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Use of a human-centered manual interaction patterns analysis methodology for the specification of dexterous robotic grippers*

Thomas Mokadim, Florian Gosselin

Abstract— **The advent of robots in our daily life depends on their ability to navigate and intervene efficiently in our environment. Whether considering household or industrial applications, one of the most important functions they should have is the ability to grasp and manipulate a large amount of objects, tools and machines that can vary in form, size and weight, but share the fact that they were designed for humans and have functional elements, e.g. buttons or handles, fitted to the human hand. The development of biologically inspired anthropomorphic robotic hands thus appears as a natural research path to allow robots replicating these activities. Such devices however prove to be complex to design and control, and they remain in practice limited to date to laboratory experiments. They hardly reach a sufficient simplicity, robustness and cost allowing for their widespread adoption in our houses or factories and industrial robots still make use of simple bi-digital grippers or dedicated tools which in turn suffer a poor versatility. To overcome this situation, novel dexterous grippers are required, that are sufficiently versatile to adapt to various situations and objects yet simple enough and cost effective. This compromise is however difficult to achieve and the specification of such grippers is still an open issue. This paper introduces a human-centered manual interaction patterns analysis methodology that intends to contribute to fill this gap. After a presentation of our approach, we apply it in different contexts and show how it can be used to orient a robotic gripper design that will fit given use-case requirements.**

I. INTRODUCTION

Robotics has made tremendous progress in the last decades. Long limited to repetitive tasks in controlled environments in the context of large factories automation, e.g. car bodies welding and painting, robots are now used to perform various tasks in an increasing number of contexts, e.g. logistics, inspection and maintenance, robotically assisted agriculture, subsea and space exploration, etc. Several research teams even try to use advanced robots in daily household or work environment, as for example Valkyrie, Armar 6, TRI, HRP-4 or TORO [1] [2] [3] [4]. Such systems remain however limited to date to research and test environments as they are too complex and not robust enough for real life conditions. One of the sole example of the use of a bimanual torso robot in an industrial setting is the Glory factory in Saitama, Japan, where Kawada Nextage robots are used to assemble money-handling machines [5].

As a matter of fact, the widespread diffusion and adoption of robots in our surroundings requires, as for human beings with which they would have to share space, the integration of various functions (sensing, reasoning, action planning and monitoring, mobility and manipulation, notwithstanding human-robot and robot-robot interactions). Despite recent progress is various kinds of sensors, embedded electronics, mechatronics, artificial intelligence or control, none of these functions still compares to human in terms of performance, robustness and adaptability.

This assertion also holds for grasping and manipulation. To date, no existing device allows replicating the subtle musculoskeletal and sensory apparatus of the human hand. Still, as our environment is full of man-made objects fitted to our hands, e.g. machines buttons and knobs, tools and furniture handles, etc., biologically inspired anthropomorphic robotic hands could appear as a natural and appealing solution for replicating human-like grasping and manipulation abilities. As a consequence, numerous dexterous robotic grippers with a kinematic structure resembling the human hand were developed. Among others, we can cite the initially pneumatically then electrically actuated Shadow Robot Hand [6] [7] and its backriveable actuation equivalent developed by CEA-LIST [8], or the DLR AWIWI hand [9]. Such devices, some equipped with additional tactile sensors, are capable to reproduce part or all of the grasps found in usual grasping taxonomies [10] [11] [12] and to perform dexterous tasks either under direct human control in telerobotics [13] or autonomously after learning [14]. They prove however to be highly complex, both in their design and control, and they remain in practice limited to laboratory experiments. On the contrary, industrial (and service) robots still most often make use of simple bi-digital grippers or dedicated tools which in turn suffer a poor versatility.

To overcome this situation, novel dexterous grippers are required, that are sufficiently versatile to adapt to various situations and objects yet simple and cost effective enough to allow their widespread adoption and use. As the most bulky, heavy and complex part of a robot hand is its actuation system, an appealing solution to answer this challenge is to reduce the number of actuators and couple the hand's degrees of freedom (DoF), as for example on the Schunk hand [15], which has only 9 actuators for 20 joints. Even if it allows a more compact and more robust design, this solution however introduces some limitations in terms of the number of available grasps, with for example only 14 of the 16 Cutkosky's grasps feasible with the Schunk hand. Soft couplings allow increasing this number and push this principle to an extreme without suffering this limitation. As an example, the Pisa/IIT SoftHand [16], which implements the principle of synergies to drastically limit the number of actuators, allows grasping a wide range of objects despite

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having only one actuator. The fingers and consequently the objects movements are however not fully controlled, notwithstanding a limited dexterity. Indeed, to allow for fully controlled in-hand manipulation, several fingers with several actuated joints each are required. The most straightforward solution to limit the device's complexity is then the reduce the number of fingers, as for example on the ROBIOSS hand which has only 4 fingers with 4 actuators each [17]. However, this device does not answer the requirement for simple and rugged design and this principle can unfortunately not be pushed very far, as more simple grippers with only 3 fingers (e.g. BarrettHand [18]) or even 2 prove to be unsuitable for dexterous tasks (i.e. in-hand manipulation).

