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## ► To cite this version:

Jonatan Martin Escorcia-Hernandez, Mathieu Grossard, Florian Gosselin. Task-oriented methodology combining human manual gestures and robotic grasp stability analyses: application to the specification of dexterous robotic grippers. *Journal of Mechanical Design*, 2023, 145 (4), pp.041408. 10.1115/1.4056493 . hal-04077647

**HAL Id: hal-04077647**

**<https://hal.science/hal-04077647>**

Submitted on 25 Apr 2024

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# Task-oriented methodology combining human manual gestures and robotic grasp stability analyses: application to the specification of dexterous robotic grippers

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*The objective of this article is to present a comprehensive task analysis methodology that can provide guidelines for the design of dexterous robotic grippers that are versatile enough to perform various tasks, yet simple to manufacture. This methodology combines a human-centered gestures analysis and an object-centered grasp stability analysis. The former relies on a careful examination of a human operator's hands gestures while performing a specific process, providing designers with tools that help specifying the number of fingers, the number of degrees of freedom, and the placement of tactile sensors. The latter exploits a grasp quality metric to compute the efforts required to handle the involved objects, providing guidelines for the specification of the actuation system. Using observations of operators at work as a source of inspiration allows guarantying the ability to perform the considered tasks (with guaranteed stability thanks to the grasp analysis), contrary to technologically driven optimization methodologies, which often sacrifice manipulation capabilities for the sake of simplicity. Yet our task-oriented approach allows focusing on certain tasks, hence simpler*

*solutions than bio-mimetic designs that try to fully mimic the human hand. In other words, the methodology introduced in this article intends to help specifying multi-fingered architectures able to maintain a high degree of dexterity with a reduced kinematic complexity, favoring the best possible compromise between grasp capabilities and design complexity. This approach is exemplified by defining technical specifications for the design of a multi-fingered robotic gripper intended to perform the tasks involved in a sterility testing process.*

## 1 INTRODUCTION

The design of complex mechatronic devices is a tricky issue as they must be both performant and adapted to their context of use, and robotics is no exception. In the race for performance, existing systems can serve as a basis for improved designs, with well-established mathematical modeling tools allowing to rank their respective benefits. Conversely, when considering usage, biological system, and especially humans, can also be a source of inspiration. This is especially true when considering robotic hands. Owing to its formidable, dexterity, versa-

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tility, and tactile perception capabilities, the human hand has been the inspiration and starting point in the design of numerous dexterous multi-fingered robotic grippers [1], [2], [3]. Its great grasping and manipulation abilities are due in part to its complex kinematic construction which has been approximated with several kinematic models with different number of Degrees of Freedom (DoF), e.g. 24 [4], 25 [5], 26 [6], or 27 [7]. Indeed, the analysis of the human hand is crucial for the development of multi-fingered grippers designed to accomplish tasks that human beings commonly perform in environments made for them [8]. According to [9], guaranteeing the autonomy of robot manipulators in human environments is really challenging, due to the involvement of unsuspected factors in the work environment, the need for versatile tools, or the interaction with different objects having a wide variety of shapes, sizes, and textures, most of them designed to be manipulated by human beings. Attempting to exactly reproduce the anthropomorphic architecture of the human hand in a multi-finger robotic gripper becomes a highly challenging task due to the complexity of the required mechanisms, the large number of actuators, the coupling between some DoFs, and highly nonlinear dynamics, among other issues [10]. As a consequence, the few existing anthropomorphic hands, as for example the Shadow Hand [11] or the AWIWI Hand [12], remain limited to laboratory applications, despite their remarkable design. These limitations have led to the proposal of simpler designs that, consequently, have a lower degree of anthropomorphism. Some researchers have stated that a multi-fingered gripper should have at least three fingers for grasping, while if manipulation is desired, it should contain at least four fingers [13]. Such simplifications are however most often driven by technical considerations and/or stereotypical situations which can vary from real-world use in terms of both the variety of grasps and their prevalence in the to-be-performed actions. Interestingly, designing a simpler gripper that diverges from an anthropomorphic approach does not mean that it has less dexterity [14]. The above is based on the fact that for certain types of activities, humans tend to use a reduced number of grasps. The analysis of the frequency of use of different grasps performed by a professional housemaid and a machinist during their daily work activities presented in [15] shows for instance that nearly 80% of the time, the machinist uses only nine different grasp types, whereas the housemaid employs only six different kinds of grasps in the same percentage of time. These results lead us to infer that for specific human activities, we can rely on a human-centered gesture analysis to identify the most commonly used grasps and propose architectures of multi-fingered robotic grippers that are simpler yet sufficient to perform

all the tasks encountered in this context. Nevertheless, the design and construction of efficient multi-fingered robotic grippers combining a simply kinematic design with a high degree of dexterity still represents a tremendous challenge for roboticists [16]. A key aspect of the design process is to define certain kinematic, mechanical, and sensing characteristics that the future gripper must satisfy in order to successfully perform the target activity. This research aims to present a novel methodology to rationally define such specifications for multi-fingered robotic grippers (i.e. number of fingers, number of phalanges per finger, kinematic configuration, dimension of mechanical elements, placement of tactile sensors, and the specifications for the actuation system). Our proposed approach relies on two main studies:

1. A human-centered gesture analysis which is inspired by ergonomic-based grasps classifications and used to set the kinematic structure parameters.
2. An object-centered grasp stability analysis used to determine the force/torque that the actuation system of the gripper must provide to accomplish the task for which it is designed.

The proposed methodology is intended to allow specifying optimized multi-fingered gripper that are sufficiently versatile to perform specific sets of tasks with a high degree of dexterity, yet simple enough for an efficient mechanical design. In the literature, researchers have tried to address this problem by proposing systematic methodologies, some of them are discussed in the following subsection.

### 1.1 State-of-the-art

Based on a certain application expected to be performed by a robotic multi-fingered gripper, designers must stipulate a list of technical specifications for the to-be-designed device, such as the number of fingers, degrees of freedom, the weight of the gripper, output force at the fingertips, type of actuators (electric, pneumatic, hydraulic), kind of transmission (cable and pulley, screw-driven mechanism, rack and pinion, etc.), and sensors (position, velocity, force/torque), among others [17], [18].

Certainly, the manner to define these parameters is an open field of research and, so far, there is no fixed methodology that can determine each of them as each application has its particular challenges resulting in certain particularities in the design process. The design guidelines proposed by the designer are creative but with solid analytical foundations supporting the selected specifications. One can briefly describe some of them.

For instance, Honarpardaz et al. [16] summarize the

finger design process for grippers into three global stages: (i) synthesis and analysis of the grasp; (ii) finger design in function of the grasp information and collision detection, and (iii) experimental verification of the gripper design, which can be performed in two ways, virtually or physically.

Puig et al. [19] introduced a design methodology consisting of the following steps: (i) problem definition, (ii) concept design, (iii) preliminary design, and (iv) design communication. Problem definition analyzes two aspects: target application, and analysis of the human hand. Concept design is the step where the designer establishes the specifications for the actuation system, sensors, and control algorithms. The designer makes a pre-selection of these parameters which serve as an input for the dimensional synthesis of the kinematic chain of the fingers. The appropriate dimensions can be achieved by solving multi-criteria optimization problems which also make adjustments to the aforementioned specifications.

Martell and Gini [20] presented a design method in which a set of cameras capture the positions of the human hand performing a grasp/manipulation task. The obtained information is used to build a virtual model of the human hand, and to generate the input and output data for the control system of the to-be-constructed robotic gripper. Since no mathematical model is available but only the inputs and outputs of the system, the authors make use of neural networks to generate the control signals that produce the desired outputs. The resulting control signals are used to provide specifications for the actuators and sensors to be implemented in the gripper.

Lee and Tsai [21] developed a systematic process to define the structural synthesis of multi-fingered hands (i.e. the number of fingers and the number of phalanges and joints in each finger). The method considers the mobility equation and constraints equations based on the contact degrees of freedom to derive these parameters.

Ciocarline and Allen [22] proposed a quasistatic tool for highly underactuated robotic hands which can be extended to other types of grippers. The described method consists in an optimization approach to find the optimum efforts values applied to the grasped object. This method requires: establishing a set of possible grasp patterns together with the case study objects, defining the parameters to be optimized, and establishing a range of admissible values for these parameters. By using computational tools, combinations between all the parameters to be defined are made. For each combination, the objective function is evaluated iteratively with all possible grasp patterns applied to a given object to know which of the best parameters combination guarantees the highest number of stable grasps. This method was conducted to

define the stiffness and torque ratios of the shape deposition manufacturing (SDM) hand. The authors claim that their methodology can be used to provide other specifications for grippers, such as the links lengths and shapes, number of fingers, kinematic chain design, etc.

## 1.2 Proposed framework

The present research has the objective to introduce a new methodology allowing to define as complete as possible technical specifications for to-be-designed multi-fingered dexterous grippers. Our proposed formulation can be used to complement in certain aspects those detailed in the state-of-the-art.

