Task-oriented approach to simulate a grasping action through underactuated haptic devices*

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Abstract. Force rendering is important in underactuated haptic systems. Underactuation means that some force directions at the contacts cannot be rendered because of the lack of actuation. In this paper we propose to exploit the knowledge of the task to mitigate the effect of the underactuation. The simulation of a grasp is considered and two alternative algorithms are proposed to improve the sensitivity in the underactuated system. The basic idea is to exploit the actuated force direction, optimizing the force feedback according to the type of forces involved in the specific grasping task. These forces can be squeezing forces or forces able to move the grasped object. Experiments show that the proposed task–oriented force rendering considerably increases the ability of perceiving the properties of the grasped virtual object.

Keywords: Haptics, Underactuation, Grasping

1 Introduction

The first haptic interface has been designed to simulate a single point contact interaction with virtual environments [1] and this happens for many devices available out of the laboratories. Only recently, multi-contact haptic interfaces have been released, such as the CyberGlove&Grasp (CyberGlove Systems LLC, San Jose, CA) [2]. This complex device exploits the combination of two technologies, tendons and exoskeletons and it is provided with up to twenty sensors to retrieve the position of the hand, and five actuators, one for each finger. In [3], Giachritsis *et al.* present the MasterFinger-2, a novel multi-finger haptic interface that allows bimanual manipulation of virtual objects with precision grip. Each arm has a serial-parallel structure with 6 DoF for movement and 3 DoF for force reflection, allowing grasping actions in any direction.

However simulating the interaction with multiple contacts can be difficult. Assume that each finger shares a contact point with an object; according to the

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Hard-Finger contact model (HF) [4], three actuators are needed to simulate the force interaction at each contact point, leading to more complex haptic devices.

When size and weight constraints arise in a haptic device, a simplification of its design is needed. A promising solution is to reduce the number of actuators, that leads to an underactuated haptic interface. For instance Iqbal *et al.* in [5] present a robotic exoskeleton, in which each finger is equipped with only one actuator. However, this lack in terms of actuation can introduce a discrepancy between what the user expects to feel and the forces actually fed back through such an interface. In the case of the Da Vinci surgical system advantages and disadvantages of the use of underactuation are under investigation. As stated in [6], in some circumstances, it may be effective for users to obtain force information along certain directions and not along others. For instance, while performing a teleoperated needle insertion, only the force feedback related to the shearing force, i.e. force parallel to the surface of the tissue, can be provided to the operator. Axial force feedback could lead to overshoot and vibrations of the telemanipulator, since the needle penetrates through tissues with different stiffness. Thus, in such a case, partial force feedback is beneficial for the operator. However, in [7], investigating upon the partial force rendering effects, it is pointed out that force rendering does influence the user's confidence in her/his perception of a remote environment during a telemanipulation task.

The focus of this paper is the development of force feedback algorithms for underactuated haptic devices. The main idea of our approach is to emphasize the more relevant forces, accordingly to the task at hand, and achieve a good perception even if the number of actuators is not sufficient to simulate the whole set of contact forces. Information lost due underactuation can be partially recovered exploiting some geometric properties of the task considered.

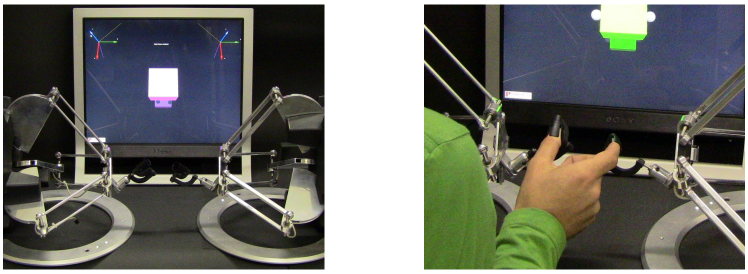
The paper is organized as follows: in Sec. 2 the haptic rendering is described, together with the geometric and mathematical bases underneath the proposed algorithms. In Sec. 3 two experiments are characterized and the performance, during a grasping and a lifting tasks, are analysed. Finally Sec. 4 addresses concluding remarks and perspectives of the work.

