Towards an objective evaluation of underactuated gripper designs

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Abstract—In this paper we explore state-of-the-art underactuated, compliant robot gripper designs through looking at their performance on a generic grasping task. Starting from a state of the art open gripper design, we propose design modifications, and importantly, evaluate all designs on a grasping experiment involving a selection of objects resulting in 3600 object-gripper interactions. Interested in non-planned grasping but rather on a design’s generic performance, we explore the influence of object shape, pose and orientation relative to the gripper and its finger number and configuration. Using open-loop grasps we achieved up to 75% success rate over our trials. The results indicate and support that under motion constraints and uncertainties and without involving grasp planning, a 2-fingered underactuated compliant hand outperforms higher multi-fingered configurations. To our knowledge this is the first extended objective comparison of various multi-fingered underactuated hand designs under generic grasping conditions.

I. INTRODUCTION

Robotic platforms requiring to interact with objects have made use of a wide range of end-effectors. From parallel-jaw grippers and simplified multifingered hands to highly articulated humanoid hands remain among the most widely used.

In spite of numerous advances in the development of general purpose robotic hands, most of the designs are based on designers’ assumptions and pre-conceptions which are often hard to verify when the system is implemented in a real robot; among other problems this translates in developments struggling to receive wider acceptance among researchers. In the specific case of robot hands, these are often designed by starting with a high-level organizing principle that defines the hands main features. An example of this are the anthropomorphic hands, which are based on the idea that by reproducing a human hand the robot will be able to perform human tasks. Another example are the designs which build-up upon strong mathematical principles using parameters such as force, workspace or contact area.

Although some systems have achieved impressive results in specific circumstances, there is always the issue of balancing design complexity, generality and or performance. Intuitively, an increased number of fingers offers a higher number of contact points which can arguably lead to a more robust grasp; however, it usually comes with an increased control complexity and high manufacturing cost. On the other hand, reducing the number of fingers or degrees of freedom brings lower complexity and relatively lower cost, with the downside of possibly reducing the dexterity of the system or limiting the objects that the hand can grasp.

Until recent years, robotic grasping was dominated by analytic approaches that took into account simplified 3D object models, complex dynamics, contact-point information, etc. that allowed to compute high quality or optimal grasp configurations for diverse objects [1]. On the other hand, many recent approaches have used a different approach where the grasp synthesis rely on sampling candidates for and object, ranking them according to a specific metric using grasp experience generated through demonstrations, trial and error, labeled data and heuristics [2].

As can be seen in [1], [3], [4], [5], most state-of-the-art robotic grasping approaches make use of quality metrics that require information such as hand joint positions, applied forces/torques and contact points. On the contrary, real robotic systems often face challenging situations which include uncertainties in several aspects of the grasping task. In this type of scenario it is often not possible to compute a reliable grasp metric; instead, a metric based on the performance of the grasp results more suitable. While the most recent commercially available robotic hands have plenty of sensors to provide all sorts of information, these hands result expensive and require complex control algorithms.

In response to these challenging issues, underactuated hands offer the advantage of requiring less actuators to control degrees of freedom, having a lower complexity and in most cases a low manufacturing cost. Moreover, adding compliance to an underactuated hand offers advantages for working under uncertainty as joint positions do not need to be exactly known. Research has focused on the use of design parameters like: limits of the exerted forces, configuration of the workspace, degrees of freedom and anthropomorphism. Whereas these have proved to work to certain degree, one can also note that most usually they are tested using reduced object sets or larger sets containing multiple objects of the
same classes. Designs are usually put to test in a proof-of-concept setup rather than an extended scenario showing the variety and amount of objects that the device can actually grasp.

In this paper, we carried out experiments to investigate the grasping behaviour and performance of an underactuated compliant hand using different finger configurations in a setup comprising of shelves in 3 levels. The experiment allowed to evaluate and compare the performance of the grasps using objects with variable geometries and sizes, and how this performance is affected when the number and configuration of fingers is changed. All of this with an extensive number of grasp trials. To the best of our knowledge there has not been a study that investigates underactuated grasping behaviour in this fashion.

The paper is organized as follows: Section II describes the compliant approach to robotic grasp. Section III describes the robotic setup and experimental results of our study. Finally, Section IV summarizes our findings and Section VI our conclusions.

