A framework for the classification of dexterous haptic interfaces based on the identification of the most frequently used hand contact areas

F. Gonzalez, F. Gosselin, W. Bachta

A Framework for the Classification of Dexterous Haptic Interfaces Based on the Identification of the Most Frequently Used Hand Contact Areas

Franck Gonzalez, Florian Gosselin*
CEA, LIST, Interactive Robotics Laboratory,
F-92265 Fontenay-aux-Roses, FRANCE.

Wael Bachta†
Institut des Systèmes Intelligents et de Robotique,
UMR7222, UPMC-CNRS, F-75005 Paris, FRANCE.

ABSTRACT

Haptic interfaces are purposed for the simulation of physical interactions with a virtual environment in a realistic way. Their design is often based on a compromise between the interaction capabilities and mechanical design complexity. This paper is aimed at providing a methodology that helps tuning this trade-off. A survey of both manipulation and exploration taxonomies allows the identification of elementary hand contact areas with their associated frequency of use. The relative importance of these areas is illustrated by the building of an interaction map for the hand. Some combinations of these elementary areas, with their frequency of use, are then organised into a graphical tree as a function of their complexity. This tree allows to review some existing devices and to propose some guidelines for improved designs.

Index Terms: Dexterous haptic interfaces; Interaction taxonomies; Hand contact surfaces; Quantified design trade-off

1 INTRODUCTION

Haptic interfaces are purposed for the simulation of physical interactions with a virtual environment in a way as realistic as possible. This asks for the highest level of transparency, i.e. the user should be able to grasp and move the interface in the same way as real objects and get the same feedback as for real interactions. Therefore, such systems should be designed to perfectly track the hand motions and to apply forces on any area of its surface. This challenges the current available technological solutions. Interaction capabilities of haptic interfaces are then often reduced to keep an acceptable level of technological complexity: a trade-off is made between interaction and design efficiencies.

Throughout the literature, three categories of haptic interfaces can be considered. The first one, including most of the commercially available interfaces, is based on universal 3 or 6 degrees of freedom (DOF) mechanisms, equipped with handles or tool-shaped props. Although allowing a realistic tool manipulation simulation, these devices offer a limited subset of tasks and reduce the users dexterity. The second category is made up of interfaces that focus on finger interactions. Because of the difficulty to address all degrees of freedom of the hand, developers of such systems often focus on specific activities. These tasks are analyzed to narrow the number of DOF to the required minimum. Two examples can be found in [1] and [2]. In the former, several educational applications involving fine manipulation of small objects are reviewed: it led to the conclusion that a two-finger device allowing for interactions with the index and thumb fingertips is sufficient for such tasks. An interface based upon these specifications was developed with only 12 passive and 6 active DOF (respectively 6 passive and 3 active DOF for each finger) [3] and proved useful for practical teaching applications [4]. In the latter, a study of hand interactions with a car cockpit led to the development of a three-finger interface [5] addressing the thumb, index and middle fingertips. Both interfaces allow efficient interactions but are limited to the considered applications. The third category is composed of the encounter-type interfaces, i.e. reconfigurable devices that can physically replicate various object shapes in the real world. The hand is theoretically thought to interact with these objects in a realistic way. As an example, the authors in [6] roughly extracted contact profiles from grasps of various daily life empirical objects. They concluded that the contact points are distributed over a sphere which centre is located in the middle of the back of the hand. Their device was designed to conform to this shape as much as possible. It is however limited to such geometries.

This short survey reveals that haptic interfaces design is usually application-dependent, and points out the lack of a general methodology allowing to easily tune the trade-offs between the interaction capabilities and mechanical complexity. This paper is aimed to provide a tool that could help in choosing an appropriate design. It consists in a graphical tree organising different combinations of elementary contact areas of the hand, associated with their frequency of use during technical manipulations, as a function of their complexity. The tree is constructed thanks to a survey and a review of the existing hand manipulation and exploration taxonomies. The use of the proposed tree is illustrated by a ranking of some available haptic interfaces.

The remainder of the paper is organised as following: the review of the existing taxonomies is achieved in section 2. This allows extracting elementary contact areas, which are first organized into a hand interaction map to highlight their relative importance. The construction of the graphical tree is then presented. In section 3 the ranking of some available haptic interfaces is developed, and some guidelines for improved designs are discussed.

2 CLASSIFICATION OF THE HAND INTERACTIONS

2.1 Analysis of Hand Interaction Patterns

Hand interactions can be divided into *manipulation*, in which the hand is mostly used to act on the environment, e.g. moving an object, and *exploration*, characterizing movements performed in order to acquire further information about the surrounding objects, e.g. their temperature. Both aspects are to be investigated hereinafter.