At CEA-LIST, we have already proposed useful tools based on a human-centered gesture analysis for designing as simple and efficient as possible dexterous haptic interfaces and hand exoskeletons [23], [24]. For instance, [25], and [26] introduce interaction maps that provide a graphical representation of the percentage of time each elementary contact surface of the hand is solicited during a manipulation procedure. Moreover, in [27], the concept of interaction maps was enhanced by incorporating knowledge about the direction of the forces applied on each contact surface.

These ergonomics-based analyses are very useful to provide technical specifications for hand exoskeletons and haptic interfaces. The mentioned works can even be a starting point to establish some technical specifications for multi-fingered grippers. However, according to the research papers cited in the state-of-the-art, this information is insufficient for grippers due to the absence of a tool able to quantify the efforts that the multi-fingered gripper must provide. The human-centered gesture analysis provides us with indispensable information to define certain specifications such as the number of fingers, degrees of freedom, range of motion, and placement of tactile sensors. However, it does not provide information about the required amount of efforts needed to be applied on each elementary surface forming each grasp pattern used to grasp and manipulate the objects implied in the use-case.

To solve this deficiency, we propose to complement the human-centered gesture analysis methodology developed at CEA by integrating a force-based grasp stability analysis allowing us to compute the required efforts to be applied to the grasped object. Grasp stability analysis and fiction models allow for determining where to place the fingers or gripping elements on an object and the amount of effort that must be applied to keep it firmly gripped even in the presence of external disturbances [28], [29].

Our proposed methodology will provide design guidelines to answer the following questions that every

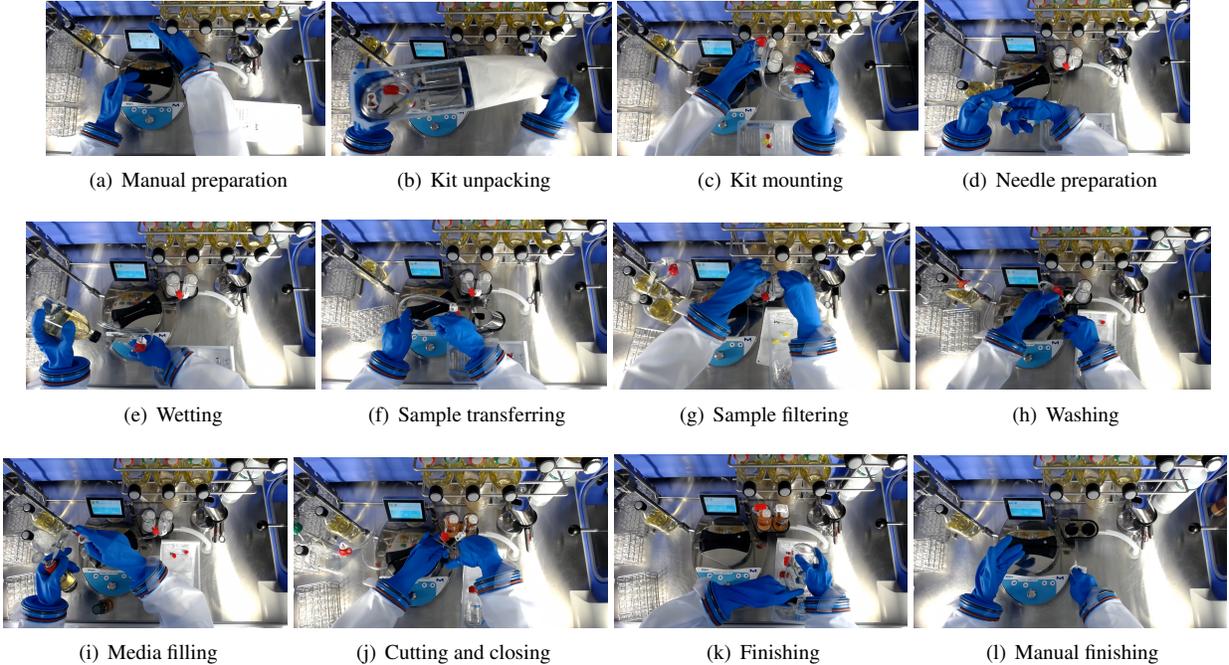


Fig. 1. Tasks identified through recorded videos of the sterility testing use-case provided by ©INVITE GmbH<sup>1</sup>.

designer of multi-fingered grippers should ask himself. *What is the optimum number of fingers? What dimensions should each finger have? How many degrees of freedom? Where to place touch sensors? What amount of force/torque should the gripper provide in order to perform a specific procedure?* We first perform a meticulous analysis of videos of the use-case to identify and classify the hand-objects interaction patterns. Then, we generate illustrations of the contact surfaces on the hand for each grasp pattern. Subsequently, we calculate the frequency of use of each grasp pattern, and the direction of the applied forces. All this information is used to generate interaction maps (one for each direction in which forces are applied) associating each elementary contact surfaces with the percentage of time it is used throughout the process. The resulting data will provide us with criteria for answering the first three questions stated above. Regarding the force-based grasp stability analysis, we propose to firstly make use of software tools to generate a 3D mesh representation of all the objects involved in the use case and to virtually associate each mesh with the grasp patterns identified in the human-gesture analysis stage. Then, through laboratory experiments with the objects involved in the use case, we proceed to estimate the values of the external disturbances involved in each action. To estimate the magnitude of the forces required at the hand-object contact surfaces to counterbalance the exter-

nal disturbances exerted on the objects of interest, including their weight, we propose a quality metric consisting in *minimizing the value of the norm of the contact efforts required to balance the associated external efforts applied at the center of the object's frame*. The proposed quality metric, which will be described in detail in the next sections, was inspired by the *Normal components of the force* quality metric described in [30]. The computed efforts solicited to guarantee the stability of the object grasped will determine the required amount of forces/torques that the actuation system of the gripper must provide, hence providing an answer the last question formulated previously. The proposed methodology is exemplified in a sterility testing process which serves as the reference use-case in the framework of the European project TraceBot.

### 1.3 Positioning with respect to previous works

Our proposed methodology is based on an *experimental-theoretical analysis*. It shares some features with the approaches described in the state-of-the-art, but it also has remarkable differences. For example, Martell and Gini [20] consider the human-gesture analysis to

<sup>1</sup>For a better understanding of the TraceBot use-case, the reader may consult the following link, which contains the videos of the sterility testing process: [https://tracebot.gitlab.io/tracebot\\_showcase/root\\_index/](https://tracebot.gitlab.io/tracebot_showcase/root_index/).

make a virtual model of the human hand. However, in our case, the video analysis is employed to identify and classify the grasp types involved in the whole process. The methodology presented in [19] considers firstly a careful selection of the actuators, sensors, and control algorithms to carry out the dimensional synthesis of the fingers. Although the authors argue that the selection of these elements depends on the task to be carried out by the gripper, there is no mention of a method to make a proper selection of them. So, our proposed methodology may complement the mentioned work. In [16], the design of the fingers is based on the information obtained from the grasp synthesis study, while in our proposal, the criterion is based on the frequency of use of each elementary surface of the hand when handling the use-case objects. In [21], the structural synthesis of a multi-fingered gripper is obtained by applying the mobility equation and some constraint equations, whereas in our case, these features will be selected through the interaction maps obtained from the Human-centered gesture analysis. Similar to the research described in [22], our work also relies on numerical computations to solve multi-objective optimization problems in order to estimate the level of contact forces applied to the grasped objects. Nevertheless, the mentioned approach requires a predefined architecture of a robotic gripper in order to optimize a selected number of parameters. In contrast, our method does not require a predefined gripper architecture, since the human-gesture analysis provides enough criteria to establish a suitable kinematic architecture (i.e. define the number of fingers, degrees of freedom, and placement of tactile sensors).

#### 1.4 Organization of the paper

The remainder of the paper is organized as follows. Section 2 describes in detail the steps that comprise the Human-centered gesture analysis as well as the use-case description; the Force-based grasp stability analysis is performed in Section 3, Section 4 discusses the technical specifications of the future gripper, and finally, the conclusions of this paper are addressed in Section 5.

## 2 HUMAN-CENTERED GESTURE ANALYSIS

Before starting with the analysis let us define the use-case. *Sterility testing is the process of measuring the presence or absence of contaminating microorganisms in pharmaceuticals or drugs for human use. All pharmaceutical products, i.e. drugs, that are administered to humans require sterility testing to obtain regulatory approval [31].* With the help of 12 videos provided

by ©INVITE GmbH, we have been able to characterize the manual interaction patterns involved in this use-case. These 12 videos illustrate the 12 main stages in this particular process which are illustrated and briefly described in Fig. 1. These videos show the use of a Steritest™ pump in a glove box and the different objects that the operator holds and manipulates during the process. These objects are a Steritest™NEO, which is a sterility testing kit from Millipore®, a petri dish, scissors, a marker with cap, several rinse glasses, and glass vials. The sterility testing kit includes red and yellow plugs, two canisters connected through flexible tubes to needles for fluids transfer. Each needle includes its own needle cap for safety purposes. Besides, a set of tube clamps is integrated with the flexible tubes allowing the operator to transfer or block fluids.