As a technological compromise is difficult to reach when considering a generic gripper, we propose in this paper to come back to its specifications, in order to try to release them. Therefore, we introduce a methodology allowing an in-depth analysis of the tasks performed by a human operator, with the goal to better characterize the range of tasks made feasible as a function of the gripper's characteristics. While this analysis can be made in a general context, we apply it here for specific use-cases, as a generic gripper would for sure fall within the aforementioned contradictions. Also, focusing on different use-cases better allows to show how the obtained results can orient the gripper's design. This work is inspired by [19] and [20]. This previous research however focused on the design of hand exoskeletons, and the problem was slightly different as it consisted in trying to find the most suitable structure for stimulating the human hand which cannot be changed, while we consider here the reproduction of its grasping and manipulative abilities with a potentially more simple design. To our knowledge, it is the first time this method is used for orienting the design of a robotic gripper. Also, this methodology is enhanced with improved characterization of the hand surfaces and a refined study of their combination and integration.

This article is organized as follows: the user-centered manual interaction patterns analysis methodology is first presented and applied in different contexts in section II. The results are then discussed in section III, and a brief conclusion is given in section IV.

II. USER-CENTERED MANUAL INTERACTION PATTERNS ANALYSIS METHODOLOGY

A. Introduction and use-cases description

The human-centered analysis method presented in this section is based on a methodic identification and analysis of the grasp types and manual interaction patterns observed when considering a set of tasks performed by a human operator. The principle is the following: we first draw surfaces on the inner surface of the hand representing the contact areas associated with the different interaction patterns used by the operator. This information is exploited in two ways. First, these surfaces are weighted by their frequencies of use and displayed on maps that allow to quickly isolate the most frequently used hand areas, given a certain set of tasks. Second, they are used to generate interaction trees which inform the designer on the available grips given a set of contact surfaces that can be controlled. In other words, they give an indication on the versatility of the device as a function of the gripper complexity. This methodology, composed of the 6 steps further presented below, allows to maximize the compromise between grasping and manipulation capabilities and design complexity (thus cost).

It is applied in three different contexts. All of them require handling both rigid and flexible material but they differ in the type of grasped and manipulated objects and tasks performed:

- Grasping and manipulation of food packaging: this first use-case is provided by a food packaging industrial. Packaging machines are usually filled using rails full of empty plastic pouches. This requires upstream that rails are filled with empty pouches. We focus here on their manual extraction from large boxes and alignment in the rails.
- Grasping and manipulation of fabric for lingerie manufacturing: this second use-case is provided by a women lingerie manufacturer. The targeted demonstration focuses on bra thermoforming. Some previously cut textile parts are thermoformed in working cells consisting of a set of previously configured forming presses (usually two). A worker continuously feeds the presses by placing the fabric inside them and ensuring its flatness and orientation using two hands. Once the piece is in final position, the worker activates the press. The rest of the thermoforming process is automatic. When it is finished, a new bi-manual manipulation is required to proceed with a quality inspection to ensure the depth of the bra cup.
- Grasping and manipulation of fiberglass fabric for composite panels manufacturing: this third use-case is provided by a composite panels manufacturer for the automotive sector. The targeted demonstration focuses on the layup process necessary for the manufacturing of composite panels. This use-case involves the manipulation of large fabric pieces and reinforcement foam blocks, up to several meters in length and / or width, requiring several operators to work in cooperation. Several fabric layers and flexible foam blocks are successively placed in the mold until it is ready for the resin infusion.

B. Identification of manual interaction patterns

The proposed methodology begins with an observation of the human operators at work. Due to the COVID-19 pandemic, it was not possible in practice to go on-site at the time of the work and we had to rely on videos shot in the industrial premises of the involved companies. The food packaging videos last only 26s but they focus on the subtasks of interest, with a close-up view of the hands of operators filling the rails then the machines (these tasks being very fast, they are repeated many times). The total length of the lingerie manufacturing videos is about 2 minutes. They also focus on the subtasks of interest which are repeated several times. The composite panels manufacturing videos are much longer. They last more than 1 hour, the process being more complex, with various successive steps.

Each video was edited with the Windows video editor, allowing to play it frame by frame. The aim of this review, performed by two people in order to double validate the information as proposed in [21], is to identify the successive grasps and interaction patterns used by the operators. Some of the observed motion patterns correspond to those found in Cutkosky's and Feix commonly used taxonomies [11] [12] or to canonical exploration patterns found in [22] (see Fig. 1 and Fig. 2 below).

