Precise and realistic grasping and manipulation in Virtual Reality without force feedback

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Abstract

This paper introduces a physically-based approach of grasping and manipulation regarding virtual objects that would enable fine and stable grasping without haptic force feedback. The main contribution is to enhance an existing method which couples a virtual kinematic hand with a visual hand tracking system. The mismatches between the tracked and virtual hands often yield unstable grasps, especially for small objects. This is overcome by the implementation of grasping assistance based on virtual springs between the tracked and virtual hands. The assistance is triggered based on an analysis of usual grasping criteria, to determine whether a grasp is feasible or not. The proposed method has been validated in a supervised experiment which showed that our assistance improves speed and accuracy for a "pick and place" task involving an exhaustive object set, sized for precision grasp. Moreover, users' feedback shows a clear preference for the present approach in terms of naturalness and efficiency.

Index Terms: [Human-centered computing]: Virtual Reality—Virtual grasping; [Human-centered computing]: User interface design—Dexterous interaction Precision grasp; [Human-centered computing]: User studies—

1 Introduction

Along with the development of affordable virtual reality but also augmented reality technology, some complex applications like remote operation, entertainment industry, training simulation, industrial use, have emerged. Hence, the realism of the virtual environment as well as the user's interaction with the virtual elements are key aspects to cover in order to insure an immersive and efficient user experience. Nowadays, handheld controllers tracked in the virtual environment are mainly used such as HTC vive controllers, Occulus controllers, Valve Controllers or the Hololens clicker. They allow fundamental interaction tasks like grasping or manipulation with a certain robustness thanks to interaction metaphors. However, they are intrusive and barely intuitive and so downgrade the user experience of virtual manipulation. Besides, they suffer from a lack of realism preventing some complex interaction with the object.

One particular case is precise grasping task (Figure 1). According to Cutkosky, the human grasp attributes of a precise grasp are dexterity, precision and sensitivity [7]. In terms of analytic grasp measures, their equivalents are manipulability, isotropy and compliance [7]. Manipulability is the capacity of the fingers to impart arbitrary motions along with a high degree of freedom between the object and the hand. The grasp isotropy refers to the capacity of the joint fingers to apply wrench to the object accurately through the grasp configuration. Conversely, the power grasp attributes are stability and resistance to slipping. In general terms, grasping tasks have to comply with the capacity to resist disturbances in any direction when object immobility is ensured by fingers positions (form closure) or by the forces applied by the fingers (force closure) and thus by avoiding the fingers to slip [7, 27, 32].

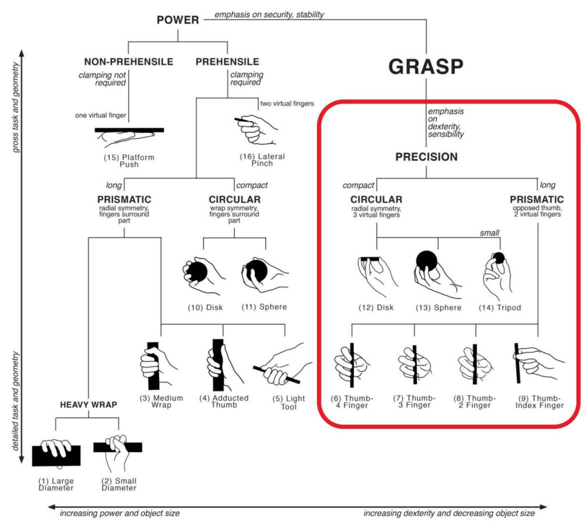

Figure 1: The Cutkosky grasp taxonomy diagram [6]. We take into account only the precise grasp cases framed in red.

Other hardware setups and methods have been developed to improve the interaction. Thus, tracking sensors capture accurately the user's hand. This is however insufficient to provide a realistic and efficient manipulation of the object. The possible penetration of the real tracked hand in the virtual object Figure 2 (on the left) remains a major issue. Indeed, this penetration prevent us from meaningfully determine neither the hand configuration nor the contact points on the object surfaces leading to unstable manipulation.

In precise manipulation cases, due to the small volume of the manipulated object, there is a risk that the tracked finger moves out the manipulated object volume Figure 2 (on the right). In that case, the virtual fingers could "release" the object unintentionally. This appears when the object is too small to "contain" the tracked hand fingers possible displacements.

Whatever happens, the difference between the real and the virtual hand (due to his interaction with the manipulated object and the lack of force feedback) constitutes a major drawback.

