Efficient Modular Grasping: an Iterative Approach

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***Abstract*— This paper introduces a new modular approach to robotic grasping that allows for finding a trade off between a simple gripper and more complex human like manipulators. The modular approach to robotic grasping aims to understand human grasping behavior in order to replicate grasping and skilled in-hand movements with an artificial hand using simple, robust, and flexible modules. In this work, the design of modular grasping devices capable of adapting to different requirements and situations is investigated. A novel algorithm that determines effective modular configurations to get efficient grasps of given objects is presented. The resulting modular configurations are able to perform effective grasps that a human would consider "stable". Related simulations were carried out to validate the efficiency of the algorithm. Preliminary results show the versatility of the modular approach in designing grippers.**

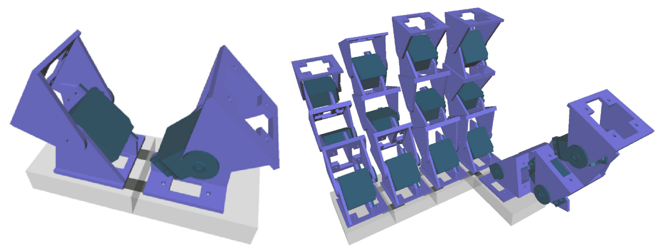

Fig. 1. The modular grasping idea: thanks to its flexibility, the device can reproduce both simple grippers and more sophisticated kinematics like anthropomorphic robotic hands.

I. INTRODUCTION

Bio-inspired robots and humanoid robots have been developed rapidly in recent years. The effort to mimic the human beings capabilities is becoming a very important challenge [1], [2]. One of the most challenging efforts in bio-inspired robotic research consists in mimicking the human hand's ability to perform very versatile and delicate grasping tasks. In spite of the great success of bio-robotics in mimicking certain human behavior patterns there is still a large gap between the performance of anthropomorphic robot hands and human hands. Human hands are capable of grasping an astounding variety of objects of different shapes, textures, weights and spatial orientations. Building a robotic hand with sufficient dexterity and multi degrees of freedom has become one of the most attractive steps in order for a robot to fully mimic the movement of the human hand. However, development of such hands is challenging because it is required to fit large number of degrees of freedom.

A possible solution consists in limiting the device to the minimum number of degrees of freedom necessary to accomplish the desired task. In [3], Cobos et al. analyzed the kinematic behavior of the human hand in order to obtain simplified human hand models with minimum and optimal degrees of freedom, and thus achieving an efficient manipulation task. The main disadvantage of this approach is that such simplified robotic hands are usually difficult to adapt to different grasping operations or to the grasping of objects with dissimilar size.

In the authors opinion, another promising approach to get such flexibility is to use a modular approach [4], [5]. The modular approach allows using only the necessary number of degrees of freedom to accomplish the grasp. In this way it is possible to find a trade off between a simple gripper and more complex human like manipulators. Moreover, great advantages are obtained in versatility since the robotic hand can be disassembled and reassembled to form new morphologies that are suitable for new tasks. Modularity offers also robustness considering that robot parts are interchangeable [6]. The production cost can also be considerably cut by building a specialised device capable of grasping objects by using only the number of actuators and DoFs required. Besides, the weight of the manipulator would be minimized to the bare necessities. This would be very useful in space applications where it is really important to reduce the weight of the device to be sent into space.

In this paper, a modular approach for designing a device that can adapt its structure to the object to grasp or to the task to fulfill is investigated. In other words, we define the guidelines for creating a device capable of adapting its structure and functionality to the characteristics of an object or a set of objects to be grasped. In doing this we want to respect the principle of minimalism: choose the simplest mechanical structure, the minimum number of actuators, the simplest set of sensors, etc., that will do the job, or class of jobs. We introduce the concept of *modular grasping* to indicate when identical modules are used to build linkages in order to realize the grasping functions. From a mechanical point of view, even if it is not the most efficient grasping approach, the modular grasping still

This work was partially supported by the European Commission with the Collaborative Project no. 248587, "THE Hand Embodied", within the FP7-ICT- 2009-4-2-1 program "Cognitive Systems and Robotics" and the Collaborative EU-Project "Hands.dvi" in the context of ECHORD (European Clearing House for Open Robotics Development).