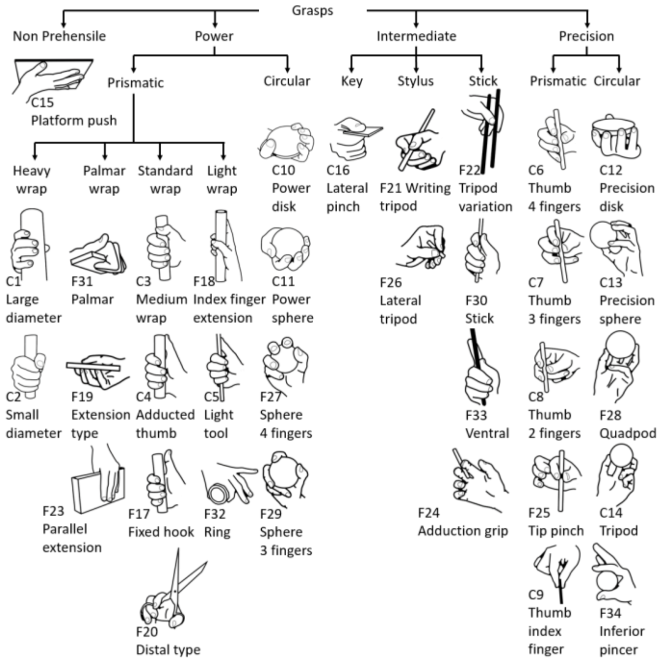


Figure 1. Taxonomy of grasps (Ci: grasps proposed by Cutkosky [11], Fi: grasps proposed by Feix [12])

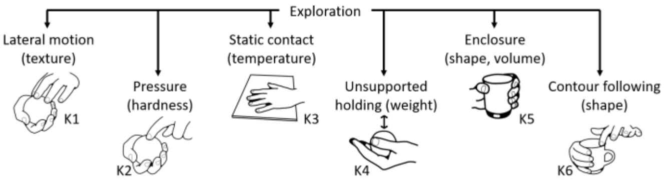


Figure 2. Canonical exploration patterns (Ki: patterns proposed by Lederman and Klatzky [22])

Figure 3. Specific interaction patterns encountered in handling of food packaging and manipulation of fabric for lingerie and composite pannels (for confidentiality reasons, the displayed use-case photos are in limited number and do not allow illustrating all hand pictures which can be depicted in configurations that slightly differ from the photos)

These patterns are however not sufficient to cover the use-cases activities. Indeed the taxonomies found in the literature only account daily used rigid tools and objects (e.g. plate, pen, handle, book, …) and usual grasps used to interact with them. They are not sufficient to account for specific technical gestures necessary for example for grasping flexible objects like lingerie or fiberglass fabric. As shown in Fig. 3, in the use-cases videos, expert operators also make use of very specific interaction patterns (labelled FPi for food packaging handling, WLi for women lingerie manufacturing and CPi for composite panels manufacturing):

- In food packaging manipulation, different grasp types are used to catch pouches in boxes and to place them in the rails, depending on the operators' personal preferences. The rack is hold either with the 5 fingertips or with 4 fingertips except the index (which serves as a rest on whatever support). Picking a pouch can be achieved with 3, 4 or 5 fingertips. Once the charger is full, the operator shifts the rail in horizontal position and moves it to the machine with both hands (the rail is relatively long). Usually, operators use 5 fingertips to carry the rear of the rail and drive the front with a 3-digits grasp. After setting the rail into position, operators usually use the back of the hand that drives the rail to push the back of the stack and transfer it from the rail to the machine.
- Lingerie manufacturing workers have to pick raw pieces of fabric and place them into a thermo-morphing press. After the fabrics have been shaped, they are pulled from the machine and operators check the depth of the shaped cups with a Vernier. Then they stack the fabric next to their workstation and go for another piece of fabric. The analysis of the videos shows once again that, depending on their personal preferences, operators use different grasp types to grasp the pieces of fabric or press buttons to launch the machine. For security reasons, the thermo-morphing machine can only be started if 2 buttons placed on both sides of the workstation are pushed simultaneously. To do so, some operators prefer to use their thumb, other fingers resting on the edge of the workstation plane. Other workers tend to push the buttons with the middle finger, all fingers out of the workstation plane. Workers have also their own fashion to grasp and transport fabric. Some use both hands as 2 pairs of pinches: one pair between the thumb and the index apex or the lateral side of the index, and the other pair between the middle and the side of the ring finger.
- The last use case focuses on the preparation of fiber panels molding. This task is performed by 2 to 3 operators working together. Not surprisingly, depending on their personal preferences, they use different grasp types. Some workers prefer to rest their hand by the fingertips and use their thumb to place a layer accurately, others prefer to rest their hand by the palm and use their index, middle and ring. Also, when picking a large piece of fiber, many workers use similar grasps as in lingerie manufacturing, but others use a 3 fingers lateral pinch grasp.

C. Identification of hands-objects contact areas

The second step consists in identifying, for each interaction pattern, the hands-objects contact area. Fig. 4 below illustrates some examples associated with standard grasps and exploratory movements and with use-cases specific interaction patterns. For the latter, we distinguish hand areas that are used only as supports (in red below) and those that are used for functional operations (in grey and green). Supports are useful for humans but they are not required for robots. Red areas will thus not be considered in the remaining of the process. When several alternatives exist which involve different supports but the same functional hand areas, they are grouped together (e.g. the middle fingertip in WL1, or the index, middle and ring fingertips used to stretch the fabric in WL4).