Manipulation has been widely studied in the field of ergonomics. Much of grasping research refers to the work of Schlesinger, summarized in [7]. Six different grasps are depicted: *cylindrical, fingertip, hook, palmar, spherical* and *lateral*, driven by the object shape. Napier introduced a distinction between *power grasps*, utilized in case of tasks involving strength, and *precision grasps* for fine control [8]. The posture of the hand is said to be mostly influenced by the object being grasped, and by the intended activity. Kamakura et al. proposed another classification of static prehension patterns with novel *intermediate grip* and *adduction grip* categories along with the *power* and *precision* ones [9]. The most known taxonomy of human grasps was proposed by Cutkosky [10]. It is based on previous works, esp. [7] and [8], and observations in workshops, using task dexterity and precision as discriminants. As a whole, 16 different patterns are depicted. Contrary to [9], only two categories are considered, i.e. power and precision. Intermediate graps are missing, e.g. tripod grip and its variations used for example for holding a pen. Besides, numerous variations on the grasps are noticed to depend on the context (sizes of the hand and object, personal pref-

*e-mail: {franck.gonzalez, florian.gosselin}@cea.fr
†e-mail:{bachta}@isir.upmc.fr

erences). These works were extended by Feix et al. [11]: based on a review of 17 taxonomies, mostly variations on [10], 33 characteristic patterns are proposed and sorted in an array. The classification is based on the power/precision requirements and considers *power*, *intermediate* and *precision grasps*. The role of the thumb is also emphasized, being in adducted or abducted position. One can note that other approaches exist for the classification of human manipulation behaviours. As an example, [12] proposes to also take the hand's or objects' motions into account, esp. within hand. However, the categorization is less detailed for prehensile patterns. Consequently, we will refer to [10] and [11] for our work.

As regards exploration, researchers seem to have come to the agreement that some invariant properties during movements are maintained in order to evaluate the weight, shape, temperature, size and stiffness of a material [13]. Six different patterns are highlighted, each one associated to a specific property [14]: *Lateral motion* (texture): fingers rub across the surface; *Unsupported holding* (weight): the object is held in a hand and there is hefting of the arm and wrist; *Pressure* (hardness): normal forces are applied; *Enclosure* (global shape and volume): the hand is in contact with as much of the object's envelope as possible; *Static contact* (temperature): one hand passively rests on the object; and *Contour following* (global and exact shape): the hand moves dynamically while in contact with the object.

Each pattern can be further analyzed in order to get the associated hand-environment interaction area. From the observation of the 34 manipulation patterns (the 33 patterns from Feix et al. [11] plus the non-prehensile power grasp defined by Cutkosky which is not included in Feix et al.'s array), in the framework of [9], we identified 21 characteristic interaction areas as a whole, from the inner side of the index and middle fingers (M_1) to the whole inner hand surface (M_{21}). Similarly, from the 6 stereotypical exploration patterns, we extracted 4 characteristic contact areas, from the index fingertip (E_1) to once again the whole inner hand surface (E_4).

Figure 1 maps these interaction patterns with the corresponding areas. A dark grey box means that a given pattern (in the box' column) can be performed if a given interaction area (in the box' row) is involved, and conversely that this interaction area allows performing this manipulation or exploration pattern (in order to limit the number of columns, some of them gather several patterns which involve the same contact areas). Of course these areas are inclusive, as shown with light grey boxes (if a contact area encompasses another one, it allows performing the included one's patterns). White boxes mean incompatible patterns and contact areas.

As a whole, a given interaction area allows performing all interaction patterns marked with a light or dark grey box in the corresponding line. The whole hand allows all kinds of interactions while the index fingertip allows only few exploration patterns. Similarly, a given pattern can be performed provided that any contact area marked with a light or dark grey box in the corresponding column be involved.

In each column, the dark grey box is the lowest grey box. It refers to the minimal contact area strictly necessary to perform the pattern(s) in this column, which we will call in the sequel *reference interaction area* for this (these) pattern(s). Conversely, in each row, it is the left-most (resp. right-most) grey box for manipulation (resp. exploration) patterns. It refers to the pattern(s) that cannot be performed if other interaction areas which do not encompass it are involved. Such pattern(s) will be called below *reference interaction pattern(s)* for this area.

2.2 Adding Interaction Patterns Frequencies

Figure 1 shows how many types of interaction patterns can be performed for a given interaction area. Intuitively, the number of available interactions increases in accordance to the size of the interaction area.

This information alone is however not sufficient to guide the design of a generic haptic interface. The most important goal is not to be able to perform the highest number of patterns but those which are the most frequently used. This requires the knowledge of the relative frequency as to which each pattern is used, i.e. how long each interaction pattern occurs over a given amount of time.