### 2.1 Identification and classification of manual interaction patterns

As previously mentioned, human grasps are traditionally organized in taxonomies. The most commonly used is the one proposed by Cutkosky [32], which is widely used for robotic and prosthetic hands designs. This taxonomy depicts 16 different patterns using task dexterity and precision as discriminants. Some usual grasps as e.g. holding a pen are however missing in this classification. Feix et al. proposed a more complete grid which includes intermediate grasps and is designed with respect to the posture of the hand [33]. The combined taxonomy obtained when merging both authors' work is displayed below. Each pattern is called  $C_i$  (with  $i \in [1; 16]$ ) or  $F_j$  (with  $j \in [17; 34]$ ) whether it is part of the Cutkosky or Feix et al. taxonomy respectively. This classification is easily readable and provides a wide overview of grasping as it takes into account non prehensile, power, intermediate and precision grasps as can be seen in Fig. 2. Researchers also seem to agree that some stereotyped behaviors are used in order to evaluate the physical characteristics of an object or a material. These gestures are usually classified according to the taxonomies proposed in [34] and [35], which group them in six exploratory procedures, each one being optimal to a certain kind of information. These procedures are named  $K_i$  (with  $i \in [1; 6]$ ) and are illustrated in Fig. 3. Previous work however only refers to situations as typically encountered when manipulating "classical" objects such as tools (e.g. hammers, screwdrivers) or household objects (e.g. glass, plates). They are not sufficient to describe the way expert operators manipulate the Steritest™ kit in a glove box. This task indeed involves the manipulation of flexible objects (e.g. flexible tubes) which are not covered in usual taxonomies. Also, operators make use of non-typical grasps

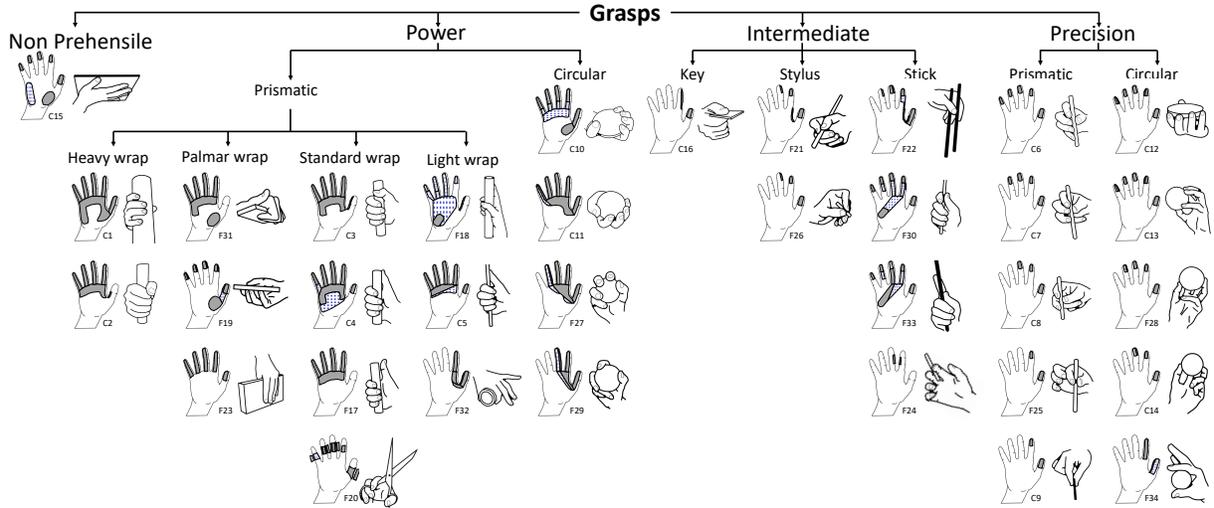


Fig. 2. The Cutkosky and Feix grasp taxonomies with their corresponding hand-object contact surfaces representation.

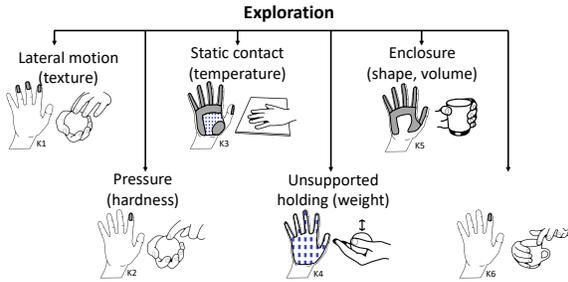


Fig. 3. The exploratory gestures' taxonomy derived from the work of Lederman and Klatzky with their corresponding hand-object contact surfaces representation.

in order to grasp difficult to access objects, and they tend to grasp several objects at the same time. To cope with these grasps, we introduced a novel grasp category called *Ti*. In practice, we identified 80 of those grasps (hence  $i \in [1; 80]$ ). To describe them, we first drew schematic representations of each of them. The TraceBot grasps are displayed in the taxonomy presented in Fig. 4, being classified as non-prehensile, power, intermediate, and precision grasps similarly as in Cutkosky and Feix's work.

## 2.2 Definition of hand-objects contact areas

The next step consists in identifying, for each interaction pattern, the hand-object contact area. For standard grasps types and exploratory movements, we refined the characterization of the contact areas compared to [26], [25] and [27]. Indeed, in previous studies reported in the

literature, the palm is considered as fully involved in most power grasps, while in practice the palmar arch prevents contact with the center of the palm for most objects. We thus decided to refine the characterization of the contact area for all grasps and interaction patterns. Therefore, we took in hand objects representative of the different usual grasps and we tried to insert a thin metal sheet between the hand and the object. We considered that the skin is in contact with the object only when we were not able to insert this tool between their surfaces. The results are depicted in the hand-object contact surfaces representation of Figs. 2 and 3. As in practice the contact surface may vary according to the size of the grasped objects, we tried to grasp objects of different sizes. The contact surfaces in dotted texture represent this variability. For the specific TraceBot interaction patterns also, we tried to identify the hand-objects contact surfaces' as precisely as possible (see Fig. 4). As the gloves used by the operator do not always allow a clear vision of the way the objects are held, we reproduced the grasps with bare hands as Fig. 5 illustrates. Also, we took into account the information gathered during the whole duration of the grasp and not only at the time the picture was extracted (for most grasps, the user moves the held object from an initial to a final configuration which have different orientations, allowing to better see how the fingers are placed on the objects). The results of this analysis are reported in Fig. 4. For some grasps, we distinguish hand support areas (in texture of diagonal lines) and functional areas (in shaded). Supports are useful for humans but they are not required for robots. The areas of diagonal lines will thus not be considered in the remaining of the process. These



Grasp number	Start of the grasp	End of grasp	duration (s)	Grasps	Hand contact area	Hand	Object	Name of the Video	Static / manipulation
16	00:07,00	00:08,33	01,33	C1		L+R	Canister	b : Kit Unpacking	Static
17	00:00,00	00:01,40	01,40	T26		L	Canister	c : Kit mounting	Re-grasping
18	00:01,40	00:03,80	02,40	T2		L	Canister	d : Kit mounting	In-hand manipulation

Fig. 7. Information gathered during the analysis of the use-case videos (left hand, a similar analysis was made for the right hand).

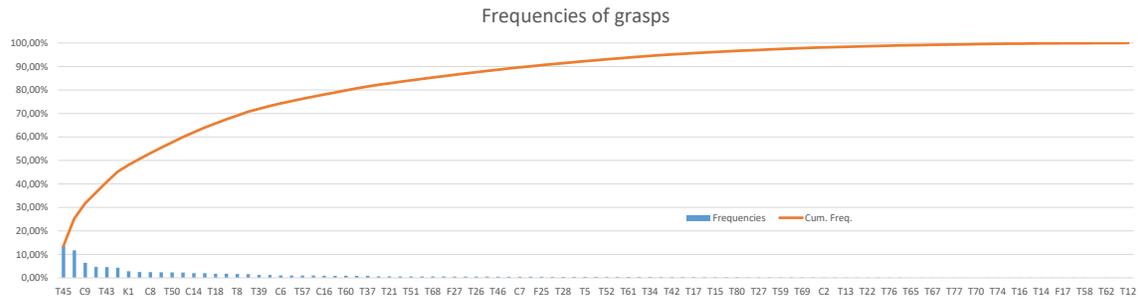


Fig. 8. Frequencies of use of the different grasps used in the sterility testing use-case presented in descending order, and cumulated frequencies.