II. BACKGROUND

A. Underactuation and Compliance in robotic grasping

Underactuated compliant hands leverage passive mechanisms and joint coupling to reduce the number of actuators required to achieve robust grasps. This reduction in the actuation comes with the benefits of decreasing cost and improving planning efficiency. As stated before, there is always the trade-off among cost, complexity and effectiveness when it comes to choosing the end effector in robotic grasping applications. Designing this type of hand typically involves some initial choices involving numbers and arrangements of fingers, types of actuators, etc. followed by parametric variations of finger lengths, transitions ratios, joint angles, often seeking to optimize the hand using a standard grasping metric [6], [7], [8], [9].

Recent efforts attempting to join underactuation with compliance in the hand mechanics have allowed to further simply topologies of robotic hand actuation, at the same time affording passive adaptation to unstructured settings and providing robustness against sensing uncertainties [6], [10], [11], [12]. In this way, robot hands have increased robustness to unexpected collisions with obstacles or unplanned contacts while grasping objects.

Compliant underactuated hands have thus prompted a wide variety of designs e.g. [13], [12], [14], [10], [6], most of which show remarkable results in being able to grab unknown objects robustly.

Dollar and Howe [6], presented the SDM Hand, a 4-fingered hand capable of grasping objects of regular geometries such as prism, cylinders and spheres. In [12], [9], 3 and 4-fingered hands are introduced, both of them with complex actuation and sensory systems designed to met the DARPA ARM-H challenge requirements; therefore, they are intended to perform well defined tasks and grab specific classes of objects. [15] introduces a hand design for precision grasp and manipulation of small objects placed in a table. Inspired by [6], Zisimatos et al. in [14] developed a “general purpose” robotic hand with some important advantages such as modularity, low cost and low weight; however, only preliminary results are reported.

We chose to follow the open design proposed in [14], which represents a good trade-off between cost, complexity and ability to grab objects. A few modifications are introduced in order to adapt such prototype to our requirements and to further test the grasp reliability, these are detailed in Section IV. The hand design used for this study is shown in Fig. I. Briefly speaking, this design has the following characteristics: i)compliant flexure joints, ii) modular basis with multiple slots, iii) differential disk mechanism (underactuation), iv) low cost parts and v) cable driven actuation.

B. Metrics and Performance

When assessing the grasp performance or quality of a robotic system, evaluation metrics usually fall into two broad categories: location of the contact points on the object and hand configuration. These metrics take into account properties such as disturbance resistance, dexterity, equilibrium and stability. In essence, given an object and a hand there are many possible grasps that satisfy a desired goal, an optimal grasp is chosen using a quality metric that measures the goodness of that grasp. However, most of the widely accepted metrics assume fully actuated multifinger hands, very few of them have been adapted or developed for underactuated hands [1]. And methods intended to optimize underactuated grasping [7], [9], are based on metrics that assume a well defined contact model and optimized through simulations. When the hands are built, designs are tested against prototypical objects such as cylinders or prisms [6], [10], [12] or by measuring the pulling force that the hand is able to resist [12], [9], [8]. In general, robot grasp planning and automatic generation of grasps has been done using performance metrics not stable when applied to real environments; this makes it difficult to reproduce the planned grasp configuration with a real robot hand, making the quality evaluation less useful in reality.

When considering compliance into the grasp performance measure the outlook remains somewhat the same. Researchers have adopted simplified 2D models [11], [16], [8], [10], simulations [17], [18] or a combination of them. Other works have used mathematical models that take into account stiffness matrices, rigid body models, friction coefficients and contact models. All of these studies apply, to some extent, standard grasp metrics in order to evaluate algorithms and hand designs.

Due to the fact that most hand designs make use of kinematic models and contact-based or wrench-space metrics, it has been showed that a higher number of fingers provide more stable and reliable grasps. This can be seen on earlier studies [19], where the necessary condition to stable grasp are deducted. This kind of analysis is based in concepts as form closure and force closure, where the grasp hold by the multifingered hand can cancel external wrenches applied.
to the object, either using finger positions (form-closure) or forces (force-closure). In spite of this, state-of-art robotic grasping approaches have made use of a wide spectrum of devices, from 2-finger grippers up to highly articulated 5-fingered hands.

We focus on studying the performance of grasps achieved in a real, non-simulation-based setting, involving uncertainties in object pose and modifying the number of fingers (contact points) involved in the grasp. We believe that before moving to grasping algorithms that add further intelligence when trying to grab objects, we must make sure of using a device that actually can grab most objects. For that matter, we investigate the performance of the state-of-the-art robotic hand described in Section III; using a setup of what we believe approaches a commonly occurring real robotic scenario: a multi-level shelf object picking task. Furthermore, since we want to measure to what extent the hand is able to grasp objects “by itself”, we have reduced the degrees of freedom for hand/wrist placement and conducted open-loop grasp experiments. In this way, we could evaluate the grasping performance prior to any intelligence or grasp planning algorithm.