As regards manipulation, this knowledge can be retrieved from [15]. The authors give the frequency of use of each grasping pattern for machinist activities. This data corresponds to the associated *reference interaction area* defined in section 2.1 and can be associated with the dark grey box in the referring pattern's column and area's row (no percentage is associated with the light grey boxes). As for exploration, [14] indicates the typical duration of each exploration pattern. Given an *a priori* equal importance to all environment properties, a pattern frequency (and thus the frequency of the corresponding reference interaction area) can be obtained by dividing its duration by the sum of the durations of all patterns. In a similar way to manipulation, frequencies are connected to the related dark grey boxes. It is worth noting that a reference interaction area may correspond to several manipulation or exploration patterns (e.g. M_6). In this case the frequency given in the area's dark grey box is the sum of the frequencies associated with each pattern.

Considering typical applications of haptic interfaces (e.g. digital design, fitting, ergonomic studies, exploration of virtual worlds and their physical properties – esp. inaccessible ones like nanoscale behaviour), we hypothesized that most applications require exploration (as defined in [14]) and manipulation in workshop-like environments (as studied in [15] for a machinist), with a ratio of 3/4 for manipulation and 1/4 for exploration (for specific activities, their relative importance may be different). The aforementioned frequencies of use are combined through these ratios to obtain a weighted average for each reference interaction area. It is worth noticing that a null exploration (resp. manipulation) contribution is assigned for the exclusive manipulation (resp. exclusive exploration) reference interaction areas. This way, the relative frequency of use of each of the 24 interaction areas (21 for manipulation, 4 for exploration, 1 being common to both) can be obtained and reported in the lines of figure 1 (one can notice that the machinist does not use 3 of the 34 manipulation patterns. They are not reported in figure 1, so as for the associated interaction areas).

2.3 Building a Hand Interaction Map

By overlapping the 24 interaction areas and combining their associated frequencies, a hand interaction map can be obtained (see figure 2). As a whole, we can distinguish more than 20 different *elementary* interaction areas, i.e. skin surfaces that can be combined to produce any of the interaction areas. As an example, the thumb fingertip, involved in the interaction areas M_2 to M_{13} and M_{15} to M_{21}, is used 77 % of the time as a whole.

At first glance for such technical activity, the map fits the intuition: the fingertips are the most utilized parts of the hand, then the rest of the fingers, and the palm comes in the end. A closer look reveals that the thumb and index fingertips are the most used, then comes the middle, then equally the lateral surface of the index and the ring pad.

It is worth noting that the palm involves 9 *elementary* interaction areas between which the frequency of use does not vary from more than 2 percent. Similarly, the metacarpus involves 6 areas among which 5 have no more than 2 percent difference. We chose to gather these zones. This way a simplified hand interaction map is obtained, based on only 12 *simplified* interaction areas (SIAs). All interaction areas can still be obtained from these SIAs, however some of them make use of a limited part of the palm and metacarpus areas.