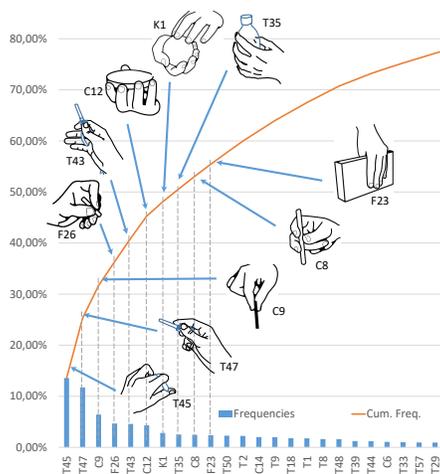


Fig. 9. Illustration of the 10 most frequent grasps.

contrary, it is only the case of few grasps like for example the adduction grip used to grab a cigarette). Since using finger edges is common in this study, it was chosen to standardize all fingers by placing an edge on each side of

each phalanx. Moreover, as some of the TraceBot grasps use the back of some fingers, we also added the dorsal side of each phalanx (the representation of the dorsal areas is done by adding a small area next to the fingers). Thus, each phalanx of each finger is divided according to its four faces: palmar face, radial face, ulnar face, and dorsal face. To allow representing the thumb similarly as the other fingers, we introduce an offset angle so that these four faces are also visible for this finger. This results in the hand surface decomposition scheme, which can be appreciated in Fig. 6.

The labels used to describe the elementary contact areas obey the following logic:

1. The labels of the finger areas have 1 digit and 2 letters:
  - (a) The digit is used to designate the finger: 1 for the thumb, 2 for the index, 3 for the middle, 4 for the ring and 5 for the little.
  - (b) The first letter is used to designate the phalanx: P for proximal, I for intermediate and D for distal.
  - (c) The second letter corresponds to the face of the

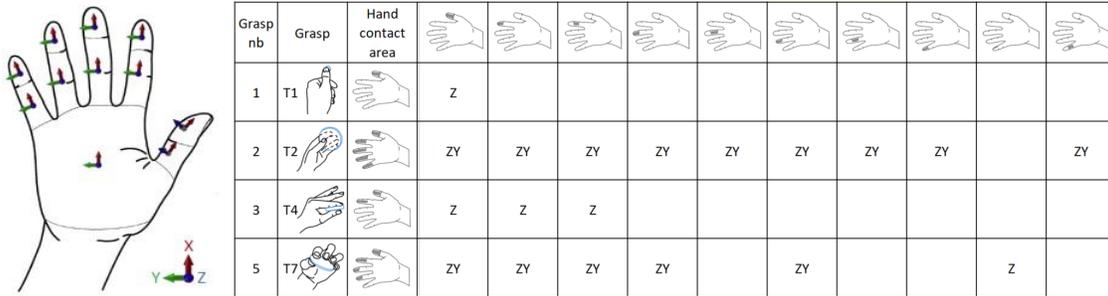


Fig. 10. Example directional force analysis.

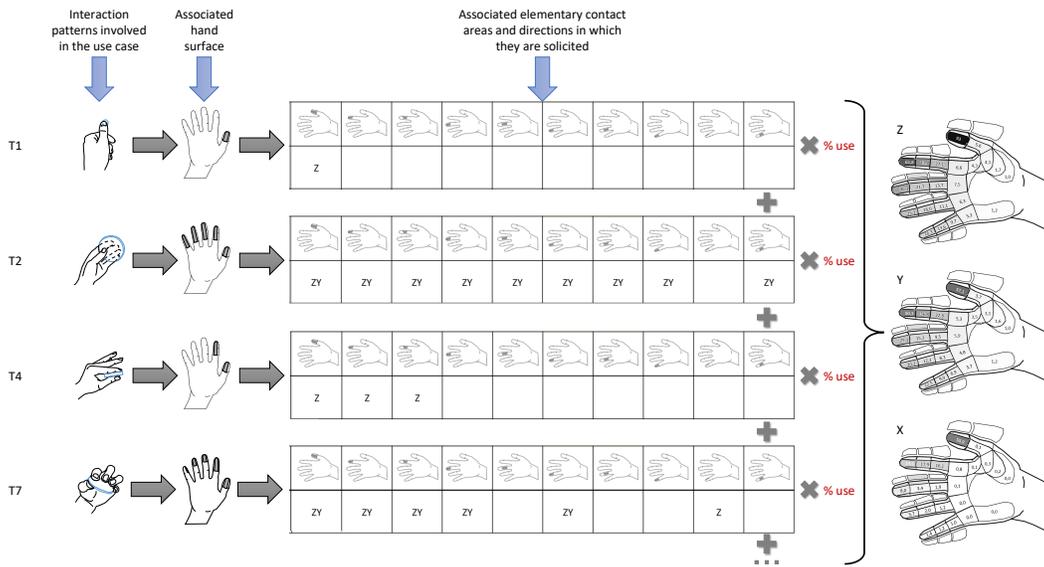


Fig. 11. Generation of the interaction maps.

finger: P for palmar, R for radial, U for ulnar and D for dorsal.

2. The palm is referred to as 0, and the associated labels have 1 additional letter and digit:
  - (a) The digit 0 indicates the palm.
  - (b) The letter is used to indicate the palm subdivision: T for the Thenar, O for the Opposition, H for the Hypothenar, M for the Metacarpal areas and C for the Central triangular.
  - (c) The last digit allows to differentiate the palm subareas.

### 2.3 Identification of the frequency of use of each pattern

As previously explained, the frequency of use of each interaction pattern is obtained from a video analysis of

the operators' gestures. As proposed in [15], several observers carefully look at the videos and identify the interaction patterns used by the operators. As shown in the example video analysis displayed in Fig. 7, we note for each grasp the time it begins and the time it ends to be used. By subtracting the former from the latter, we get the grasp duration. It is worth noting that in practice, some grasps are used several times and/or with both hands. In such cases, we cumulate the times they are used over the whole process in order to get the total amount of time each grasp is used. These durations are further used to compute the relative frequency of use of the different grasps and interaction patterns, which is the duration of a given grasp divided by the duration of all grasps. The results obtained for the sterility testing use-case are displayed in Fig. 8 considering all grasps, and the 10 most frequent ones are represented in Fig. 9.



### 3 FORCE-BASED GRASP STABILITY ANALYSIS

This section focuses on explaining the details of object-centered force analysis. However, before presenting in detail the steps to be followed, we will briefly describe the mathematical models used for contact objects, friction, and the proposed grasp quality metric, which are indispensable to calculate the required levels of force to perform the TraceBot tasks.

#### 3.1 Grasping background

##### 3.1.1 Object-finger contact models

Assuming an unique, well-defined, tangent plane at each contact point  $\mathbf{c}_i \in \mathbb{R}^3$  between the finger and the grasped object, we can define a contact frame  $\{\mathbf{C}\}_i$  whose axes are denoted as  $\{\mathbf{n}_i, \mathbf{t}_i, \mathbf{o}_i\}$ , with  $\mathbf{n}_i \in \mathbb{R}^3$  defining the contact normal, directed towards the object and  $\mathbf{t}_i, \mathbf{o}_i \in \mathbb{R}^3$  the tangential ones. The contact efforts locally transmitted at  $\{\mathbf{C}\}_i$  will then be denoted by the static wrench  $\mathbf{f}_{c_i} = [f_{cni} \ f_{cti} \ f_{coi}]^T \in \mathbb{R}^3$ , where  $f_{cni} \in \mathbb{R}$  denotes the normal component of the transmitted contact forces,  $f_{cti} \in \mathbb{R}$  and  $f_{coi} \in \mathbb{R}$  the tangential ones. Among the main contact types in grasping, we adopted the Hard Finger (HF) one in our study [36]. In such a case, contact forces are transmitted in the contact tangent plane following the inequality constraints:

$$\begin{cases} f_{cni} \geq 0 \\ \sqrt{f_{cti}^2 + f_{coi}^2} \leq \mu f_{cni} \end{cases} \quad (1)$$

where  $\mu$  defines the tangential friction coefficient between the finger and the grasped object, which may vary depending on several contact characteristics.

The above standard sets of inequality constraints form a *friction cone*  $\mathcal{F}_i$  (see Fig. 13), that can be approximated by a polyhedral cone for an appropriate formatting for optimization, defined by a *local friction cone matrix*  $\mathbf{F}_i$  in the following way [37], [36]:

$$\mathcal{F}_i \approx \{\mathbf{f}_{c_i} \text{ s.t. } \mathbf{F}_i \mathbf{f}_{c_i} \geq \mathbf{0}\} \quad (2)$$

In the following sections, such approximation will be referenced to through the *global friction cone matrix*  $\mathbf{F} = \text{blockdiag}(\mathbf{F}_1, \dots, \mathbf{F}_{n_c})$ , which allows to easily test the respect of contact types for all contact points  $n_c$  at once, through the following linear inequality:

$$\mathbf{F} \mathbf{f}_c \geq \mathbf{0} \quad (3)$$

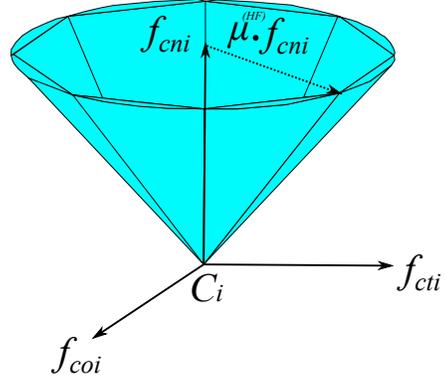


Fig. 13. Representation and approximation of a spatial friction cone with vertices in the case of HF contact modeling.