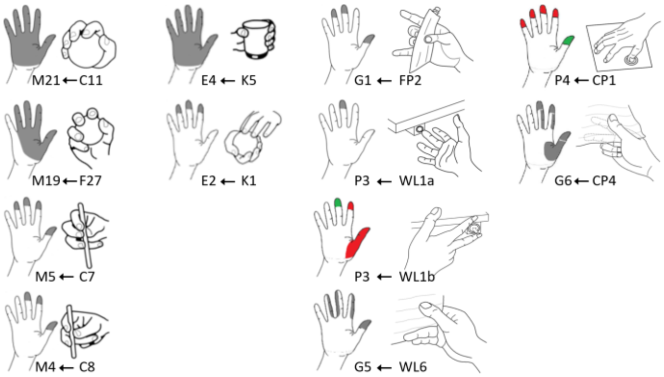


Figure 4. Example hand-object contact areas (a table of correspondance between the usual grasps types Ci or Fi or the canonical exploration patterns Ki and the associated hand areas Mj or Ej can be found in [19])

These areas are labelled E1 to E4 for those associated with exploration movements (they come in lower number than the interaction patterns as several patterns may share the same contact areas), M2 to M21 for those associated with grasp taxonomies (M1 is not accounted for as it shares the same area as E1), and G1 to G6 for those associated to novel grasps, P1 to P4 for non-prehensile push type interactions encountered in those contexts.

D. Identification of the frequency of use of each pattern

The frequency of use of each interaction pattern is obtained from a video analysis of the operators performing their task. Several observers (two in our case) carefully look at the videos and identify the interaction patterns used by the operators, as explained in [21]. Each grasp type and/or interaction pattern is accounted as a specific step. For each step, we note the type of pattern, the time it begins and ends, and its duration. In practice, we distinguish left and right hands when both hands are used. At the end of the process, we sum for each pattern the total amount of time obtained for both hands, and for the different operators when several people collaborate to perform the work. This work allows identifying the total time as well as the relative frequency (i.e. the percentage of time) each pattern is used.

The figures below summarize the results obtained. Grips are sorted from left to right according to their frequency of use (grasps with a percentage of use well below 1% are not represented).

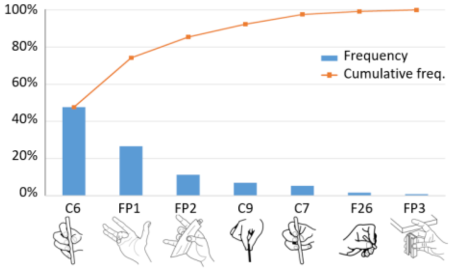


Figure 5. Food packaging grasps frequencies of use

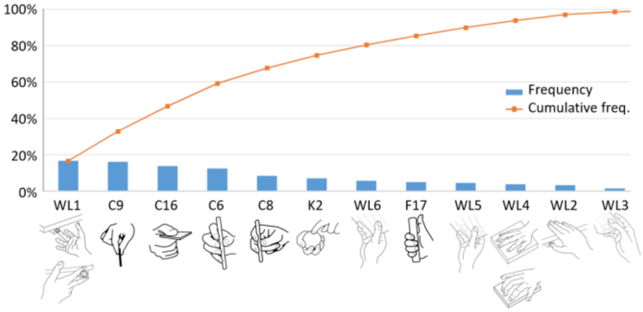


Figure 6. Women lingerie fabric grasps frequencies of use

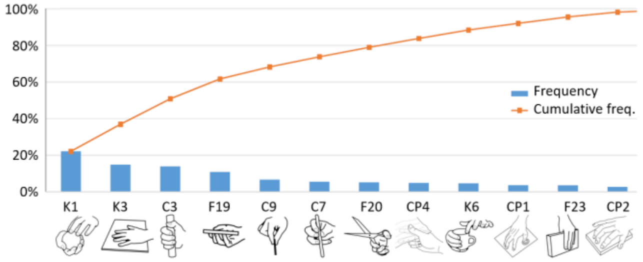
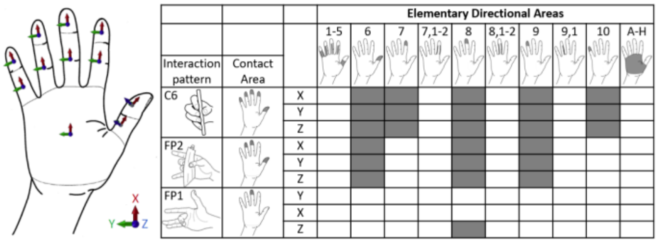


Figure 7. Composite pannels grasps frequencies of use

E. Identification of the directions of the efforts at the level of the hand-object contact areas

During the analysis of the videos, we also identify visually the directions in which forces are applied on the hand. This analysis has to be made on each of the elementary hand areas as all areas may not be involved similarly during a given manual interaction. The first step consists in setting a Cartesian frame on every phalanx (distal, intermediate and proximal) and on each area on the palm. Then the observers evaluate the direction(s) in which each area is stimulated, as shown for example in Fig. 8 for some of the food packaging interaction patterns. It is worth noting that when coming in contact with an object to interact with it or grasp it, forces are first applied in the Z direction. Then depending on the forces exerted on the object, forces may also appear in the Y and/or X directions. As a result, the Z direction is the most used direction when manipulating objects, followed by the Y and X directions.