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meets the requirements of standardization, modularization, extendibility and low cost. A "proof of concept" is showed in Fig. 1. The modules can be assembled to realize very dissimilar kinematic structures.

Usually the design of modular robot is either bio-inspired [7] or generated by optimization procedure as, for instance, genetic algorithms [8]. In this work, an iterative procedure for designing the structure of the modular grasping device is proposed. The main idea is to use a simulation tool to tests the grasps of an object obtained starting from a simple gripper configuration and adding modules until a certain value of grasp quality is achieved.

The paper is organized as follows. In Section 2, a review of the related research work is given. In Section 3, we focus on the description of the algorithm for modular gripper design. Section 4 presents the related simulations and the results obtained. The conclusion and future work are outlined in Section 5.

II. Related Research Work

Modularity in robotics is a well known concept. To the best of our knowledge, few works investigate the possibility of developing a modular gripper. In literature, some initial studies are related to the self-reconfigurable robots. Chen and Burdick [9] defined a generally applicable task related objective function which evaluates a modular robot assembly configuration for a given task. They used genetic algorithm as optimization method. In [10] a cellular robot capable of adapting its shape and functions to changing environments and demands by rearranging its mutual mechanical connection is presented. In [11], the authors proposed an algorithm for grasping objects with a self-reconfigurable system. Although the idea that a modular gripper can handle objects of unknown shape and size was pointed out, the work reported preliminary results still far from a real implementation. Yu and Nagpal [12] introduced a generalized distributed consensus framework for self-adaptation tasks in modular robotics demonstrating that a variety of modular robotic systems and tasks can be formulated within such a framework. The authors presented three main contributions: an adaptive column that can respond to external forces, a modular tetrahedral robot that can move towards a light source, and a modular gripper that can wrap around fragile objects. The decentralized control used in their work is based on the sharing of information about pressure given by sensors included in each module. This solution is not applicable when, for instance, fingertip manipulation is required. Furthermore, investigation on grasp stability is missed by the authors.

As well as the self-reconfigurable framework, the realization of modular grippers has been used in rapid prototyping and part holding problems. In [13], the design and techniques for part insertion into a non-assembly, multi-articulated, dexterous finger prototype built with stereo-lithography are presented. This solution permits a rapid development of robotic systems that have all the necessary components

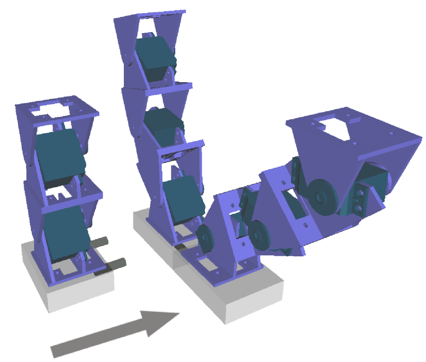

Fig. 2. Concept of modular base: each finger has its own base plate that can be connected to form the gripper base.

inserted, with no assembly required, and are ready to work when the manufacturing process is complete. However, the actuation and control of such a device is still an open problem. Alternatively, Brown and Brost [14] presented a modular vise which is a parallel-jaw vise, with a regular grid of precisely positioned holes on each jaw. Parts are held by placing pins in the holes so that when the vise is closed, the parts are reliably located and completely constrained. Even though the modular vise concept can be adapted to the design of modular parallel-jaw grippers for robots, no application to dexterous manipulation can be applied.

However, in our opinion, a modular organization of the device is one of the most promising ways to obtain flexible grippers and to solve some of the grasping problems in human environments and in the automation industry.

Our preliminary studies on using modular robots to perform object manipulation started by considering a simple hyper-redundant manipulator. Consequently, the possibility of developing a novel modular grasping approach that combines manipulation capability and locomotion mobility to implement possible tasks has been investigated. A snake-like configuration has been proposed which introduces a task priority approach to manage both grasping and locomotion capabilities [15]. Even if several robot configurations leading toward stable grasping have been outlined, the characteristics of snake-like robots are more suitable for Search and Rescue missions than for the manipulation of objects in human environments or industrial scenarios.

III. Modular Grasping Design Algorithm

In this section a new algorithm for modular grasping is presented for designing a flexible grasping device through an iterative procedure and considering human grasp quality values. In this preliminary study, the *Y1* modular robot [16] with one DoF has been used as the basic element for the modular device because of its versatility, robustness, low-cost and fast-prototyping features. In section IV, the possibility of using a different kind of module is discussed.

