ease of creating interactions with reliable outcomes outweighs this disadvantage for hands. A current limitation of PneuFlex actuators is their fixed stiffness, which indirectly limits the attainable strength of a grasp: The actuators can easily be made stronger, but they would simultaneously get less compliant too. Therefore, hand design would benefit from an actuator with variable stiffness. Finally, needles and sharp edges are able to damage the actuator. This disadvantage could be remedied by using cut-resistant gloves, or by following work safety rules designed for human manipulators. Also, the robot currently does not adapt grasping strategies or plan new ones to accommodate for a large variety of situations. Integration of a suitable perception, representation and planning with the actuation principle is an open issue requiring further research.

1.7 Discussion

Recent research on human grasping indicates that humans intentionally exploit environmental constraints, and that they do this to improve robustness and reliability of grasping under uncertainty and disturbance. We attempt to implement this principle on robots too, and for this we analyzed three example interactions that exploit constraints and can serve as components of robust example grasping strategies. These interactions were then used to formulated several beneficial design goals for hand hardware: low inertia, no reaction delay, robustness to arbitrary collisions, and safety to the environment. Soft Robotics technology offers these properties as we demonstrated by building the RBO Hand 2 and implementing a grasping strategy with it. In turn, grasping seems to be a promising reference application to drive the development of Soft Robotics, as it strongly benefits from compliance and many passive joints. The manufacturing process developed to rapidly prototype soft hands may also help in other research areas.

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