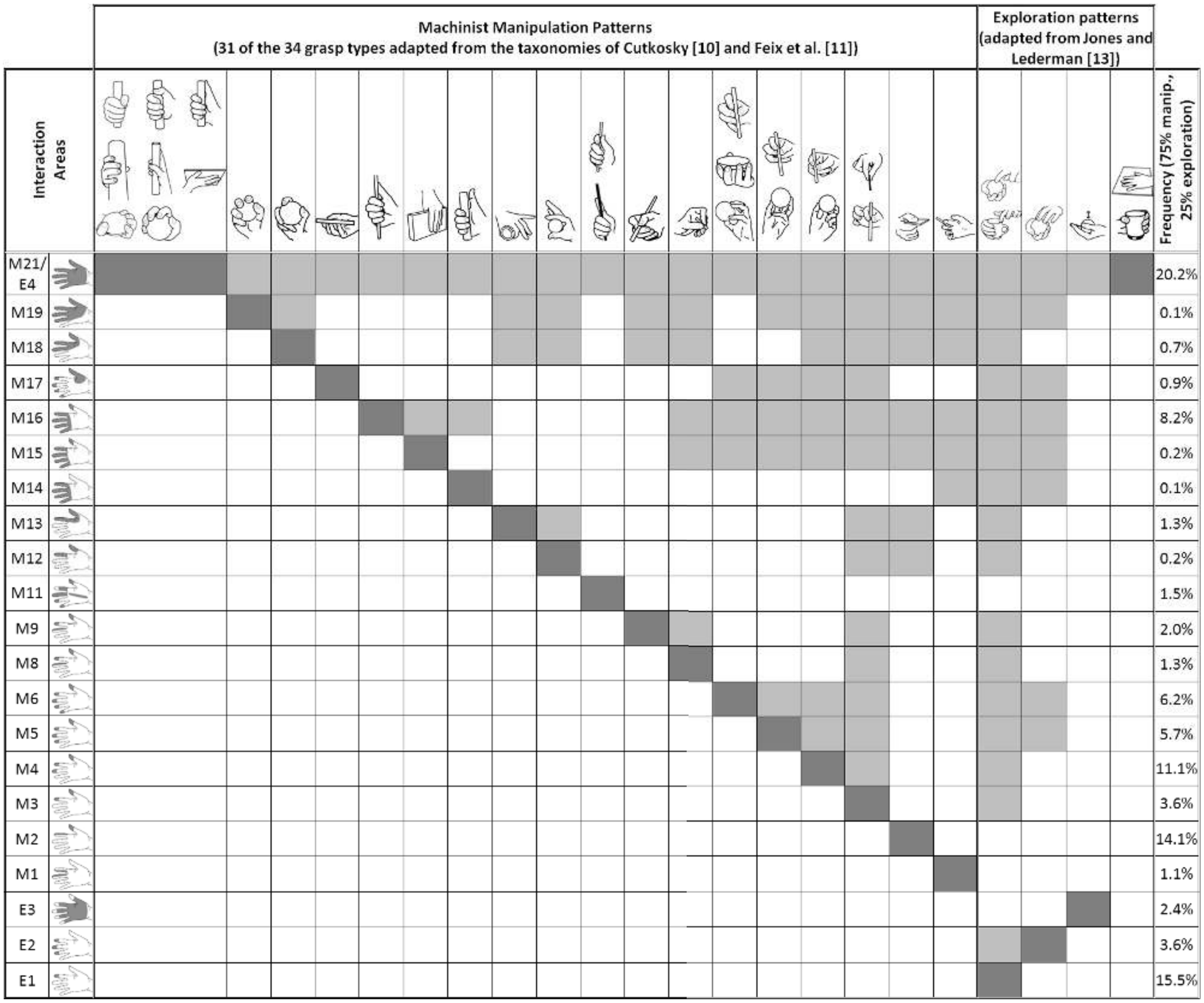
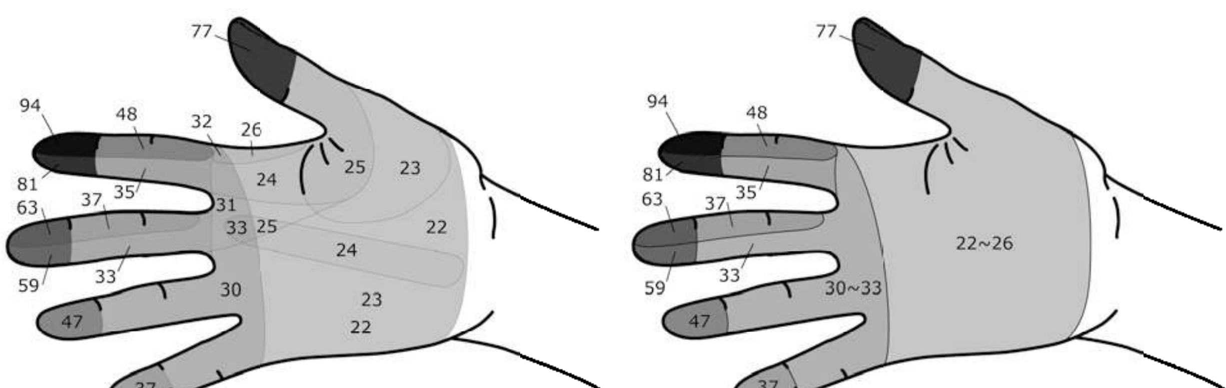


Figure 1: The interaction areas and their associated frequency of use as a function of manipulation and exploration patterns.



(a)

(b)

Figure 2: Hand interaction map for a machinist (for 75 % manipulation, 25 % exploration),
(a) elementary interaction areas, (b) simplified interaction areas.