##### 3.1.2 Description of the task quality metric

A specifically tailored task-oriented approach for grasp quality assessment is proposed as a new metric adapted to our class of problems. It is defined as *the magnitude of forces required at the hand-object contact locations required to counter an external effort exerted at the center of the object frame*. One interest of this metric lies in its ability to provide insight into the to-be-designed gripper's ability to counter given external perturbations. It provides, for each identified object and each external effort considered in the TraceBot use-case, an estimation of the grasp force necessary to hold still the object. In practice, we denote by  $\mathbf{d}_{W_{ext}} \in \mathbb{R}^6$  the fixed direction of the studied external effort and its variable magnitude by  $\alpha \in \mathbb{R}$ , such that:

$$\mathbf{g} = \alpha \mathbf{d}_{W_{ext}} \quad (4)$$

reports for both forces and torques applied to the object (the last three components of  $\mathbf{d}_{W_{ext}}$  will be normalized according to a characteristic length  $L$  of the grasped object). The magnitude metric is computed by resolving the following problem (P1):

$$\begin{array}{l} \text{(P1) } \min \|\mathbf{f}_c\|_2 \\ \text{s.t. } \mathbf{G} \mathbf{f}_c + \alpha \mathbf{d}_{W_{ext}} = \mathbf{0} \quad (\text{Static equilibrium}) \\ \mathbf{F} \mathbf{f}_c \geq \mathbf{0} \quad (\text{Friction cone}) \end{array} \quad (5)$$

where the grasp matrix  $\mathbf{G} \in \mathbb{R}^{3n_c \times 6}$  maps the contact wrench given in their local frames onto the object frame. The proposed problem (P1) roughly embodies the mechanical limitations of the gripper actuators and helps

finding the minimal requirement about the maximal force.

### 3.2 Framework for grasp study

The application of the previously presented grasp analysis tools on the considered TraceBot objects is thereafter detailed. The global outline of the proposed analysis is summarized in Fig. 14.

#### 3.2.1 Overall architecture and workflow

##### 1. Specifications

The grasp synthesis takes as inputs a batch of parameters, which help formulating the mathematical problem.

- (a) Firstly, a whole set of *object data* deals with the geometry, the inertial properties of each of the to-be-grasped objects, as well as their potential restricted areas.
- (b) A second set of data comprises the identified *external disturbances* (seen as external wrenches from a mechanical point of view) applied to each object involved in the task. This last feature is task-oriented, since it aims at documenting the perturbations applied to each object as imposed by the TraceBot use-case. These are related to inertia and gravity effects, as well as mechanical interaction forces that may occur between two objects during certain tasks (e.g. insertion or assembly).
- (c) Finally, a third set of parameters, also known as *grasp type settings*, describe useful characteristics of the human or gripper grasp pattern: the number of fingers (including the palm) and the number of contacts (the contact type being chosen as HF for all fingers) as defined by each grasp pattern from the taxonomy.

##### 2. Mapping between human hand/gripper and object

First, a reconstructed meshed version of each object to be grasped is done. Then, the issue of finding the appropriate positioning of each finger and palm on the object's envelope according to the grasp patterns identified during the human-gesture analysis is solved. For each pair of *grasp type settings* and *object data*, the selection procedure computes a collection of *contact positions*, which maps the identified elementary contact areas of the human hand or gripper to the object. All associated elements form a *ready-to-analyze grasp*.

##### 3. Grasp stability analysis tool

A comparative tool is built: it is able to hold the *grasp quality metric scores* computed from (P1) for each *ready-to-analyze grasp*. The tool takes into account a multi-parametric analysis that includes all the combinations of parameters (*object data*, *grasp type settings* and *external perturbations*). Let note that, prior to solve (P1), each *ready-to-analyze grasp* is classified as “indeterminate or not” and as “graspable or not”, based on the mathematical study of the grasp matrix  $\mathbf{G}$  computed for each *ready-to-analyze grasp*: the analysis of the rank of the null space of  $\mathbf{G}$  and  $\mathbf{G}^T$  helps us understanding, from a control point of view, if the considered grasp allows to control all internal object forces and twists.

##### 4. Extraction of solution and derivation of design guidelines

The previously obtained analysis tool is post-processed to identify a satisfactory level of required forces at contact points resulting from the normal component of the applied force. The list of obtained metric values, computed from an object-centered point of view, happens to hold interesting insights concerning the required maximal force capability to be produced by the to-be-designed gripper considering a specific pair of *object data* and *grasp type settings*. Finally, according to scores from grasp quality metric, a specific ordering between the proceed grasps can be derived.

#### 3.2.2 Consideration about human hand and object mapping

An in-depth analysis of the whole use-case has led to the documentation of all the pairs that combine objects and grasp types extracted from the TraceBot taxonomy. These pairs are summarized in Table 1, some pairs being subjected to several perturbations as explained in the next subsection. For each pair made of one object and one grasp type, the procedure infers a collection of theoretical *contact positions*, which maps the elementary contact areas of the human hand involved in the current grasp type to the meshed CAD of the current object. From a mathematical point of view, one elementary contact area from the human hand is assumed to be modeled as one punctual Hard Finger (HF) contact with Coulomb friction. In short, at the interface between the phalanx/palm and the object, only normal and tangential force components are transmitted.

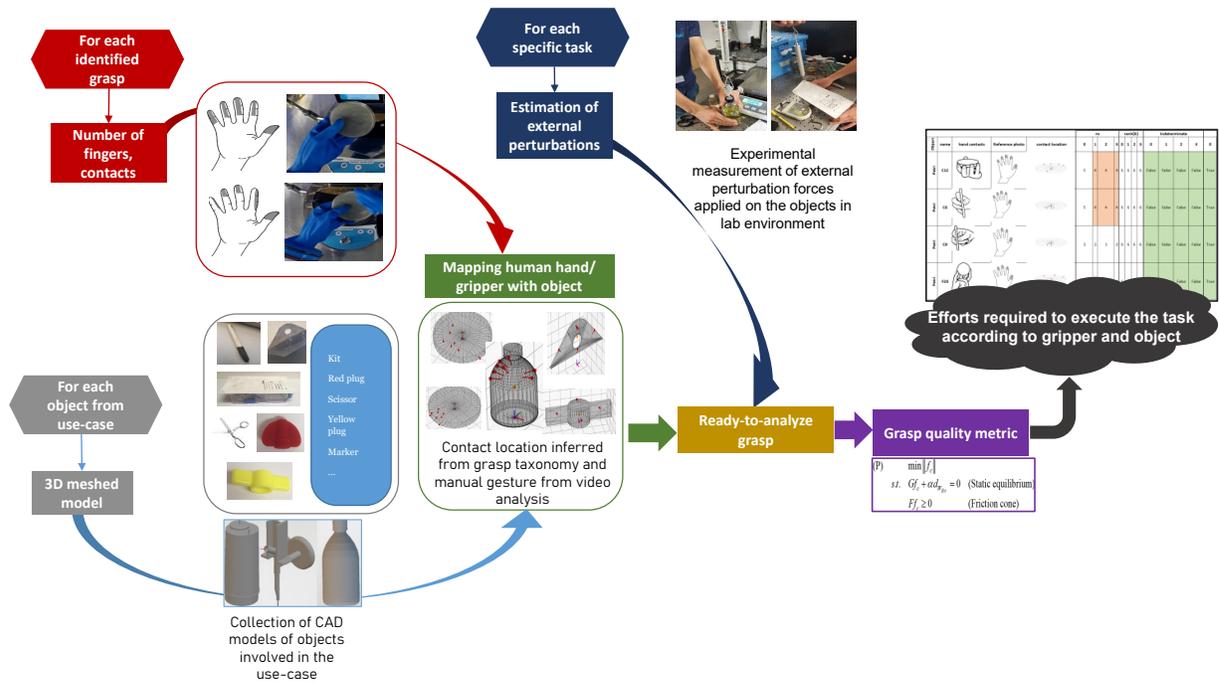


Fig. 14. Global outline for grasp analysis methodology.