			Elementary Directional Areas									
Interaction pattern	Contact Area		1-5	6	7	7,1-2	8	8,1-2	9	9,1	10	A-H
C6		X		▨	▨		▨		▨		▨	
		Y		▨	▨		▨		▨		▨	
		Z		▨	▨		▨		▨		▨	
FP2		X		▨			▨		▨			
		Y		▨			▨		▨			
		Z		▨			▨		▨			
FP1		Y										
		X										
		Z					▨					

Figure 8. Example of the identification of the directions of applied forces

F. Generation of hand interaction maps

By associating the inner surface of the hand used to execute a given grasp or interaction pattern with its frequency of use, we can get the frequency of use of each of the elementary interaction areas it is composed of in each direction. By overlapping the results associated with the different grasp types, it is possible to draw interaction maps. As shown in Fig. 9, the accumulated frequency of use on a given elementary contact area in a given direction is computed as the sum of the frequencies of use of all grasps requiring this elementary contact surface in this direction.

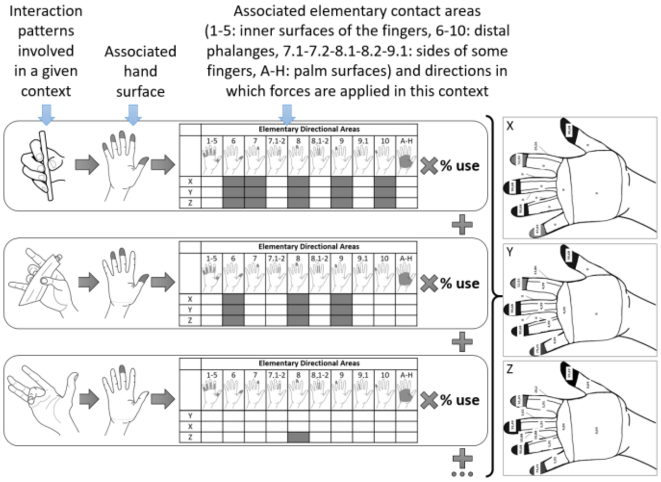


Figure 9. Generation of hand interaction maps

The food packaging handling interaction maps displayed on Fig. 10 below show that the 5 fingertips are clearly the most used surfaces of the hand, with forces applied on them in all directions. On the contrary, as almost only precision grasps are used, intermediate and proximal phalanxes, as well as the palm, are almost not involved.

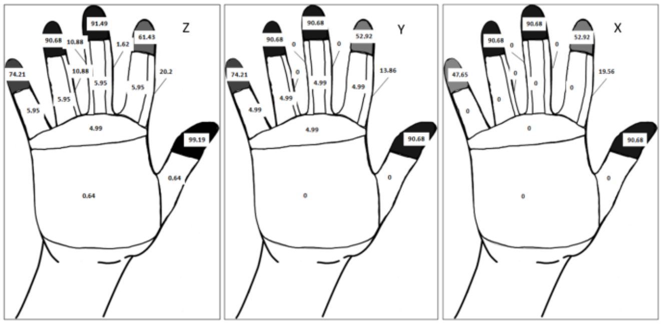


Figure 10. Food packaging handling interaction maps

In the lingerie manufacturing use-case also, the fingertips are the most used hand areas while the palm and inner side of the proximal phalanges are almost not used (see Fig. 11). This map however differs from food packaging handling in two aspects. First, the thumb, index and middle are much more used than the middle and little finger. Second, the side of the index finger is almost as used as the ring fingertip.

On the contrary, composite panel manufacturing workers' interaction maps show that, even if the fingertips are still the most used hand areas, the palm and inner side of the proximal phalanges are also involved in Z and Y (see Fig. 12).

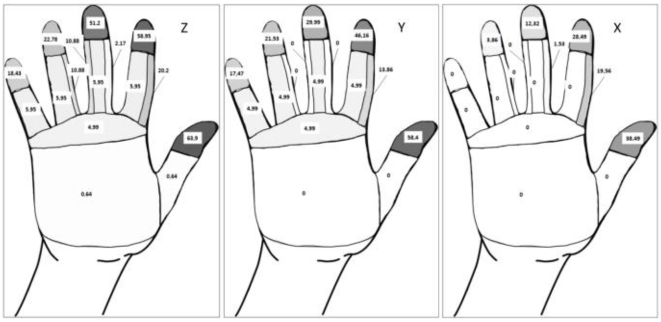


Figure 11. Lingerie manufacturing interaction maps

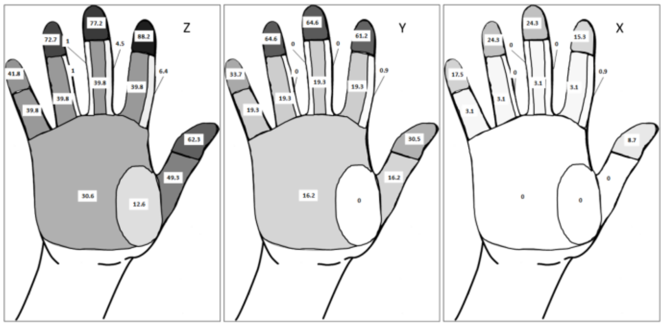


Figure 12. Composite pannels manufacturing interaction maps

G. Generation of interaction trees

Interaction maps give an overview of the way the hand is excited while performing a given set of dexterous activities. But they do not allow to determine how many of those activities can be achieved considering a set of hand contact surfaces. To answer this question, interaction trees, a tool matching the available percentage of feasible interactions with a given set of contact hand surfaces, were proposed in [19]. They are constructed as follows:

- The simplest contact surfaces (e.g. index fingertip) enabling to execute one or several basic interaction patterns are first considered as leaves of the tree. They are associated with the percentage of time they are used in the considered context, and their tag is colored in grey scale according to this percentage.
- More complex hand areas, i.e. stimulated in more directions and/or composing an interaction pattern made of a larger set of elementary contact areas, are then successively added to the tree, constituting increasingly large branches. The percentage of time they are stimulated is computed on an additive basis, that is as the sum of the percentages of time of all patterns they allow to realize, and their tag is colored in grey scale according to this percentage.
- All leaves and branches are associated with a given number of DoFs computed as the product of the number of elementary contact areas they are composed of, and the number of directions in which each of these areas is stimulated. They are sorted vertically as a function of their DoF number.
- Leaves and branches are linked together if the hand surface areas and directions in the latter includes the areas and directions in the former.

- The tree generation is over when all the branches starting from a leave reach a final tag (i.e. trunk) allowing 100% of dexterous interactions.

It is worth noting that when considering inclusions, we consider each single area and each combination of directions separately. Let's consider Fig. 13 below to illustrate this principle. This picture depicts an arbitrary example in which only four grasps are implied (in this figure HA(Ci-Cj-Fk-Fl)/ZYX is used for naming the hand area (HA) allowing to reproduce the interactions patterns Ci, Cj, Fk and Fl, provided each elementary hand area the HA is composed of can be stimulated in directions Z, Y and X; %HA(Ci-Cj) (resp. %HA(Fk-Fl)) designates the percentage of time the patterns Ci and Cj (respectively Fk and Fl) are used). The hand areas involved in C6 and C12 being similar, they are grouped in a single leave, while the hand areas involved in F19 and F23 constitute different leaves, as they differ from each other. Let's further make the hypothesis that the objects in hand are manipulated so that forces are applied in X, Y and Z on all elementary hand areas. In this case all leaves will have a complexity index of 15 as they have 15 DoFs, that is 5 times X, Y and Z. Their efficiency is computed as the percentage of time each pattern is used. As patterns C6 and C12 are associated with the same hand area, their scores are added. These hand areas can then be combined together, and their tags linked. Tags are linked if and only if the areas of the larger branch include those of the smaller one (should some areas not be involved in 3 directions, branches would be linked only if the directions in which the areas of the larger branch are stimulated include the directions in which those of the smaller one are). The hand areas associated with larger branches allowing to perform all the grasps of the smaller ones they are linked with, their efficiency scores are computed as the sum of the scores of the smaller branches (scores are accounted only one time even if the associated areas appear in several branches). The trunk is composed of a tag allowing to perform all grasps. Its score should be 100%.

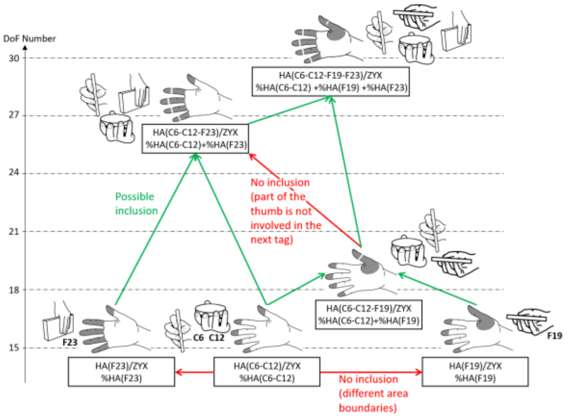


Figure 13. Example factice interaction tree

As real use case interaction trees are more complex, it is difficult in practice to indicate all areas and directions in each tag. To cope with this issue, the hand areas pushed in different directions are labelled with a second number (e.g. M3.1 and M3.2 at the bottom of Fig. 15 share the same areas but in different directions). Also, the areas obtained by a combination of areas are labelled with a '+' (e.g. M4+M8 in Fig. 14 represents the surface combining areas M4 and M8).

The food packaging handling interaction tree displayed in Fig. 14 below confirms the results of the interaction map, i.e. the interest to focus on the five fingertips. A gripper with only 1 to 4 DoFs only allows to reproduce at most 10% of the tasks, whereas with 10 properly chosen DoFs it can reach up to almost 36% of the tasks, 47% with 13 DoFs. A milestone is reached with 15 DoFs (five fingertips with 3 DoFs each) as it is expected that such a gripper could reproduce more than 98% of the tasks. Adding a 16th DoF only offers less than 2% more. This doesn't justify the extra-complexity.

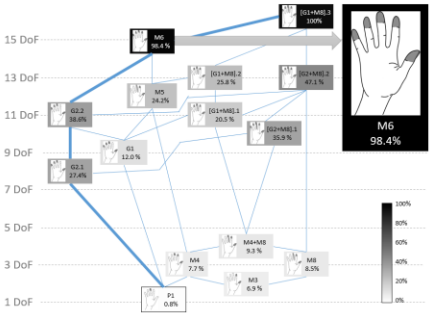


Figure 14. Food packaging handling interaction tree

The lingerie manufacturing interaction tree, shown in Fig. 15, is much more complex, with tags well distributed on the vertical axis.