2 Modelling the underactuation

To formalize the problem of underactuation, consider a haptic interface able to simulate a certain number of contact forces, grouped in a vector λ. Assume that not all the contact force components of vector λ can be independently actuated. In particular assume that the relationship between the real actuator action λ_a and the vector of contact forces λ is given by

$$\lambda = M_a \, \lambda_a \ , \tag{1}$$

where M_a is referred to as the *actuation matrix*, whose structure and size strictly depend on the number of contact points, the number of available actuators, and the geometry of the system. In this paper we assume that the set of contacts defines a certain grasp configuration, whose geometry is described by the grasp matrix G [4]. G is frequently used to asses the equilibrium of a grasp through



(a) (b)

Fig. 1. The experimental setup, composed of two Omega 3 haptic interfaces with thimbles as end-effectors and a virtual environment to interact with. (a) General overview. (b) Detail of the thumb and index fingers placed inside the thimbles.

the equation $w = G\lambda$, where w is the external wrench applied to the grasped object, and λ is the vector of all contact forces applied by the hand on the object. From the equilibrium equation, two important subspaces for contact forces can be defined. (1) The subspaces of internal forces, *i.e.* self balanced forces whose net wrench on the object is zero and that belong to the nullspace of the grasp matrix $\mathcal{N}(G)$ [8]. (2) The subspace of external forces, *i.e.* forces that cause a non zero net wrench on the object and belong to the complementary set of the nullspace of the grasp matrix $\mathcal{R}(G^T)$ [8]. Different solutions of the underactuated forces λ_a can thus benefit different components of the full contact forces λ. The straightforward solution to eq. (1) is

$$\lambda_a = (M_a)^{\#}\ \lambda\ , \tag{2}$$

where $(\cdot)^{\#}$ is the Moore-Penrose pseudoinverse operator. It minimizes the sum of the force squared residuals upon all the space [9], regardless of the task's aim. Taking into account the task at hand and projecting the eq. (1) onto the subspace of interest, we can propose better solutions in terms of algorithms.

Internal Forces Algorithm (IF) The *IF Algorithm* projects the contact forces onto the nullspace of the grasp matrix $\mathcal{N}(G)$, solving the system of equation

$$\begin{cases} (N_G)^T\ \lambda = (N_G)^T\ M_a\ \lambda_a \\ \lambda = M_a\ \lambda_a \end{cases} ,$$

where N_G denotes a matrix whose columns form a basis for $\mathcal{N}(G)$. Forces exerted by the actuators can be expressed as

$$\lambda_a = \left[B^{\#}\,(N_G)^T\right]\ \lambda\ + \left[N_B\,(M_a\ N_B)^{\#}\left(I_{6\times 6} - M_a B^{\#}\,(N_G)^T\right)\right]\lambda\ ,$$

where $B \triangleq (N_G)^T M_a$, N_B is a matrix whose columns form a basis for $\mathcal{N}(B)$, and $I_{6\times 6}$ is an identity matrix of size 6. Imagine to handle a regular object, e.g. a

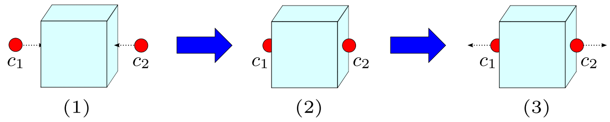


Fig. 2. Schematic overview of the first experiment, consisting of grasping a virtual cube with two fingers placed on its opposite side faces. Experiment steps: (1) grasp the cube, (2) 3 s exploration of the cube's stiffness, (3) release the cube.

solid cube, with two fingers. We naturally grasp it placing our thumb and index on its opposite faces. The more relevant forces belong to the subspace described by $\mathcal{N}(G)$. The *IF Algorithm* can then be really convenient when it comes to deal with most of grasping tasks.