Table 1. List of combinations between grasps and perturbations considered in the use-case

Objects	Grasp type identified from taxonomy	Related perturbations
Petri dish	C6, C8, C12, F28, T2, T3, T4, T7, T8, T18	HOLD, WRITE
Marker	C8, F26, F28, T9, T10, T13, T16, T18	HOLD, UNCAP, RECAP, WRITE
Marker cap	C16, T17, T53	HOLD, UNCAP, RECAP
Kit	C6, C7, C8, C11, F28, T22, T35	HOLD, OPEN
Kit tab	T21	HOLD, OPEN
Canister	C1, C6, C8, T2, T18, T26, T57	HOLD, INSERT, REMOVE
Tube	C2, C6, C7, C8, F17, F26, T4, T17, T23, T24, T27, T28, T29, T30, T70	HOLD, INSERT
Needle	C8, T21, T28, T33, T60	UNCAP, HOLD, PIERCE, UNPIERCE
Needle cap	C14, T4, T28	UNCAP
Rinse glass	C6, C12, T2, T18, T34, T35, T38, T39, T51, T58, T69	HOLD
Red plug	F26, T21	HOLD, INSERT, REMOVE
Glass vial	T45	HOLD, OPEN
Yellow plug	T21	HOLD, INSERT
Tube clamp	C16, T28, T65	HOLD, CLAMP, UNCLAMP
Scissors	C8, C16, T68, T68_	HOLD, CUT

Table 2. Summary of estimated magnitudes  $\alpha$  of both direction-dependent and direction-independent external disturbances for all objects of the use-case.

Object	External disturbances											
	Weight (in N)	Direction-depended perturbations applied to the object in (N)										
		WRITE	UNCAP	RECAP	OPEN	INSERT	REMOVE	PIERCE	UNPIERCE	CLAMP	UNCLAMP	CUT
Petri dish	0.147	2.5	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Marker	0.098	2.47	23.0	34.4	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Marker cap	0.022	N.A.	23.0	34.4	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Kit	1.677	N.A.	N.A.	N.A.	20.0	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Kit tab	0.004	N.A.	N.A.	N.A.	20.0	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Canister	0.368	N.A.	N.A.	N.A.	N.A.	87.2	110.0	N.A.	N.A.	N.A.	N.A.	N.A.
Tube	0.304	N.A.	N.A.	N.A.	N.A.	45.7	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Needle	0.103	N.A.	9.4	N.A.	N.A.	N.A.	N.A.	23.4	11.0	N.A.	N.A.	N.A.
Needle cap	0.010	N.A.	9.4	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Rinse glass	5.511	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Red plug	0.007	N.A.	N.A.	N.A.	N.A.	35.9	23.0	N.A.	N.A.	N.A.	N.A.	N.A.
Glass vial	0.147	N.A.	N.A.	N.A.	30.0	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Yellow plug	0.010	N.A.	N.A.	N.A.	N.A.	2.3	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Tube clamp	0.039	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	40.8	3.1	N.A.
Scissors	0.593	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	55.0

### 3.2.3 Considerations about external loads

One interest of the computation of stability equilibrium (P1) lies in its ability to provide insights on the required level of effort to be applied at each contact point to counter *external disturbances*, which can be classified according to whether or not they are direction-dependent.

1. Objects being grasped, lifted and manipulated over space randomly by the operator, gravitational effects can be directed along any axis of the object local frame. As a consequence, the weight of the objects is seen as an external disturbance that is independent of the direction. In practice, the required forces to be applied at contact points to withstand the objects weight, action named “HOLD” in Table 1, are computed with the weight given in Table 2 applied in local directions -X, +X, -Y, +Y, -Z and +Z to reflect the fact that this solicitation can be applied whatever the orientation of the object in space is.
2. Other external disturbances, such as UNCAP, OPEN, INSERT, PIERCE, etc., have specific direction-dependent features: the assumed loads are caused by frictional forces to be overcome along certain privileged axes of the object frame, arising during the execution of certain tasks very specific to the use-case (such as the insertion of the canister or the needle).

Either voluntary pessimistic upper bound estimation of such efforts or direct measurement using experimental test bench at CEA (Fig. 15) have made possible the documentation of the magnitudes of efforts  $\alpha d_{W_{ext}}$  in the problem formulation (P1) for all objects as can be appreciated in Table 2. In practice, the associated hand-object contact efforts are computed with an external wrench corresponding to this effort plus the weight of the object applied along the axis that is vertical during the considered action.

### 3.3 Preliminary results about force considerations

For the sake of clarity, the previously presented grasp analysis methodology using the metric (P1) is first carried out for a unique task in order to illustrate in detail how the input data is considered, and then for all *ready-to-analyze grasp* configurations. It should be noted that the present study of force-based grasp stability analysis can be applied to most of the grasp taxonomies defined in section 2, with the exception of the following cases:

1. Non prehensile grasp patterns.
2. Grasp patterns holding two or more objects.

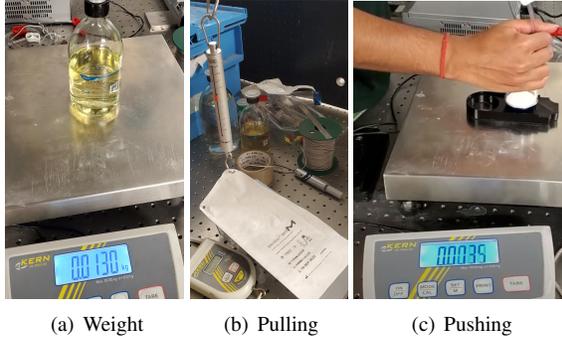


Fig. 15. Identification of external disturbances magnitudes when replicating use-case manual gesture using force sensors and laboratory balance at CEA.

### 3.3.1 A simple example of the force-based grasp stability analysis

In this illustrative example, we selected the Needle UNCAP action. As mentioned previously, the goal is to compute the required contact forces  $\mathbf{f}_c$  necessary to be applied to it in order to counter the uncapping forces that occur at the level of the contact between the needle and the needle cap and the needle weight that is applied the level of its Center of Mass (COM) which, measured from the inertial frame of the object  $\{\mathbf{B}\}$ , is placed at:

$$COM = [0 \ 0 \ 0.07]^T \quad (6)$$

The input data for this grasp analysis is represented in Fig. 16, where a photograph illustrates how the operator holds the needle with the right hand using the grasp identified as T21, while the left hand applies the external perturbation identified as UNCAP. The figure also contains two illustrative models of the hand, indicating the three elementary surfaces in contact with the object, and the mesh model representation of the needle, denoting its COM and the contact points. We can consider Fig. 6 to indicate the labels of the implied contact surfaces of the hand. The contact points resulting from the interaction of the distal phalanx of the thumb (1DP), the distal phalanx of the index (2DR), and the intermediate phalanx of the index (2IR), are denoted by  $\mathbf{c}_1$ ,  $\mathbf{c}_2$ , and  $\mathbf{c}_3$ , respectively. The coordinates of these contact points, measured from  $\{\mathbf{B}\}$ , whose units are specified in meters (m), were estimated as follows:

$$\begin{aligned} \mathbf{c}_1 &= [0.007 \ 0 \ 0.0725]^T \\ \mathbf{c}_2 &= [-0.007 \ -0.0075 \ 0.0725]^T \\ \mathbf{c}_3 &= [-0.007 \ 0.0075 \ 0.0725]^T \end{aligned} \quad (7)$$

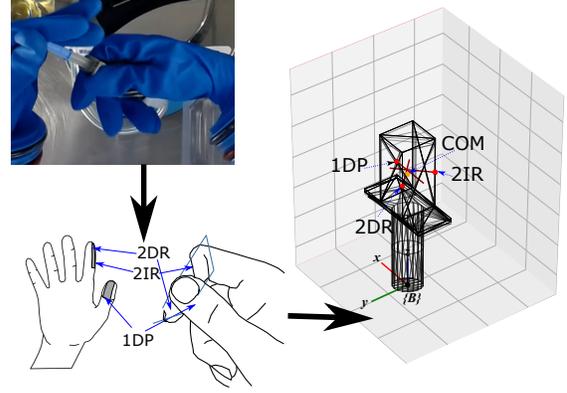


Fig. 16. Input information for the force-based grasp stability analysis applied to Needle-UNCAP using the grasp T21.

The perturbation UNCAP for the needle (that is the combination of the uncapping force of 9.4 N applied along Z in the object's frame and the weight of 0.103 N applied along Y) is denoted by  $\alpha \mathbf{d}_{W_{ext}} \in \mathbb{R}^6$ , whose estimated values are designated in the following vector:

$$\alpha \mathbf{d}_{W_{ext}} = [0 \ 0.103 \ -9.4 \ 0 \ 0 \ 0]^T \quad (8)$$

where the units for the first three elements of the vector are given in N, while the last three elements are in Nm. By considering Eqs. (6), (7), (8), as well as the friction coefficient  $\mu = 0.3$  as the input data for the optimization problem (P1) stated in Eq. (5), we obtain the following vector  $\mathbf{f}_c \in \mathbb{R}^9$  containing the minimum contact forces required to counterbalance the external perturbation UNCAP described in Eq. (8).

$$\mathbf{f}_c = [16.6 \ 5 \ 0 \ 10.5 \ 2.3 \ -1 \ 14.1 \ -2.3 \ 0]^T \quad (9)$$

Since the HF model considers only the transmission of normal forces, we can formulate the following vector containing the normal components of the applied forces:

$$\mathbf{f}_{cn} = [16.6 \ 10.5 \ 14.1]^T \quad (10)$$

From Eq. (10), one can select the maximum value of the required normal contact forces needed to counterbalance the perturbations resulting from the "Needle-UNCAP" task. Such value is computed by applying the infinity norm as follows:

$$f_{cn_{max}} = \|\mathbf{f}_{cn}\|_{\infty} = \max(|\mathbf{f}_{cn_1}|, \dots, |\mathbf{f}_{cn_n}|) \quad (11)$$

The resulting value (in this case  $f_{cn_{max}} = 16.6$ ) should be considered as the minimum force value that each finger involved in the grasp must provide at the tip level to successfully perform the “Needle-UNCAP” task.