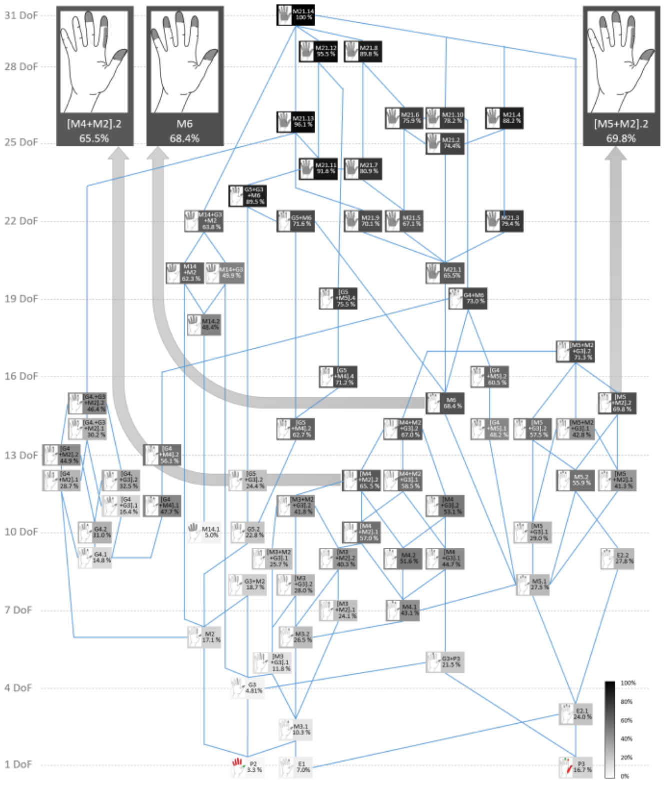


Figure 15. Lingerie manufactruring interaction tree

Among the tags that favor the best compromise between capabilities (i.e. ability to reproduce a large amount of interaction patterns) and complexity (i.e. low amount of DoFs), we can emphasize E2.1 which can reproduce about 24% of the grasps with only 3 DoFs, M4.1 that reaches a score of about 43% with only 7 DoFs, [M4+M2].2 with a score of about 65% for 12 DoFs, M6 and [M5+M2].2 with a score of about 68% and 70% for 15DoFs, and [G5+G3+M6] with a score of almost 90% for 23DoFs. The former's efficiency is however too limited to allow for an efficient robotization of the task while the latter are quite complex to implement. A good compromise is obtained with [M4+M2].2, M6 and [M5+M2].2 which are composed of a combination of four to five elementary areas chosen between the thumb, index, middle, ring and little fingertips plus the side of the index, all these four or five areas being stimulated in 3 DoFs each.

The composite panels manufacturing interaction tree, displayed in Fig. 16, is also quite complex. Scores above 65% require the involvement of the palm, and the basis of the thumb is mandatory to go above 32%. Fortunately, the palm can usually be passively involved by pressing the object against it with the fingers. Hence palm DoFs can to some extent be considered as 'free', provided the fingers have a sufficient mobility. A good compromise is obtained with areas [M5+G4+G6] and M21.4 which allow to reproduce grasps used 55.4%, respectively 57.6% of the time, with 16 DoFs. Contrary to previous cases, both of these areas involve at least part of the palm. M21.4 involves the whole palm, but only in Z, that is normal to the skin, corresponding to a power grasp. [M5+G4+G6] involves the thumb, index, middle and ring fingertips which are stimulated in 3 DoFs plus the base of the thumb and the side of the index and middle which are excited only in Z, corresponding to a combination of intermediate grasping and manipulation.