External Forces Algorithm (EF) The *EF Algorithm* is based on the same idea of the *Internal Forces* one, but, differently it takes advantage of the complementary space of $\mathcal{N}(G)$, the range of the transpose of the grasp matrix $\mathcal{R}(G^T)$, as follows

$$\left(R_{G^T}\right)^T \lambda = \left(R_{G^T}\right)^T M_a \, \lambda_a \ ,$$

where R_{G^T} denotes a matrix whose columns form a basis for $\mathcal{R}(G^T)$. Since in this case we assume that $\mathcal{N}(G \, M_a) = \emptyset$, the forces exerted by the actuators can be simply computed as

$$\lambda_a = (G \, M_a)^{\#} G \, \lambda \ .$$

This time all the force components belonging to $\mathcal{N}(G)$ are disadvantaged despite of all the others that are not part of such a subspace. For instance the weight of an object does not usually belong to the nullspace of G during a common grasping task.

3 Experiments

In order to validate the feasibility of the proposed methods two experiments have been carried out. They basically consisted of two contact points pinch grasps, where underactuated forces were rendered through the different methods aforementioned. Force rendering performance has been evaluated in the different cases with a just noticeable difference (JND) analysis on the collected data [10]. Different properties of the virtual object have been tested during the two experiments, so then to give a greater role to internal forces rather than to external ones, and vice versa.

Two Omega 3 haptic interfaces, one for each contact point, were exploited. Since the Omega 3 can render a contact force vector with three independent components, we simulated an underactuated system via software, selecting two actuated directions according to a given geometry. This setup can indeed be used as an experimental testbed for rapid prototyping of underactuated solutions in haptics. We used two thimbles as end-effectors of the haptic interfaces to make the grasp more realistic for the operators during the trials proposed. The virtual

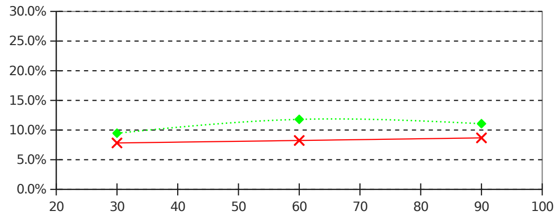


Fig. 3. JND ratio values when the pseudoinverse of eq. (2) (dotted green line) and the *IF Algorithm* (red solid line) are used to render the stiffness of a virtual cube in a two fingers grasping simulation. The horizontal axis shows the range of stiffness expressed in N/m.

environment was composed by a cube, the object aimed to interact with, and a black background (see Fig. 1). Virtual walls and a virtual ground limited the area of interaction. Two spheric grey cursors allowed the operator to locate their fingertips in the virtual world.

3.1 Experiment 1: grasping task

The first task proposed consisted of grasping the cube, with two fingers on the opposite faces. Being interested in internal forces only, the dynamic of the object was not considered and the cube was fixed in the middle of the virtual workspace. This experiment aimed to compare the JND, when the stiffness of a virtual object was rendered through the *IF Algorithm* and the pseudoinverse of eq. (2).

Five participants, four males, one female, age range 20-33, took part to the experiment, all of whom were right-handed. Four of them had previous experience with haptic interfaces. None of the participants reported any deficiencies in their perception abilities. Subjects were asked to suit the thimbles connected to the haptic devices on their thumb and index fingers of the same hand and complete the task proposed. It consisted of grasping the virtual cube for no more than 3 seconds. After the first exploration the user had to leave the grip to allow the change of the object's stiffness, then he could start a new interaction for 3 seconds again. When the time was over, he had to release the grip and state whether the second touched object was stiffer than the first one. All the experiment steps are summarized in Fig. 2. The comparison was between a *Standard stiffness* (Ss), constant for an entire series, and six *Comparison stiffnesses* (Cs), computed as different ratios of Ss and changing on each trial. Each Cs was proposed 10 times to the subject in a pseudo-random order. Once all the trials were considered, the standard stimulus was increased and a new series started with the same modality. Three series of 60 trials, one per standard stimulus in the set [30 60 90] N/m, were performed per subject under each of the considered force rendering conditions, i.e. *IF Algorithm* and pseudoinverse method. All the answers were collected to be elaborated and statistically analysed. A pink noise was continuously provided to participants through headphones throughout the experimental trials, in order to guarantee a better isolation from the surrounding