The hypothesis of selecting the maximum calculated value as the minimum value that the actuation system should provide has two main reasons: (i) it allows to guarantee the stability of the grasp patterns, (ii) some grasp can be performed by different combinations of fingers, so it is important that all of them can provide the same amount of force.

The procedure illustrated in this subsection is extended below to all other combinations involving the objects, grasps and external disturbances of the use-case, allowing to have a complete knowledge of the forces that are required to perform all tasks of the sterility testing process. This way, we can establish the force requirements that the mechanical system should provide.

### 3.3.2 Multi-parametric data generation

A multi-parametric analysis that includes all the combinations of parameters (*object data, grasp type settings and external perturbations*) is used to generate and store data for post-processing analysis. It helps better understanding the theoretical levels of effort that are required for achieving the use-case. Among the useful extracted information, the minimum required tightening force to be applied at contact points when holding the current object in order to perform the task (i.e. withstand the external disturbances applied on it) gives preliminary insights for further gripper design. These calculations were carried out in two ways: the first by considering all contact surfaces involving the grasp patterns using all five fingers. And the second one by removing the contact surfaces produced by the little finger (i.e. a four finger configuration). Fig. 17 presents the comparison of the required force values to perform the tasks of the use-case using five-finger and four-finger configurations with friction coefficients of  $\mu = 0.3$  and  $\mu = 0.5$ .

Comparing the required levels of effort between them highlights several analysis results.

1. Realizing the tasks of the sterility testing process involves a wide variety of effort levels to be produced, ranging from a few mN up to 80N.
2. The majority of tasks (93% and 90% for a five-finger and four-finger configuration, respectively) require moderate efforts (less than 20N).
3. A 20N force threshold can be considered as a realistic upper bound for the physically reachable force to be produced by a robotic gripper.

4. The tasks that require the highest levels of effort deal with specific use-case related operations that involve direction-dependent external disturbances (such as INSERT, PIERCE, etc.).

The few tasks that exceed the 20N level in both finger configurations are:

1. “Red plug - INSERT” corresponds to the action of plugging the object at the top of the canister.
2. “Canister - INSERT” and “Canister - REMOVE” are to put and remove the canister from its holder.
3. “Needle - PIERCE” is the action of inserting the needle into the rinse glass on the table.
4. “Kit- OPEN” is the action of robustly holding the plastic kit box with one hand, while pulling its tab with the second hand, in order to open it.
5. “Marker cap – RECAP” and “Marker cap – UNCAP” are the actions of putting on and off the cap on the marker whose required efforts are estimated for the marker cap.

And for only the four-fingers configuration:

1. “Marker – RECAP” and UNCAP are the actions of putting on and off the cap on the marker whose required efforts are estimated for the marker itself.
2. “Tube – INSERT” in the action of inserting the flexible tubes into the pump.

## 4 DISCUSSION ABOUT TECHNICAL SPECIFICATIONS AND RECOMMENDATIONS FOR A FUTURE GRIPPER DESIGN

Having presented in detail our methodology and its application to the study of the manual gestures encountered in the sterility-testing process of the Trace-Bot project, we have concluded the following regarding a robotic gripper that would be well suited for the reproduction of the associated tasks:

### 1. From the human-centered gesture analysis

- (a) A four-finger configuration will be sufficient to carry out the described use-case process.
- (b) Each finger should have three DoF for flexion-extension movement.
- (c) Tactile sensors should be incorporated in the three phalanges of each finger and the area of the palm near the proximal phalanx of each finger. The surfaces of the distal phalanges have the highest priority in the placement of tactile sensors, then the intermediate phalanges, the proximal phalanges, and finally the palm.

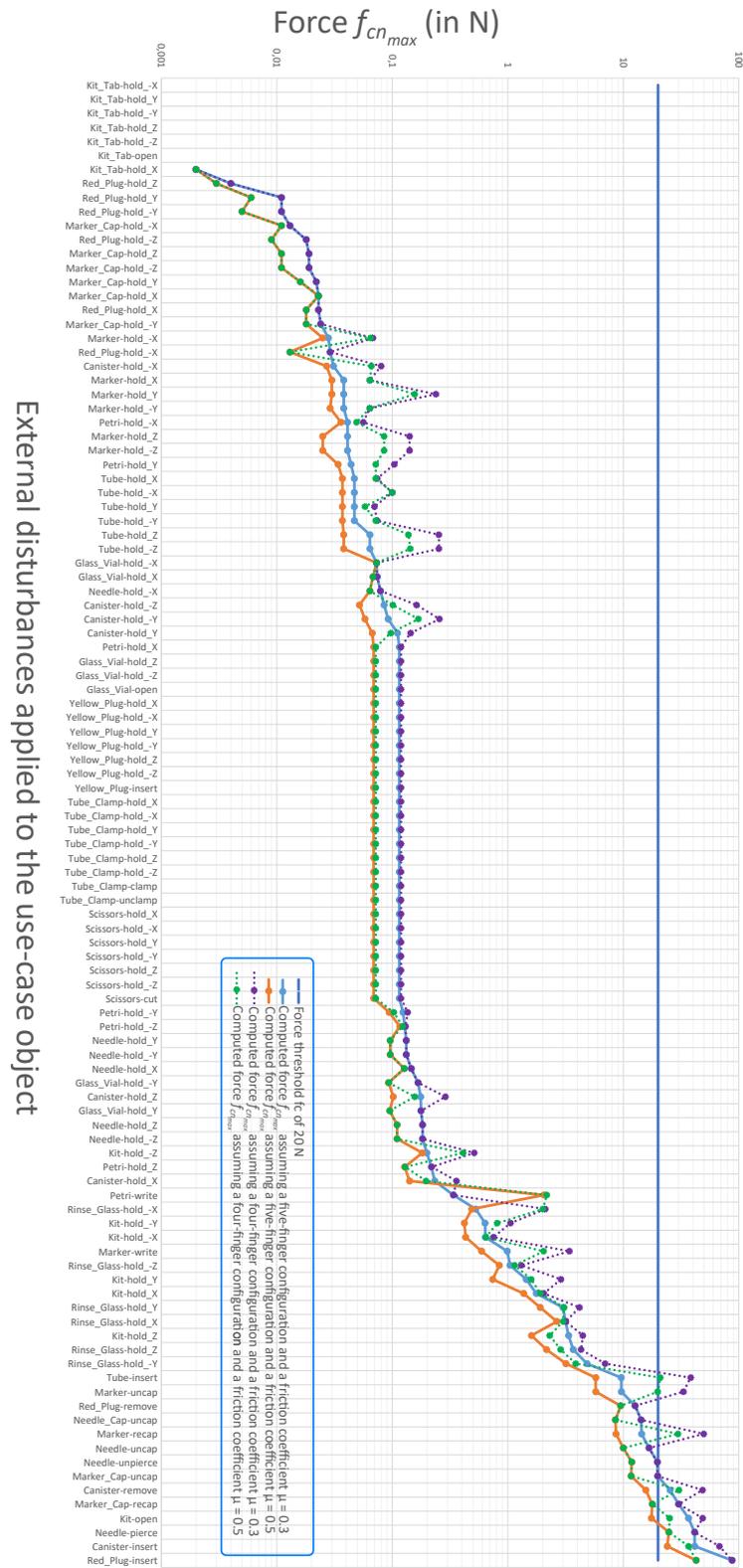


Fig. 17. Theoretical required level of force to be applied at contact points of all objects as a function of external disturbances (computed forces assuming a pessimistic  $\mu = 0.3$  and optimistic  $\mu = 0.5$  friction coefficient in the HF contact modeling) for a five-finger and four-finger multi-fingered gripper configuration.

- (d) It is highly recommended to integrate tactile sensors on the side of the intermediate phalanx of one finger.

## 2. From the force-based grasp stability analysis

- (a) In order to successfully perform the 90% of the tasks described above, the actuation system of each finger should provide 20N at the finger tip. This means that the combination of electromechanical elements (electric motors, pulleys, cables, gears, etc.) must be optimized in order to generate the solicited amount of effort.
- (b) To perform those tasks that require more than 20N, we suggest as a future work proposing non-human-based grasps, which may contain more contact points or a redistribution of them to reduce the required amount of effort. Then by using the previously described grasp-quality metric, verify to which extent the required efforts are reduced.