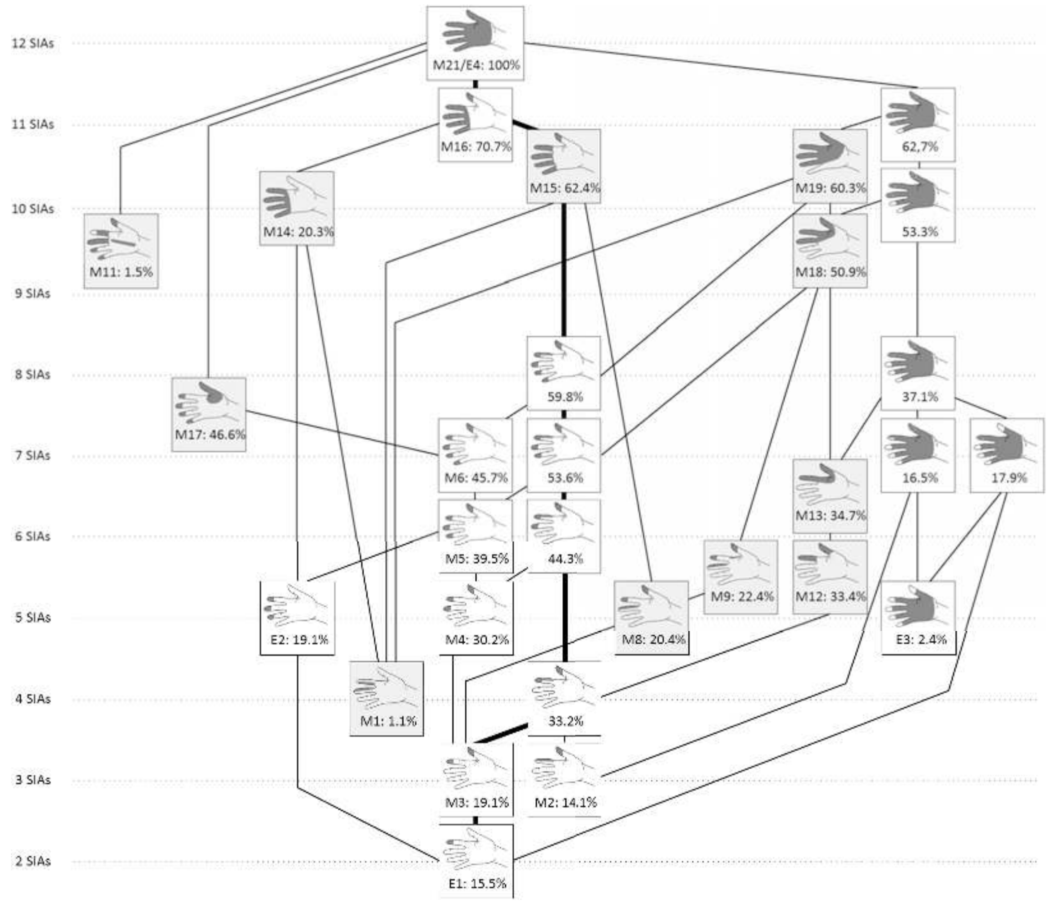


Figure 3: A partial tree of the interaction areas and their combinations as a function of the number of their constitutive simplified interaction areas (SIAs) and the percentage of time they allow to interact naturally with the environment.

2.4 Building a Hand Interaction Tree

The interaction map gives an insight on how long and which areas are utilized by a particular worker, over his actual activities. Although it gives some cues on which elementary areas are to be taken into account for the building of a generic haptic interface, this information is not sufficient since it does not allow sorting the capabilities of a haptic interface as a function of its complexity.

To make this classification possible, a tree is built (figure 3) using the interaction areas and some of their combinations. They are sorted as a function of a *complexity index*, defined as the number of SIAs that are part of each area. If the palm or metacarpus is partially involved, it is accounted for 1/2 SIA (e.g. M_{11}). For example, the interaction area M_5 is composed of 6 SIAs (thumb, left and right side of index, left and right side of middle, and ring fingertips, see figure 2). It is therefore located above the areas composed of 5 or less SIAs and below those composed of 7 or more SIAs.

This tree is composed of the 21 interaction areas from figure 1 and some of their combinations. Among the numerous possible combinations, only those which significantly increase their potential *efficiency index* are retained. The efficiency index of a given area is defined as the sum of the frequencies of use of the patterns it grants access to, since this value gives an estimation of the time during which this area will allow a natural interaction with the environment. This index is computed as the sum of the frequencies of use of the *reference interaction areas* encompassed in the considered area. It can also be obtained as the sum of the indexes of the lower areas it is connected to, minus the indexes that are accounted for several times due to multiple links, plus the percentage of this area. As an example, the index of the area M_5 is the sum of the indexes of the areas E_2 and M_4, minus the index of the area E_1 which is included in both E_2 and M_4, plus the specific frequency of M_5 (as given in figure 1), i.e. $19.1+30.2-15.5+5.7=39.5$ %.

Two areas are linked if one of them encompasses the other. Multiple links are possible if a given area is included in several others. However, redundant links are to be avoided. As an example, area M_{17} includes area E_1 but no link is drawn between them as E_1 is already taken into account through M_3, M_4, M_5 and M_6, M_6 being linked to M_{17}.

One can note from figure 1 that some *reference interactions areas* are rarely used (e.g. M_8 is used only 1.3% of the time). As a consequence, they are considered as being less interesting as they allow only few more natural interactions while being more complex (e.g. M_8 has a *complexity index* of 5 and allows interacting naturally with the environment 20.4% of the time, i.e. only 1.3% more than M_3 for an added *complexity index* of 2). Those areas are displayed in grey boxes in figure 3.

The tree in figure 3 illustrates the complexity and efficiency of the various interaction areas in a synthetic way. A critical path appears in thick line that distinguishes, in function of the number of SIAs, the areas to be taken into account to grant access to the most utilized patterns over time.