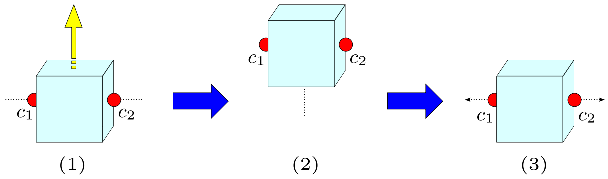


Fig. 4. Schematic overview of the second experiment, consisting of lifting a virtual cube with two fingers placed on its opposite side faces. Experiment steps: (1) grasp and lift the cube, (2) 3 s exploration of the cube's weight, (3) release the cube.

world and keep the subjects more focused. The set of Ss provided and the relative Cs have been properly tuned during a preliminary testing session to obtain a significant evaluation and exploit at its best the sensitivity of the investigated algorithms.

From the collected responses three different psychometric curves were fitted for each subject, each corresponding to a specific standard stimulus. Thresholds computed for each curve were averaged over the whole dataset among each Ss and then plotted in Fig. 3. It shows that the *IF Algorithm* increases the sensitivity of the haptic feedback in an underactuated configuration and allows to better perceive the stiffness of a virtual object performing a grasping task. Comparison of the means among the two feedback modalities was tested using a paired samples t-test, which revealed significantly statistically differences between the means for the same values of Ss. t-values of 3.074, 6.169, 2.942 and relative p-values of 0.037, 0.040, 0.042 have been computed for the standard stimuli [30 60 90] N/m respectively.

Contrary as we expected, regarding both methods, the JND index does not decrease for higher stimuli, although the higher the Ss provided to the subject, the larger the gap between the minimum/maximum Cs and the Ss itself (Cs is a ratio of Ss). Hence the higher Ss, the more difficult the perception of the object's stiffness change.

3.2 Experiment 2: lifting task

The second conducted experiment consisted of lifting a cube with two fingers placed on its opposite side faces. Contrary to the first experiment of the previous section the cube was free to move in all the directions of the 3D space and the gravity force was rendered. Our purpose was to compare the JND when an external force, i.e. the gravity force, acting on a virtual object, was provided using the *EF Algorithm* and the pseudoinverse of eq (2). The same five participants of the first experiment took part to this one and the same experimental setup was used as well. The task consisted of grasping the cube and lifting it for no more than 3 seconds. Then the user had to leave the grip to allow the change of the object's weight, so he could start a new similar interaction for the same 3 seconds. When the time was over he had to release the grip again and state whether the second raised object was heavier than the first one. All the experiment steps are summarized in Fig. 4. The comparison was between a *Standard*

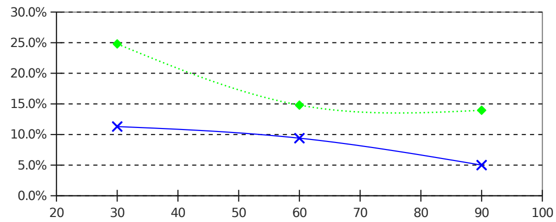


Fig. 5. JND ratio values when the pseudoinverse of eq. (2) (dotted green line) and the *EF Algorithm* (blue solid line) are used to render the weight of a virtual cube in a lifting simulation. The horizontal axis shows the range of weights expressed in g.

weight (Sw), constant for an entire series, and six *Comparison weights* (Cw), computed as different ratios of Sw and changing on each trial. Each Cw was proposed 10 times to the subject in a pseudo-random order. Once all the trials were considered, the standard stimulus was increased and a new series started with the same modality. Three series of 60 trials, one per standard stimulus in the set [30 60 90] g, were performed per subject under each of the considered force rendering conditions, i.e. *EF Algorithm* and pseudoinverse method. All the answers were thus collected to be elaborated and statistically analysed. As for the first experiment throughout the simulation, a pink noise was continuously provided to the participants. The set of Sw provided and the relative Cw have been again properly tuned during a preliminary testing session to obtain a significant evaluation and exploit at its best the sensitivity of the investigated algorithms.