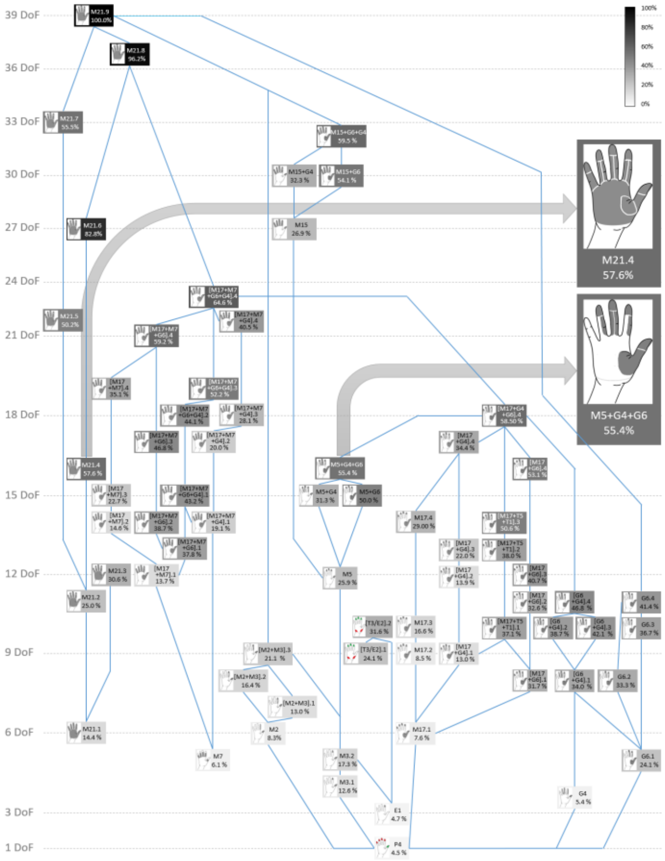


Figure 16. Composite panels manufacturing interaction tree

III. DISCUSSION

The work presented above is inspired by [19] and [20]. In the first reference however, no mention to the directions of efforts is made. This notion was taken into account in the latter, but only considering the interaction maps. It is the first time that directions are taken into account in the interaction trees. Also, the hand surface division is more precise than in previous articles, allowing to better distinguish the sides of the fingers which are much more used in fabric grasping and manipulation than during the use of usual tools accounted for in the literature taxonomies. Finally, we better characterize large areas, by distinguishing those which are stimulated as a whole (i.e. the hand configuration does not change) and those in which all their constituting elementary areas can move relative to each other (i.e. as the hand moves).

The obtained results are very rich. They can orient the design of a robotic gripper as a function of a given set of tasks to perform. Interaction maps allow showing the most used hand areas while interaction trees inform on the percentage of tasks that can be performed efficiently as a function of given combinations of elementary contact areas. It can be seen that, just as for a human being, the more independent areas involved, the higher number of possible interactions (interestingly, it is shown in [19] that when considering a larger set of tasks in order to account for a more generic use, interaction trees are highly correlated with the percentages of impairment usually considered when people are amputated from parts of fingers of complete fingers).

As shown by the related interaction maps and tree, operators involved in food packaging handling mainly use their five fingertips to grasp and manipulate plastic pouches using precision grasps. The 5 fingertips are clearly the most used surfaces of the hand, with forces applied on them in all directions. On the contrary, intermediate and proximal phalanxes, as well as the palm, are almost not used. A gripper with 15 DoFs (five fingertips with 3 DoFs each) is expected to be able to reproduce more than 98% of the tasks encountered in this context. Adding a 16th DoF only offers less than 2% more. It does not justify the extra-complexity.

Lingerie manufacturing operators also use mostly their five fingertips, but the ring and even more the little are less used than the thumb, index and middle. Another difference is that they use the side of their index finger almost as much as their ring fingertip. The palm and inner side of the proximal phalanges are almost not involved. A good choice is obtained with a combination of four to five elementary areas chosen between the thumb, index, middle, ring and little fingertips plus the side of the index, all these four or five areas being movable in 3 DoFs each. Several combinations of four or five of these six areas give similar efficiency, with scores ranging from 65 to 70% for grippers having 12 to 15 DoFs (four or five areas with 3 DoFs each). A score above 90% requires 23DoFs, which may seem quite complex to implement.

Regarding fiberglass panels preparation, operators use their whole hand, with a combination of power and precision grasps. It is worth noting here that by pressing an object against the palm with the fingers, the palm can be involved without the necessity to actuate it. Thus, we propose to mainly focus on the fingers. Once again, a good compromise is obtained with a gripper with at least 4 pads (corresponding to the thumb, index, middle and ring) able to move and apply forces in 3 DoFs against the palm.

IV. CONCLUSION

This paper illustrates how the concept of interaction maps and interaction trees, obtained from a user-centered manual interaction patterns analysis methodology, can be used to orient the design of a robotic gripper. Interaction maps clearly show how the hand is stimulated and interaction trees illustrate in a synthetic way the effectiveness of sets of contact surfaces as a function of their complexity, i.e. their capability to mirror in a natural and intuitive way human grasping tasks as a function of their number of DoFs.

It is worth noting that we applied this methodology separately for the different use cases. A global study would have also been possible, but it would result in more stringent requirements, which would be difficult to reach in practice. On the contrary, focusing on a given context, where a kind of genericity is still required, should allow developing more simple and robust grippers. Owing the recent arrival of novel rapid manufacturing techniques (e.g. additive manufacturing, printed electronics,…), it is reasonable to think that such generic yet non-universal grippers can be developed at reasonable costs, allowing to easily adapt to another context.

One limit of this work is that it is time consuming. The frame by frame analysis of the videos necessary for the identification of the different grasps and interaction patterns can take from few hours for short videos to several days for longer ones. The same holds for the second review necessary to identify the directions in which the forces are applied on the hand. An AI based recognition approach could probably help accelerating the process, but it would certainly require an important effort of development. Also, the identification of the links between the different labels in the interaction trees, still performed manually, takes a lot of time and could benefit from some automation. As a matter of fact, we are currently working on the development of trees automatic construction tools. Another limit of the work presented in this article is that it is limited to kinematic considerations. It does not inform e.g. on the level of forces required to grasps the objects of interest. Future work will focus on complementary techniques allowing to specify these aspects. Also, it makes the hypothesis that the robotic gripper will behave as a human operator. Alternative grasping strategies would worth being studied, allowing a potentially more simple design.

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