It is worth noting that the *efficiency index* of a given area represents the maximum amount of time it allows to interact naturally with the environment. Building a generic haptic interface allowing to track and apply forces on this area (i.e. on each of its constitutive

Table 1: A summary of human abilities [13, 16, 17, 18].

Smallest detectable static skin displacement	11.2 µm
Digit position resolution	0.1°
Range of orientations of the digits fingertip	260°
Force discrimination	0.06 N
Force during manipulation	peak 40 N
	mean 10 N
Velocity of the wrist	peak 0.6-1.2 $m\,s^{-1}$
	mean 0.3-0.5 $m\,s^{-1}$
Finger articulation velocity	3-8 $rad\,s^{-1}$
Movement frequency	4-7 Hz
Sensory bandwidth	320 Hz

elementary areas) is not sufficient to reach this index. Therefore tracking and feedback must be perfect (i.e. along all directions, over full position and force range and bandwidth, with a stiffness from 0 to the minimum perceived as infinitely stiff, etc.). In practice, no interface allows such perfect local interaction and the theoretical maximum *efficiency index* is hardly reached. The tree of interaction remains however a useful tool to theoretically sort the devices as a function of their potential (i.e. *at best*) interaction efficiency, along with other criteria like for instance the number of DOF with force feedback, the maximum amount of force or the feedback bandwidth. As an example, table 1 gives an insight on the required performances for a perfect interaction at the fingertips. Similar data could be obtained for the phalanxes and palm.

3 Classification of Dexterous Haptic Interfaces

3.1 Use of the Interaction Tree to Sort Haptic Interfaces

Dexterous haptic interfaces can be associated with the areas they allow interacting with (i.e. with the leaves of the interaction tree). This way, they can be sorted as a function of their complexity and their efficiency. The higher the *complexity index* (i.e. the more SIAs considered), the more independent effectors required to track the hand surface and apply forces on it. The higher the *efficiency index* (i.e. the higher associated percentage), the larger amount of time the patterns they grant access to are used.

A perfect dexterous haptic interface is due to simulate every interaction. This would require the use of the entire hand glabrous skin, i.e. the whole hand interaction area on top of the interaction tree. To our knowledge, no existing interface allows such whole

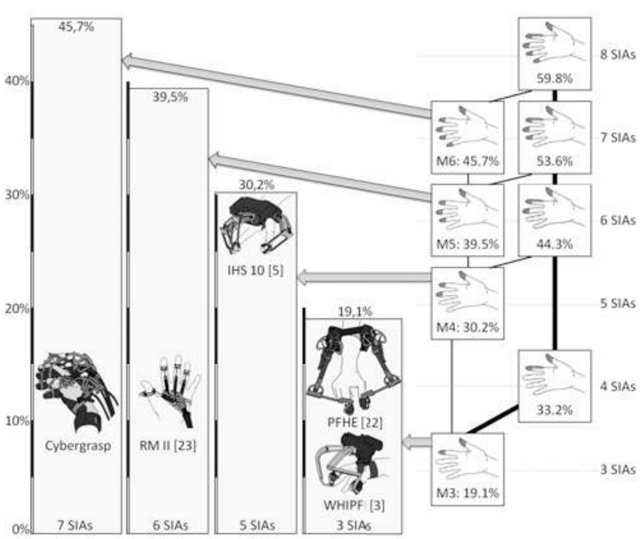


Figure 4: Some existing interfaces sorted as a function of their complexity and efficiency.

hand interaction with haptic feedback. In practice, dexterous haptic interfaces have limits and can only render *at best* the patterns allowed with the interaction area they grant access to. Some examples will be given below.

In order to simplify the discussion, we will focus on force feedback and hypothesize that rendering spatial and temporal high frequency information can be obtained with miniature tactile feedback devices mounted on the end effectors of the considered haptic interfaces (see e.g. [19], [20], [21] for a few examples of such devices).

3.2 Review of Existing Dexterous Haptic Interfaces

Without being exhaustive, a few examples are given in figure 4:

- Two thumb and index fingertip devices are first considered, the WHIPFI [3] and the PERCRO PFHE [22]. Both devices have a *complexity index* of 3. Both are composed of two 6-DOF robots with 3 motors each. They have a sufficient workspace and allow force feedback in all directions. They theoretically allow simulating patterns used 19.1 % of the time. The WHIPFI however has a limited force capability (0.8 N continuous and 4.7 N peak) and its maximum perceived stiffness is only 900 $N\,m^{-1}$. It is not sufficient to simulate stiff surfaces and its practical *efficiency index* is below the theoretical value of 19.1 %. The PFHE has higher force capability (more than 4 N continuous and 25 N peak) and stiffness (minimum mechanical stiffness in the worst case: 5900 $N\,m^{-1}$). Is allows a better fingertip interaction and an *efficiency index* close to 19.1 %, however at the expense of a more cumbersome and heavier design (it must be fixed on the forearm);