III. HAND DESIGN

The hand design implemented for this study is based on the model introduced by [14]. A few modifications have been made in order to adapt this hand to our framework. As first modification, the actuator was removed from the end-effector module. Instead, the motor is translated to the centre of mass of the entire tool, adding a pulley system and using a cable driven actuation principle. In this way we can balance the prototype and reduce the weight/load located at the end effector. Having a light-weight end-effector potentially allows us to work with heavier objects reducing torques on the rest of the structure. The design and construction shares elements from [14]. The hand palm plate, differential disk and finger phalanges are 3D printed. The finger joints are made of silicone and the system is assembled together using plastic fasteners to further decrease the hand weight.

A further addition to the design is the inclusion of a new palm plate set, this includes 2 new finger configurations: a cylindrical configuration with two fingers opposing a third one, and a cylindrical configuration with four fingers (two opposite pairs) forming a rather spherical grasp. The finger configurations tested in this study are shown in Fig. 2. To clarify the difference among the configuration of the fingers Fig. 3 depicts the hands in top-view, with annotated angles between the fingers.

Using the aforementioned design we explore the diversity of objects and poses in which different finger configurations are able to obtain a successful grasp. Furthermore, with the experimental procedure employed we are able to gain insight about which hand configuration performs best according to an object’s geometry and pose. In the next section we describe our experiment setup.

IV. EXPERIMENTAL PROCEDURE

The grasping experiments were carried out using 12 distinct household objects (Fig. 4) and placed on one of three different heights; changing in this way the approaching angle to execute the grasp. The set of objects comprises of: stapler, pen marker, memory stick, mug, bottle, tape roll, screwdriver, medicine pill box, joystick, computer mouse, soda can and a bean bag.

The device is fixed to a tripod that allows to adjust and fix the approaching angle/height of the grasp in a repeatable and controlled fashion. The tripod’s plate is set at 30 cm height...
and the three “shelves” are located at 0, 30 and 60 cm. Fig. 5 depicts the experiment setup.

![Experiment Setup](image)

Fig. 5. Grasping task setup. The hand is mounted on a tripod and objects are placed at three different heights (shelves).

With this setup, the experiment consisted in placing all objects (one at a time) in 5 different orientations on each “shelf” level and attempt grasps with each of the four hand configurations. A total of 720 combinations are obtained, performing 5 trials for each combination to obtain a success rate, these parameters are listed in Table I. Each attempt was counted as successful if the hand was able to keep grasp of the object when the arm raised from the shelf level and the grip held the grasp for 15 seconds. The accompanying video shows the hand designs, setup and tests used and Fig. 4 shows the objects considered for the experiment.

![Table I](image)

**Table I**

| Parameter          | Min Value | Max Value | Samples |
|--------------------|-----------|-----------|---------|
| Orientation [degrees] | 0         | 359       | 5       |
| Fingers            | 2         | 4         | 4       |
| Shelf height [cm]  | 0         | 60        | 3       |
| Object             | -         | -         | 12      |

**V. RESULTS AND DISCUSSION**

Fig. 6 shows the success rate of the four hand configurations tested. Each plot includes error bars showing the variance of the success rate according to shelf level, object and object orientation respectively. Somewhat surprising is that the best performance is achieved with the 2-fingered hand which achieves an overall 75% success rate. On the other hand, the worst performance is observed by the 4-fingered hands with a slight improvement in model II of this configuration.

Looking at this data, we can see that for the average performance across shelf levels the 2 and 3-fingered hands presents the highest variance ($\sigma = .17$) which makes difficult to note a difference between their performance. In contrast, both 4-fingered hands show low success rates and little variance which confirms the poor behaviour observed in most cases during the experiments. A first comparison can be made using these values, for instance there appears to be a notorious difference (25% on average) between 2-fingers and both 4-fingered hands; not so between 2 and 3-fingered or between both 4-fingered hands.

Fig. 6(C) reflects a different scenario, where 2 and 3-fingered hands seemed less sensitive to changes in the orientation in contrast to the 4-fingered configurations. No important difference is noted between the latter pair or between these and the 3-fingered configuration. However, the 2-fingered hand shows a noticeable performance difference. From the plot can be seen that all the success rates are more than one standard deviation away from the 2-fingered score.

Regarding the average performance of the hand configuration across the different objects there is no significant difference (big overlap in error bars). Whereas the 2-fingered hand seems to perform better on average, it has a large error ($\sigma = .23$).