From the collected data regarding each subject three different psychometric curves were fitted, one for each standard weight. Thresholds computed for each curve were averaged over the whole dataset among each Sw and then plotted in Fig. 5. It shows that the *EF Algorithm* increases the sensitivity of the haptic feedback in an underactuated configuration and allows to better perceive the weight of a virtual object, i.e. an external force, while performing a lifting task.

Comparison of the means among the two feedback modalities was again tested using a paired samples t-test, which revealed significantly statistically differences between the means for the same values of Sw. t-values of 27.648, 3.650, 5.867 and relative p-values of < 0.001, 0.022, 0.004 have been computed for the standard stimuli [30 60 90] g respectively.

Note in Fig. 5 that the JND values decrease with the increase of the object's weight, probably because the difference between Sw and Cw becomes larger and the subjects can better perceive the gap (Cw is a ratio of Sw).

4 Conclusions and future works

The behaviour of the two proposed force rendering algorithms in an underactuated system has been studied thoroughly. A flexible approach to simulate underactuated haptic devices through fully actuated ones has been defined and applied in two different experiments involving five people each. Our idea allows to introduce an efficient way to distinguish between the two different categories of forces, internal and external, acting in grasping, and develop algorithms that privilege the rendering of one force type despite of the other. Both the experiments show an improvement in terms of performance, when the investigated force rendering method, the *IF Algorithm* in the first experiment and the *EF Algorithm* in the second one, is compared with the pseudoinverse of eq. (2) over the entire range of data considered.

Performance might be affected by the arbitrary choice of the actuation directions, which can benefit one method with respect to the other. However the same actuation geometry has been used in both the experiments and the user's perception improved when the proposed algorithms were used.

Future developments may include a new dynamic algorithm, which can switch from rendering internal forces to external ones, according to the task being executed by the user. Benefits achieved by the different methods addressed in this work, can then be merged together to guarantee a better sensitivity to the operator while performing general tasks and using underactuated haptic devices. Moreover a larger number of participants should take part in further experiments to make the data analysis more accurate and reliable.

References

1. K. Salisbury, D. Brock, T. Massie, N. Swarup, and C. Zilles. Haptic rendering: Programming touch interaction with virtual objects. In *Proc. Int. Symp. on Interactive 3D Graphics*, pages 123–130, 1995.
2. G. Nikolaki, D. Tzovaras, S. Moustakidis, and M. G. Strintzis. Cybergrasp and phantom integration: enhanced haptic access for visually impaired users. In *Proc. Int. Conf. on Speech and Computer*, pages 507–513, 2004.
3. C. D. Giachritsis, M. Ferre, J. Barrio, and A. M. Wing. Unimanual and bimanual weight perception of virtual objects with a new multi-finger haptic interface. *Brain research bulletin*, 85(5):271–275, 2011.
4. D. Prattichizzo and J. Trinkle. Grasping. In B. Siciliano and O. Kathib, editors, *Handbook on Robotics*, pages 671–700. 2008.
5. J. Iqbal, N. G Tsagarakis, and D. G. Caldwell. A multi-dof robotic exoskeleton interface for hand motion assistance. In *Proc. IEEE Int. Conf. on Engineering in Medicine and Biology Society*, pages 1575–1578, 2011.
6. L. N. Verner and A. M. Okamura. Sensor/actuator asymmetries in telemanipulators: Implications of partial force feedback. In *Proc. IEEE Int. Symp. in Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 309–314, 2006.
7. L. N. Verner and A. M. Okamura. Effects of translational and gripping force feedback are decoupled in a 4-degree-of-freedom telemanipulator. In *Proc. IEEE Int. Conf. World Haptics Conference*, pages 286–291, 2007.
8. A. Bicchi. On the closure properties of robotic grasping. *The International Journal of Robotics Research*, 14(4):319–334, 1995.
9. G. Peters and J. H. Wilkinson. The least squares problem and pseudo-inverses. *The Computer Journal*, 13(3):309–316, 1970.
10. M. K. Stern and J. H. Johnson. Just noticeable difference. *Corsini Encyclopedia of Psychology*, 2010.