- A three fingertips device is also considered, the IHS10 Glove [5]. Its complexity is ranked as 5. It is composed of three 5-DOF robots with 3 motors each. Its workspace is sufficient for transparent use and it allows a force feedback in all directions at the fingertips. This device theoretically allows the simulation of the patterns used 30.2 % of the time. Its force capability (4 N continuous and 10 N peak) and stiffness (up to 5000 $N\,m^{-1}$ control stiffness in reference configuration) allow approaching this theoretical value;

- The Rutgers Master II [23] is given as an example of a four fingertip haptic interface. The theoretical complexity of the interaction area it is associated with equals 6 and it theoretically allows simulating the interaction patterns used 39.5 % of the time. It is composed of 4 small air cylinders located inside the palm and attached to the fingertips. It is very light and compact. However, this technological solution limits the fingers movements and provides force feedback (16 N max continuous force) only in hand closure direction. In practice, its complexity is below 6 (it makes use of only 4 motors) but its *efficiency index* is well below 39.5 % (although a precise value is difficult to provide, as a first approximation, an estimate between 10 and 15 % seems reasonable, i.e. about $1/3$ of the maximum theoretical value as it allows force feedback in only 1 out of 3 directions at fingertips);

- Finally, the Cybergrasp from CyberGlove Systems company (www.cyberglovesystems.com) is given as an example of a five fingers dexterous haptic device. Its *complexity index* equals 7 and it theoretically allows simulating the interaction patterns used 45.7 % of the time. In practice it makes use of a semi-exoskeleton architecture, and allows applying forces on the fingertips and middle phalanxes. These movements are however coupled and the corresponding areas cannot be addressed separately. It is therefore considered as a fingertip device. Its workspace is sufficient to cover the whole fingers movements. However, in order to limit its weight, a remote actuation is implemented. Transmission cables introduce friction and flexibility and the force feedback is of medium quality. Moreover, the force feedback is only provided in hand opening - closure movement. Consequently, the actual *efficiency index* is well below the theoretical value of 45.7 % (here again, it can be estimated between 10 and 15 % as force feedback is provided in only 1 direction - 12 N max continuous - while 3 would be necessary to simulate any interaction at fingertip).

It is worth noting that the tree is only valid for dexterous haptic interfaces allowing to track and apply forces on different skin areas independently. One could argue that a universal device like the Virtuose 6D 35-45 from Haption company (www.haption.com) allows whole hand interactions. It is however untrue. It allows only simulating small diameter, medium wrap, adducted thumb and index finger extension in a realistic manner, plus ring and inferior pincer. Those grasps are used only 14.3 % of the time. In this case the whole hand surface is involved but with a fixed shape. Consequently, the percentage of time the associated patterns are used drops from 100 % to 14.3 %.

3.3 Guidelines for the Design of a Novel Interface

Though not exhaustive, figure 4 shows a representative panorama of existing dexterous haptic interfaces. Let alone some complex laboratory prototypes, no four- or five-finger device exists that allows force feedback in 3 independent directions on fingertips. As a result, existing interfaces have a limited real efficiency. It is suggested to do research on simple alternative technologies allowing the development of such a device without relying on a too complex architecture. A particular attention should be paid to kinematics, design of the joints and actuation in order to allow for a sufficient workspace and force amplitude yet with a light structure. This way an efficiency up to 39.5 (for a four fingers interface associated with M_5) or 45.7 % (for a five fingers device associated with M_6) could be reached.

Considering figure 3 and its critical path, an interesting alternative could be the interaction area obtained as a combination of M_5 and M_2. It appears as a good compromise between complexity and efficiency. At the expense of a limited added complexity with respect to M_5, which itself seems attainable with the same technologies as used for example on the IHS10 Glove, it allows a higher theoretical *efficiency index*, up to 53.6 % (even more than M_6).

Finally, to approach the maximum above-mentioned theoretical efficiencies, it is also necessary to do further research on the association of such force feedback devices and miniature tactile interfaces allowing to render complementary touch information.

4 Conclusion and discussion

In this paper, we presented how hand interactions patterns can be analysed to extract associated interaction areas which can be used to set up both a hand interaction map and a hand interaction tree. The interaction tree gives a synthetic overview of the complexity and efficiency of the various interaction areas. It can be used to sort dexterous haptic interfaces as a function of the areas they grant access to. This way, theoretical *complexity* and *efficiency indices* can be associated with various interface designs. It was used to critically review some existing devices and to propose guidelines for the design of novel interfaces. Other aspects of the haptic rendering (e.g. temperature, texture, etc ...) should be taken into account to effectively reach the maximum *efficiency index*.

This analysis is based on the hypothesis that the interactions of a machinist are representative of generic VR applications. It could be enriched with data covering a larger set of applications. The authors encourage people involved in the study of humans at work to enrich Feix et al.'s database (i.e. frequency of use of the interaction areas for various activities).