A multivariate logistic regression was fitted to assess the significance of these results. Tab. II shows the outcome of this process. Here can be seen the relevance of the parameters involved in the grasping task. The null hypothesis is that the probability of a successful grasp is not associated with the value of the parameters (hand configuration, object, shelf level, orientation).

Using the information from the table we can reject the null hypothesis for all the parameters except for the type of object being grasped; which as seen in Fig 6(R) presents wider variance. In other words, the grasping success related to shelf level and orientations changes is statistically significant to select a hand superior to the rest. In contrast, the information from object types shows no statistical proof to say that a hand works best for every type of object.

![Table II](image)

**Table II**

| Estimate | Std. Error | z value | Pr(>|z|) |
|----------|------------|---------|----------|
| (Intercept) | 22.8296 | 755.3303 | 0.03 | 0.9759 |
| Hand 2 | -1.2845 | 0.3037 | -4.23 | 0.0000*** |
| Hand 3 | -2.5779 | 0.3422 | -7.53 | 0.0000*** |
| Hand 4 | -2.3535 | 0.3324 | -7.08 | 0.0000*** |
| Shelf 0 | -19.3707 | 755.3302 | 0.03 | 0.9795 |
| Shelf 30 cm | -14.3254 | 755.3308 | -0.02 | 0.9849 |
| Shelf 60 cm | -0.0584 | 1068.2704 | -0.00 | 1.0000 |
| Bottle | -19.4808 | 755.3302 | -0.03 | 0.9794 |
| Joystick | -21.6513 | 755.3305 | -0.03 | 0.9771 |
| Screwdriver | -19.4010 | 755.3302 | -0.03 | 0.9795 |
| Mouse | -19.8767 | 755.3302 | -0.03 | 0.9790 |
| Memory stick | -20.2534 | 755.3302 | -0.03 | 0.9786 |
| Mug | -14.3591 | 755.3308 | -0.02 | 0.9848 |
| Stapler | -19.9864 | 755.3302 | -0.03 | 0.9799 |
| Tape | -19.5005 | 755.3302 | -0.03 | 0.9794 |
| Shelf | -0.9448 | 0.1466 | -6.45 | 0.0000*** |
| Orientation | -0.0022 | 0.0011 | -1.94 | 0.0421 . |

**A. Hand posture**

The hand posture is associated to the shelf level in which the grasp is attempted, since a change in the height will be reflected in the angle (posture) in which the hand approaches the object. Fig. 7 shows the success rate of each hand
overall objects and orientations achieved at each shelf level in which the grab was attempted. For the low level shelf, similarities were noticed between the performance of the 2 and 3-fingered hand configurations, and between both 4-finger configurations. While the former pair achieved around 80% of successful grasp, the latter remained at around only 50%.

Concerning the middle level shelf, the 2-fingered and both of the hands with 4 fingers showed roughly the same performance with respect to the previous level. A more interesting result is observed in the 3-fingered hand, for which the success rate drops nearly 20% with relation to the previous shelf. Finally, the top level surface stood as the most challenging level to grasp objects. At this level all the hand configurations struggle to grab objects; while the two 4-fingered hands kept achieving low scores, the 2 and 3-fingered hands experienced a 20% drop respect to the success rate obtained in the previous level.

### B. Object pose

The experiments carried out also showed the variation in the grasping performance according to the objects pose. Fig. 8 details the success rate according to the object orientation, averaged along the three shelf levels. Again the 2-fingered hand achieves the highest success rate across all orientations. In an overall picture, all hands performed best when the object has an orientation closer to 0 and 180 degrees (object’s largest axis was perpendicular to the palm).

![Success rate across all levels](image1)

![Success rate across all orientations](image2)

![Success rate across all objects](image3)

Fig. 6. Success rate and variance averaged by shelf level (L), orientation (C) and object (R)

Fig. 7. Average success of all hand configurations according to shelf level where the grasp is attempted.

This plot shows that the worst outcome in all hand configurations is obtained at the top level surface. The reason of this low success rate was observed to be that many objects were out of reach for all configurations. Due to the angle in which the fingers were located at the start of the grasp, they fail to even touch the object. An example of this situation for the 2-fingered hand is shown in Fig. 12 which depicts a failed case when trying to grab a memory stick at the top-level shelf. Due to the constrained wrist posture small object generally were very few times grasped. While these conditions appear overly harsh, recall we are on purpose not considering any planning but rather interested to evaluate precisely performance in the absence of higher intelligence, or should it be relevant, when planning has great uncertainty.