The modular gripper consists of one or more chains of modules fixed on a base. Referring to a human-like hand, each chain can be considered as a finger, each module as a phalanx and the base as a palm.

The concept of modularity is also applied to the base of the proposed device model. In particular, each finger is attached on its own base plate module. The base plate modules of the fingers can be connected together using their predefined slots and hooks to form a unique base as shown in Fig. 2.

Three possible modular base configurations have been defined as shown in Fig. 3:

- *linear base*: finger opposition is avoided;
- *circular base*: the fingers are placed equally distant in a circle configuration;
- *opposable-fingers base*: one or more fingers are set to be opposable to the others.

This is a heuristic of the proposed approach since these three kinds of modular bases do not cover all possible gripper configurations. However, they are able to describe the most significant grasp models mimicking the human hand taxonomy, which is presented in [17].

In the following, the main variables of the algorithm are introduced. Let $m(i)$ be the total number of modules used for the modular gripper at the i-th iteration. Note that the base modules are not considered in this count. Let M be the maximum number of modules per finger of the modular device. M is computed at the beginning of the algorithm and depends on the features of the module and of the object to grasp. In particular, a lower bound of M is defined as (1):

$$M_{min} = \left\lceil \frac{R}{L} \right\rceil, \qquad (1)$$

where R represents the radius of the minimum volume sphere that envelops the object to grasp and L is the length of one module. M_{min} takes into account the dimension of the object to grasp. An upper bound of M is computed considering the maximum motor torque that can be exerted on the module. We considered as worst case the finger completely outstretched. In this situation, the maximum torque τ_{max} of the module closest to the finger base has to overcome the moment due to the weight w of the whole finger as defined in (2):

$$\tau_{max} > \frac{LMw}{2} \quad \Longrightarrow \quad M_{max} = \left\lfloor \frac{2\tau_{max}}{Lw} \right\rfloor. \qquad (2)$$

Thereby, M is chosen as a trade-off between M_{min} and M_{max} during the initialization phase of the algorithm. Let $f_{min}(i)$ be the minimum number of fingers that must be considered in the device design to respect the limit M at the i-th iteration. The finger configuration can be denoted as (3):

$$\{x_1, x_2, ..., x_f\}, \qquad (3)$$

where $x_j \in \mathbb{N}$ represents the number of modules of the j-th finger and f is the total number of fingers.

The goal of the proposed iterative procedure is to obtain a modular configuration that reaches a prefixed performance in terms of grasp quality using the least amount of modules possible. An evaluation of the grasp quality is thus required. The computation of grasp quality indices is known in the literature [18]. In this paper, the quality criteria introduced by Ferrari and Canny [19] is used. However, other solutions can be implemented without varying the algorithm structure. Ferrari and Canny considered a measure of the radius of the largest inscribed sphere centered at the origin that is contained in the so called *Grasp Wrench Space* (GWS) as quality index. The GWS is the set of all wrenches that can be resisted by a grasp if unit contact forces are applied at the contact points and it is given by the convex hull of the elementary wrenches:

$$GWS = ConvexHull\left(\cup_{i=0}^{n}\{w_{i,1}, \ldots, w_{i,k}\}\right), \qquad (4)$$

where n is the number of contact points and k is the number of faces of the friction cone. The measure of the radius of the largest inscribed sphere centered at the origin that is contained in the *GWS* can be also seen as the magnitude of the largest worst-case disturbance wrench that can be resisted by a grasp with a unit strength grip. It will be hereafter denoted as Q, while the desired grasp quality will be denoted as $Q_{desired}$.

In the following, the algorithm is described. In the Algorithm 1 box the pseudo code is reported.

```
define TargetObject, Q_desired, M
define BaseConfigurations set
i = 0
m(i) = f_min(i) = 0
while true do
  i++
  m(i) = m(i-1) + 1
  f_min(i) = ⌈m/M⌉
  while FingersConfigurations.generateNext(m(i), f_min(i)) do
    CurrentFingersConfiguration = FingersConfigurations.next()
    CurrentBaseConfiguration.reset()
    while BaseConfigurations.hasNext() do
      CurrentBaseConfiguration = BaseConfigurations.next()
      CurrentModularConfiguration = ModularConfiguration.generate(CurrentFingersConfiguration, CurrentBaseConfiguration)
      Q_best = Planner.launch(CurrentModularConfiguration, TargetObject)
      if Q_best ⩾ Q_desire then
        return CurrentModularConfiguration
      end if
    end while
  end while
end while
```

Algorithm 1: Iterative procedure for the determination of gripper configurations.