Acknowledgements

The authors wish to thank Prof. Vincent Hayward (ISIR) for his valuable comments and advice in writing this paper.

References

[1] F. Gosselin. UE MUVII, spécifications préliminaires de l'interface haptique IKD. Technical Report DTSI/SRSI/LPR/02.274, CEA, 2002.

[2] G. Trannoy, J. Lozada, and C. Mégard. IHS10, Etude des interactions conducteur commandes véhicule d'une voiture Peugeot 308. Technical Report DTSI/SRCI/08-522, CEA, 2008.

[3] F. Gosselin, T. Jouan, J. Brisset, and C. Andriot. Design of a wearable haptic interface for precise finger interactions in large virtual environments. In *Proc. Int. Conf. Worldhaptics*, pages 202–207, 2005.

[4] S. P. Christodoulou, D. M. Garyfallidou, M. N. Gavala, G. S. Ioannidis, T. S. Papatheodorou, and E. A. Stathi. Haptic devices in virtual reality used for education: designing and educational testing of an innovative system. In *Proc. Interactive Computer Aided Learning*, 2005.

[5] F. Gosselin. Guidelines for the design of multi-finger haptic interfaces for the hand. In *19th CISM-IFToMM RoManSy Symposium*, 2012.

[6] Y. Yokokohji, N. Muramori, Y. Sato, and T. Yoshikawa. Designing an encountered-type haptic display for multiple fingertip contacts based on the observation of human grasping behavior. In *Proc. IEEE Haptics Symposium*, pages 66–73, 2004.

[7] C.L. Taylor and R.J. Schwartz. The anatomy and mechanics of the human hand. *Artificial Limbs*, 2(2):22–35, 1955.

[8] J.R. Napier. The prehensile movements of the human hand. *J. Bone and Joint Surgery*, 38B:902–913, 1956.

[9] N. Kamakura, M. Matsuo, M. Ishii, F. Mituboshi, and Y. Miura. Patterns of static prehension in normal hands. *Am. J. of Occupational Therapy*, 34:437–445, 1980.

[10] M.R. Cutkosky. On grasp choice, grasp models, and the design of hands for manufacturing tasks. *IEEE Trans. on Robotics and Autom.*, 5(3):269–279, 1989.

[11] T. Feix, R. Pawlik, H.B. Schmiedmayer, X. Romero, and D. Kragić. A comprehensive grasp taxonomy. In *Robotics, Science and Systems: Workshop on Understanding the Human Hand for Advancing Robotic Manipulation*, 2009.

[12] I.M. Bullock and A.M. Dollar. Classifying human manipulation behavior. In *Proc. Int. Conf. on Rehab. Robotics*, pages 532–537, 2011.

[13] L.A. Jones and S.J. Lederman. *Human Hand Function*. Oxford University Press, 2006.

[14] R.L. Klatzky and S.J. Lederman. Object recognition by touch. In *Blindness, brain plasticity and spatial function*, pages 185–207. Erlbaum, 2007.

[15] J.Z. Zheng, S. De La Rosa, and A.M. Dollar. An investigation of grasp type and frequency in daily household and machine shop tasks. In *Proc. Int. Conf. on Robotics and Autom.*, pages 4169–4175, 2011.

[16] T.L. Brooks. Telerobotic response requirements. In *Proc. IEEE Int. Conf. on Systems, Man and Cybernetics*, pages 113–120, 1990.

[17] E. Kunesch, F. Binkofski, and H.J. Freund. Invariant temporal characteristics of manipulative hand movements. *Exp. Brain Research*, 78:539–546, 1989.

[18] L.A. Jones. Dextrous hands: Human, prosthetic, and robotic. *Presence*, 6(1):29–56, Feb 1997.

[19] Q. Wang and V. Hayward. Compact, portable, modular, high performance, distributed tactile transducer device based on lateral skin deformation. In *Proc. Haptic Symposium*, pages 67–72, 2006.

[20] M. Benali Khoudja, M. Hafez, and A. Kheddar. Vital: an electromagnetic integrated tactile display. *Displays*, 28(3):133–144, July 2007.

[21] I. Sarakoglou, N. Garcia Hernandez, N.G. Tsagarakis, and D.G. Caldwell. A high performance tactile feedback display and its integration in teleoperation. *IEEE Trans. on Haptics*, 5(3):252–263, 2012.

[22] A. Frisoli, F. Simoncini, M. Bergamasco, and F. Salsedo. Kinematic design of a two contact points haptic interface for the thumb and index fingers of the hand. *J. of Mechanical Design*, 129:520–529, 2007.

[23] M. Bouzit, G. Burdea, G. Popescu, and R. Boian. The rutgers master 2 – new design force-feedback glove. *IEEE/ASME Trans. on Mechatronics*, 7(2):256–263, 2002.