These technical specifications are grounded in a deep analysis of the use-case. The proposed kinematic simplifications compared to the human hand and the placement of the tactile sensors are directly in line with the statistically less, respectively more, used elementary hand surfaces. The same holds for the amount of force that was chosen in order to allow for the reproduction of a vast majority of the tasks, yet without requiring bulky and heavy actuators. These results were used as a basis for the preliminary design of a four-fingered gripper for the TraceBot project. Therefore, several CAD designs were considered and compared, based on their ability to grasp the use-case objects and on the required range of motion in each joint. The best candidate is shown in Fig. 18. It consists of four fingers, each composed of three phalanges. The surfaces in checkered texture indicate the areas on the phalanges and palm to locate the tactile sensors. Each finger has the ability to rotate around itself, besides two of them (which are located on opposite sides of the palm), have the ability to rotate around the palm. We are currently working on validating this configuration by trying to replicate the grasps described in Table 1 with the help of a CAD software (see some examples grasps in Fig. 19). In this study, the provisional dimensions of the phalanges are 1.5 times larger than in the human hand in order to have sufficient space to place the electronic components of the tactile sensors. Certainly, it is not possible to replicate all grasps due to the absence of a fifth finger. However, the proposed configuration is able to replicate most of them. Also, this configuration, intended to give the gripper a wide versatility to mimic poses that resemble those of the human hand, can also achieve alternative

postures when required.

It is worth noting that this methodology should be considered in the early design stage of a dexterous robotic gripper. It is intended to allow determining the design drivers of the gripper (number of fingers, number of joints, number of links) as well as to establish where to place tactile sensors and to determine the force that each fingertip must provide to guarantee the stability of the grasps when performing a given set of tasks. Practical aspects of mechanical integration and optimization are outside of the scope of this research and will be addressed in future work considering the aforementioned specifications as input requirements. Still, based on the observation of the preliminary design shown in Figure 18, which guarantees stable grasps of most of the use-case objects with similar contact points as the human hand (limited to four fingers which should be able to apply a force of 20 N at the fingertips), we can emphasize certain advantages of our methodology with respect to others. Using human grasps captured through ergonomics-based observations of operators at work as a source of inspiration allows guarantying a sufficient versatility to adapt to the different objects of the considered use-cases (with guaranteed performances thanks to the associated grasp stability analysis), contrary to technologically driven optimization methodologies which often sacrifice some grasping and manipulation capabilities for the sake of simplicity. For example, the methodology proposed in [38], which relies on mathematical modeling to synthesize the mechanical architecture of underactuated fingers based on the distribution condition, besides being suitable only for planar architectures, focuses on a technological solution (i.e. underactuated fingers) that allows simplifying the grippers mechanical design at the price of a limitation of their capabilities: the grasping movement is not fully controlled, and manipulation is barely possible. The best parameters are found considering arbitrary poses and objects, whereas in our approach the parameters are established through a study taking into account the specific objects and movements of the studied use-case. The same holds for the selection of the actuation system in the methodology presented in [19], where authors emphasize the importance of a good selection of the actuators but do not relate their choice to a specific process whose success can thus not be guaranteed. Compared to these technologically oriented approaches, the methodology presented in this article is task oriented. This choice allows guarantying that the tasks of interest will be feasible, yet the limitation to certain tasks leads to simpler solutions than bio-mimetic designs presented for example in [10], [11], and [12]. Compared to bio-inspired approaches which try to reproduce the whole capabilities of the human hand, whatever the asso-

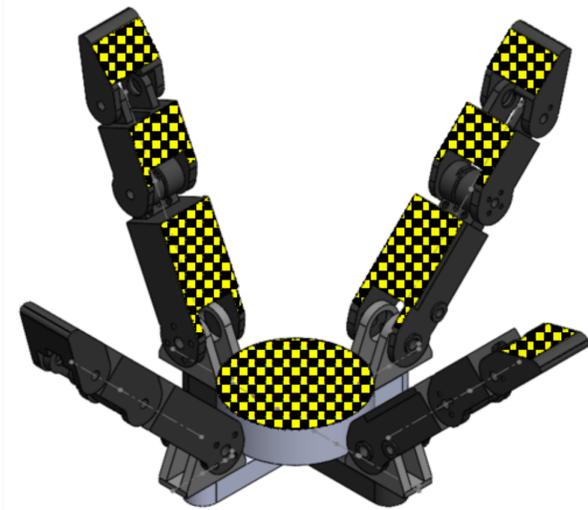


Fig. 18. Suggested kinematic configuration of the multi-fingered gripper for the TraceBot project, based on the results of the application of the proposed methodology.

ciated complexity, and to the technologically-driven solutions that try to limit the electro-mechanical complexity at the price of arbitrarily limited capabilities, our methodology intends to help finding the best possible compromise between grasp capabilities and design complexity for a given context of use and set of tasks whose performance is guaranteed.

## 5 CONCLUSIONS

The objective of this article is to introduce a novel design methodology to provide technical specifications, as well as recommendations for the design of multi-fingered grippers focused on a specific process. The proposed methodology merges two types of analyses, one centered on the analysis of the human hand gestures and grasps used while performing some task (Human-centered gesture analysis), and the second focused on the forces exerted on the object (Force-based grasp stability analysis). As an example, it was applied to establish specifications for the design of a future multi-fingered robotic gripper that will perform the tasks that comprise the sterility testing process within the TraceBot project. The first part of the methodology helped us to define the structural synthesis of the gripper, whereas the second part had the purpose of knowing the amount of effort that the future gripper must provide to perform each task of the use-case process to be automated. Moreover, the results of this research allowed us to propose a kinematic architecture for

the future gripper which we have validated in CAD by providing its ability to grasp most of the use-case objects, yet with more simple kinematics than the human hand, as expected from the application of the proposed methodology. Of course, this methodology remains generic and it could be applied to other case studies where future multi-fingered grippers are to be designed to accomplish specific processes while balancing simplicity and functionality. It could also be extended to the specification of other types of dexterous devices like prostheses or orthoses.

## ACKNOWLEDGMENTS

This research was supported by TraceBot project. TraceBot has received funding from the European Union's H2020-EU.2.1.1. INDUSTRIAL LEADERSHIP programme (grant agreement No 101017089). The authors would like to thank Clovis Bached and Ricardo Rico Uribe for their significant contributions to this research.

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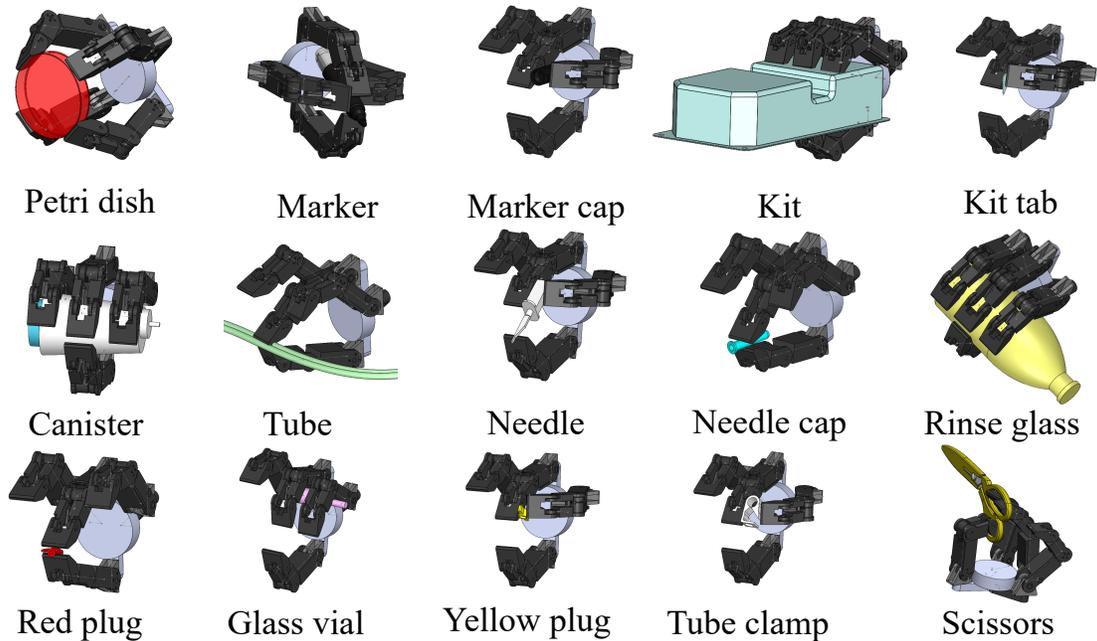


Fig. 19. CAD representation of the proposed multi-fingered gripper grasping the use-case objects (the grasps and gripper-objects contacts locations are directly inspired by the human grasps identified during the application of the proposed methodology).

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