The main iterative loop starts with the simplest modular configuration which consists of one finger with one module and one base plate. With each iteration, an additional module is added to increase the possible DoFs. The number of

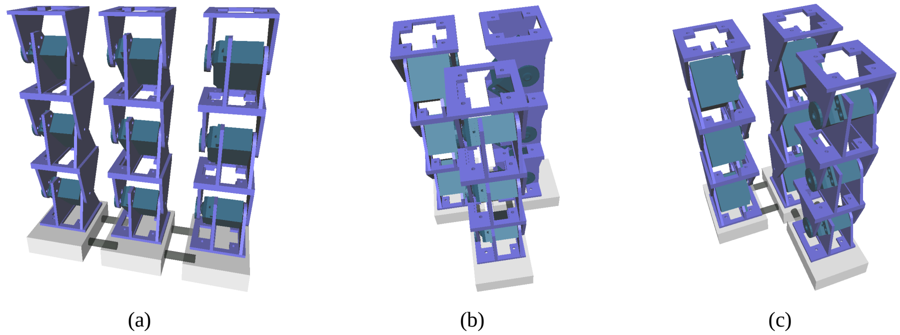

Fig. 3. Possible base configurations for a three fingers modular device: *no finger opposition* (a), *circular* (b) and 1-*opposable-thumbs* (c).

modules for each finger is then set selecting one among all the possible gripper configurations which can be obtained considering $m(i)$ modules. Consequently, a configuration for the modular base of the device is selected, depending on the number of fingers, among the set of all the predefined base configurations.

Once a configuration is generated, a grasp planner is used in order to find the best grasp achievable. If the corresponding grasp quality is less than $Q_{desired}$ and all the possible finger configurations and base configurations achievable with $m(i)$ modules have been tested, a new iteration begins and one more module is added.

In the following, the key steps of the algorithm are described.

A. Initialization of the algorithm

In this phase, the shape and the size of the $target object$ is set. The values of M and $Q_{desired}$ are assigned. $m(0)$ and $f_{min}(0)$ are initialised, $m(0) = f_{min}(0) = 1$.

B. Define base configurations

This step consists of defining the set of all the possible base configurations (*linear base*, *circular base*, *opposable-fingers base*). Note that other possible base configurations can be considered simply adding those in the predefined set.

C. Compute f_{min}

At each iteration a module is added, so $m(i) = m(i-1)+1$. The value of f_{min} has to be updated in order avoid the case of more than M modules per finger, so it can be defined as 5:

$$f_{min}(i) = \left\lceil \frac{m(i)}{M} \right\rceil . \tag{5}$$

Suppose that at iteration i, $m(i)$ is 3 and M is 3. The value of $f_{min}(i)$ is 1. At iteration $i+1$, $m(i+1)$ is 4 so $f_{min}(i+1)$ is 2. This guarantees that it is not possible to have a configuration with only one finger with four modules respecting the limit M.

D. Generate fingers configurations

In this step a new configuration of the gripper is generated. The algorithm does not generate all the configurations at the same time. Each configuration is tested and a new one is generated only if $Q_{best} < Q_{desidered}$. Otherwise the algorithm returns the current version. This approach avoids to test more configuration than those required.

E. Launch the grasp planner

A grasp planner is used to determine the grasp quality achievable with each configuration for the given object. In general, the grasp planning problem can be solved in either the forward or the backward direction. In particular, in the proposed implementation of the algorithm, we used a forward solution implemented using the grasp planning simulator *OpenRAVE* [20]. A grasp is simulated by setting an initial base position (pose) and initial joint angles (pre-shape) to the manipulator device. For each gripper configuration fifty pose and pre-shapes are tested. Then, for each of them, the approach phase is realized by moving the device along the normal to the palm plane until it hits the target object. Hence, the fingers of the gripper close around the object until they can not close any more. The contacts between the device and the object are extracted, and the grasp quality index is calculated.