Fig. 8. Average success per hand configuration according to the object orientation

The worst performance across all hands was obtained when the objects orientation was closer to 270 degrees. One might expect, as was the case in 0 and 180 degrees, a similar performance between 270 and 90 degrees; while 3 out 4 hands showed this expected behaviour, for the 2-fingered hand that was not the case. The difference in that performance (about 18%) is associated to the irregularities in the objects set shapes, strongly influenced by the performance at the top-level surface. Another important thing to notice is that the 3-fingered configuration remains as the most consistent along all orientations with a success rate around 60%, its variance was previously shown in Fig. 6.

An wider view of the results is shown in Fig. 9 which shows success rate for combinations of shelf level and object orientation. From these graphs it can be seen that the 2-fingered hand’s highest success rate was achieved at the low-level shelf with objects oriented around 90 degrees; while the worst performance resulted in a tie between the two 4-fingered hands on the mid-level shelf with objects at 270 degrees. Whereas the low performance does not results very surprising, the highest performance does. In fact, the four cases with the highest performance are observed when
grasping objects at 90 degrees. This is related to the fact that there are many objects with bladed shapes (flat and elongated), which have a significant difference between the two axis parallel to the shelf surface. When the longest axis is perpendicular to the hand palm (90 and 270 degrees in our experiments) it offers more contact possibilities when the grasp is attempted. Particularly, it often was observed during the experiments that one finger made contact with the object previously to the other(s), which made the object spin or move. The grasp results less sensitive to this effect when the fingers close along the object’s longest axis.

C. Performance by object

From previous subsection has been highlighted the large variance in the grasping performance due to the diversity of object’s shapes. Fig. 10 shows the success rate achieved by each object considered for the experiments. This performance was averaged across all hands; however, it gives insight into what happens when attempting to grasp the various objects.

It is curiously noted that objects usually employed in the robotic grasping literature for demonstrations e.g. soda can, bottle, mug and box, achieved in our experiments the highest success rates. This subset of objects is often considered when hand designs are tested and grasping algorithms proposed. As can be seen in Fig. 11 these objects did not represent a challenge for any of the hand configurations put to test, which often achieve a success rate above 80%. On the other hand, objects such as the screwdriver or the memory stick represent challenging situation in the majority of cases. We have included objects of different classes, sizes, geometries and weights which we believe is a better approximation of what can occur in a realistic environment. It is worth noticing that the score of the beanbag is within one standard deviation ($\sigma = 0.2$) from the average performance of the hand, more precisely 8% under the average which is not as low as expected, taking into account that this object is non-rigid or deformable.

As a final analysis we compared each hand using a statistical model in order to see the significance of the grasping parameters per hand. This approach is similar to the one applied to the complete grasping data in the first part of this section. Using logistic regression we can assess to what extent (statistically) the change in shelf level, type of object and orientation influence a successful grasp. Table III shows the $p$-values for the statistical significance of the parameters for each hand.

From Table III can be observed that for the 2 and 3-fingered hands the change in shelf levels is highly significant whereas for the 4-fingered one there is no significant proof of how the parameters affect the performance. In contrast, the second model of the 4-fingered hand seemed more sensitive to changes in the objects orientation. The difference among hands is more clear when these data is compared with the overall performance. For instance, the 4-fingered configurations show low (or none) statistical dependence on the task parameters but when taking into consideration their low performance conclusions can be made about the effectiveness of such designs. Similarly, statistical analysis shows that the 2 and 3-fingered success rates are actually related to the task parameters in similar ways ($p$-values); however when the overall performance is taken into account the 2-fingered design becomes superior most of the time.
VI. CONCLUSIONS

In the search for a multi-purpose end-effector we have evaluated variations of a state-of-the-art underactuated compliant hand. With the introduction of a few adaptations, it has been put to test using multiple finger configurations and an object set containing various types of objects; in what we believe is a common scenario for robotic grasping. While this type of hands have had success in performing grasp with "common" objects in the past, we have found that a general-purpose hand, remains elusive. However, we believe that the results obtained here raise interesting questions about hand design and performance evaluation. For instance, is the results obtained here raise interesting questions about general-purpose hand, remains elusive. However, we believe with "common" objects in the past, we have found that a this type of hands have had success in performing grasp believe is a common scenario for robotic grasping. While an object set containing various types of objects; in what we has been put to test using multiple finger configurations and pliant hand. With the introduction of a few adaptations, it evaluated variations of a state-of-the-art underactuated com-

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