By the end of this step, the best grasp which can be obtained with the current configuration is returned together with the corresponding initial base position.

Note that any other planner, like for instance those implemented in *GraspIt!* [21], can be used without affecting the effectiveness of the proposed iterative algorithm.

F. Stop condition

The algorithm stops when the desired grasp quality is satisfied. The current modular configuration is efficient in the sense that it allows for reaching the desired grasp quality.

IV. Simulation Results

Our approach assumes that all the modules are the same according to the modular philosophy. In particular, we used the *Y1* modular robot [16] with one DoF as fundamental block for our simulations. A single body module is 80 mm long, 50mm wide and 50 mm high. Using docking blots, the modules can connect or disconnect easily and flexibly. Each joint is actuated by a RC servo. The *Y1* module is made of plastic so that the stiffness of its mechanical structure is quite low. We assume that each module has the same assembly

TABLE I

STEPS OF THE ALGORITHM FOR THE MINIMAL CONFIGURATION TO GRASP A KETCHUP BOTTLE

iteration	step	modular configuration	Q	time
$i=1$	1	$m=1$, $\{x_1=1\}$, -	0.0011	21s
$i=2$	2	$m=2$, $\{x_1=2\}$, -	0.0028	38s
	3	$m=2$, $\{x_1=1, x_2=1\}$, lin. base conf.	0.0459	49s
	4	$m=2$, $\{x_1=1, x_2=1\}$, circ. base or 1-opp.-finger conf.	0.0543	34s
	5	$m=2$, $\{x_1=1, x_2=1\}$, circ. base or 1-opp.-finger conf.	0.0613	35s
$i=3$	6	$m=3$, $\{x_1=3\}$, -	0.1270	47s

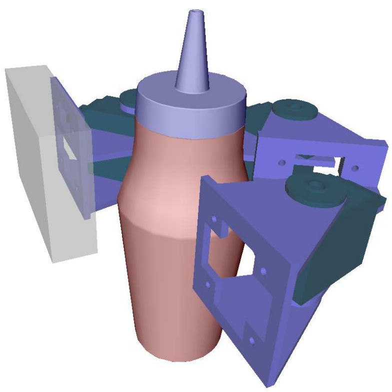

Fig. 4. Minimal modular configuration to grasp a bottle of ketchup.

selection to make the modular structure as simple as possible. However, the approach can be extended to other types of modules.

The dimension of the *Y1* module is not strictly comparable to the human phalanges. However, we decided to use it as building block in order to show the generality of our approach. The proposed model is very general and it can be extended to other types of modules with different characteristics and sizes. In this way, the modular structure can also allow the miniaturization of the device. The reduction of the size, in fact, only depends on the building block characteristics, while the kinematic structure can be kept. This property of scalability can also be useful for dealing with objects of unknown size. In fact, the dimension of the device can change without affecting the proposed algorithm to determine the modular configuration.

Related simulations have been carried out in order to test the proposed iterative approach. A JAVA software plug-in has been developed to automatically generate all the possible modular configurations according to the proposed algorithm. The grasper planner of *OpenRAVE* has been used to evaluate the grasp capability of each modular configuration.

The proposed design algorithm was used to find efficient modular configurations to grasp several daily objects. The maximum number of modules per finger M was set to 3. According to the experimental results presented in [22], the quality threshold $Q_{desired}$ was set to 0.1 since this or a greater measure of quality corresponds to grasps that a human would consider “stable”.

For the sake of simplicity, only the example of a ketchup bottle is reported in detail. It has been observed that one finger with three modules is enough to reach the desired grasp quality. In Table I experiment details are reported. Note that for two fingers devices, *circular* and *1-opposable-finger* base configurations are the same. The reported value of Q refers to the best grasp obtained by each modular configuration at the i-th iteration. The listed execution times have been obtained using an Intel i5 2.50GHz processor. The first modular configuration able to reach the desired grasp quality is shown in Fig. 4.

Other simulations have been performed in order to obtain effective configurations for grasping other objects or sets of objects. A phone, a book, a flask, a cup, a glass and an aircraft model were tested. The resulting configurations are shown in Fig. 5. Table II shows in detail the obtained modular configurations and the correspondent grasp qualities. For the aircraft model, the value of M was set to 5 and the possibility to leave the assembly selection of each module as a free parameter in the design algorithm was tested. The resulting modular configuration is quite different from classical grippers and is reported in Fig. 5-f.

V. CONCLUSION AND FUTURE WORK

An algorithm for a bio-inspired design of modular gripper has been presented. The procedure is general and flexible. It can be extended to different types of modules and to different techniques of grasp metrics. Several simulations have been carried out to test the efficiency of the method. Effective modular configurations capable of grasping several daily objects were found.

The proposed algorithm required a non trivial computational time. The most demanding part is the grasp planning phase. The amount of time required to complete this phase depends on the planner used, on the complexity of the object to grasp and on the number of modules involved. However, the structure of the proposed algorithm allows using different planners and the use of more efficient planner can reduce the execution time.

As future work, task-oriented quality measures like those presented in [23] will be used or combined with traditional metrics in order to further exploit the flexibility of the modular approach.

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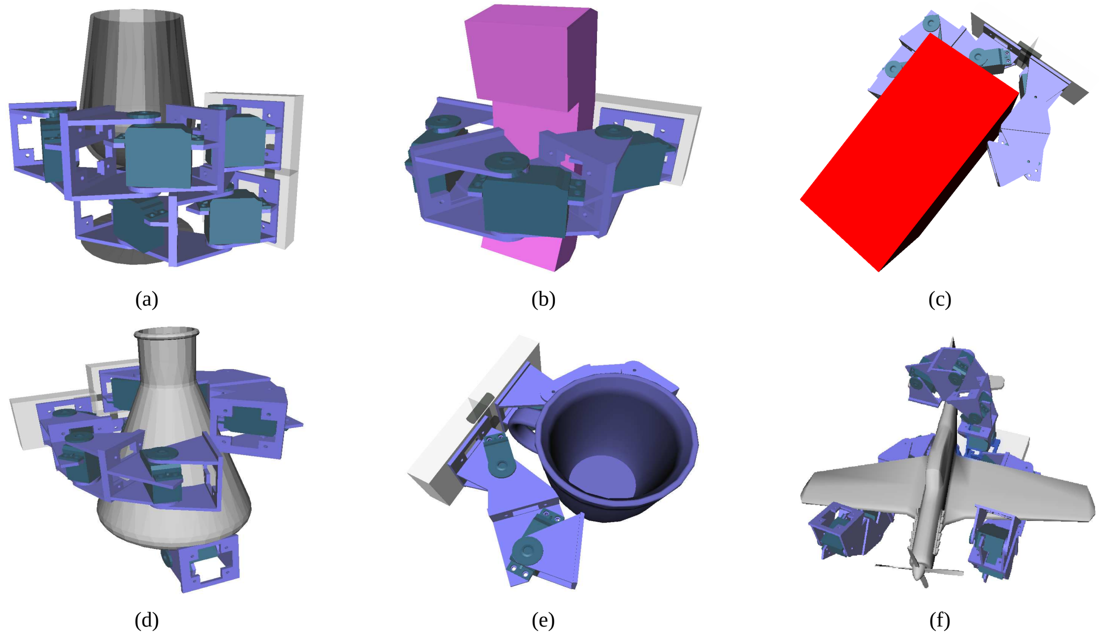

Fig. 5. Efficient manipulator configurations for respectively grasping a glass (a), a phone (b), a book (c), a flask (d), a cup (e) and an aircraft model (f). For the latter object, the assembly selection of each module has been left as a free parameter in the design algorithm was tested.

TABLE II

EFFICIENT MANIPULATOR CONFIGURATIONS FOR SEVERAL DAILY OBJECTS

target object	m	base configuration	fingers configuration	Q
glass	5	linear base conf.	$\{x_1 = 2, x_2 = 3\}$	0.12
phone	3	-	$\{x_1 = 3\}$	0.13
book	5	circ. or 1-opp.-finger base conf.	$\{x_1 = 2, x_2 = 3\}$	0.13
flask	9	circ. base conf.	$\{x_1 = 3, x_2 = 3, x_3 = 3\}$	0.14
cup	4	circ. or 1-opp.-finger base conf.	$\{x_1 = 2, x_2 = 2\}$	0.11
aircraft	14	circ. base conf.	$\{x_1 = 5, x_2 = 5, x_3 = 4\}$	0.53

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