Some approaches tend to solve these issues using different methods: some of them by fixing the object to the virtual hand [3, 28], others by refitting the virtual fingers to the object shape [24], or by freezing the fingers [26]. An alternate approach to detect a grasping

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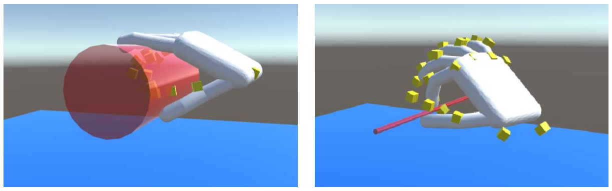

Figure 2: Left: Interpenetration of the real hand (yellow nodes) in the virtual object, the real hand is inside the red object. Right: Releasing effect of the real hand on the virtual object, the real hand is out the red object

configuration where a simplified force closure is detected. This is the case for the Liu's caging based stable grasp [19] which consists in turning off the physical properties of the object when a "caging" configuration is detected. Others try to improve the penetration by projecting the interpenetrating fingers on the object surfaces according to the friction contact model [15]. A last option tries to bring compliance by a linear and rotational spring coupling the real hand with the virtual one [1,30,31].

All of these approaches solve the issues related to power grasp attributes such as the stability of the grasp and the resistance to slipping. This most common grasping type, given its attributes and common uses, facilitates the issues by default. However, in spite of the hand tracking system allowing a relative precise sensing of the finger, some considerations of precise interactions are avoided, like manipulability and dexterity.

Our approach is more due to a balanced decision between a physics-based approach and a metaphorical-based approach. We seek an approach which provides a robust and efficient manipulation requiring a limited computational demand while being more natural than the gesture-based approaches. On the other hand, our approach needs to allow the object to move regarding the hand palm in order to perform a precise task, all of this by ensuring a certain robustness to tracking system perturbation as well as a wide variety of the object physical properties.

We turn these issues into three purposes :

- The capacity to bring a compliance between the tracked hand and the virtual hand. Indeed, the tracking system could suffer from some disturbances and artefacts. Moreover the global gap between the tracked hand and the virtual one due to their interaction and its impact on the virtual manipulation has to be minimized.
- The capacity to bring a compliance and a robust interaction in the contact area between the object and the finger by downgrading the physical properties of the interaction at a specific moment.
- The capacity to trigger this event.

2 Related Work

2.1 Gesture and metaphor-based approaches

A straightforward hand object interaction method consists in a selecting/manipulating metaphor approach where a set of simple hand gestures controls the object properties such as its position, rotation and even size. Similar to a mouse click, some common gestures such as circle, swipe, pinch, screen tap gesture and key tap gesture trigger certain types of interaction with the objects [4]. Thus, some metaphor-based manipulations called "mid air interaction" could be done. In that respect, several works in literature cover a various type of mid-air manipulation. Song et al [33] proposed a handlebar metaphor which allows to apply 9 Degrees Of Freedom (DOFs) object control (rotation , translation and size) by a bi-manual interaction. Mendes et al [21] and Caputo et al [5] explore other different bi-manual interactions techniques, the results suggest that techniques allowing 6 DOFs for the dominant hand are both satisfying and efficient. Giachetti [12] proposes a new metaphor called knob gesture which is implemented within another set of gestures (scaling and grab gesture). Although this "mid air" manipulations are robust regarding the possible tracking system contingencies and tend to be single handed, they remain non-intuitive and inefficient for certain VR applications. These approaches are nevertheless artificial, highly limited by the decoupling of the different DOFs and consequently insufficient for direct manipulation.

2.2 physics-based manipulation

Another approach is to improve the interaction between the object and the hand by taking into account their collision. Thus updating the contact points during the interaction could be a trail. The God-Object approach [37] raises this issue. Thereby, Jacobs [17] integrates the God-Object method in a 6 degrees of freedom building a fully constrained God-Hand. The God-Object approach is also adopted by Holl [15] who uses a simple ray-based technique according to a classic Coulomb contact model but for an unconstrained hand object interaction. Although this approach seems to be effective for rather voluminous objects, the unintentional object "releasing " case may still appear for small objects. Moreover a simple Coulomb contact modelling is not elaborated enough for a two-fingers interaction.

As human skin is a soft body which finger pulps forms a contact area enabling complex manipulation, a better soft finger contact modelling could be another key to that problem. A realistic physical rendering of the flesh hand is considered by Gourred [13] and by Garre [11]. However, using a high resolution skin model for a real time application requires a trade-off between computational cost and naturalness. The complexity could be reduced by modeling only the skin fingers [20]. Talvas also suggests to aggregate the multiple contact constraints into a minimal set of constraints taking into account a non uniform pressure distribution [34]. Other approaches use just a section of the deformable skin considered as soft pads and attach them to a rigid skeleton [29]. Thus, Jacobs uses a soft body model based on lattice shape matching (LSM) [16],nonetheless these soft pads can collapse in extreme cases. However these approaches require compliance between the bones and the tracker interpenetration results. Verschoor et al [20] deal with the compliance issue by integrating a coupling between the tracked skeleton (unarticulated) and the simulated skeleton (articulated and including the soft pads). The entire system consists in an energy minimizing problem. The deformation skin approach still requires huge computation costs and is limited in some extreme cases when the penetrations or the resulting efforts applied to the virtual hands are too high.

This compliance in the tracking is another trail. Borst and Indugula [1] propose a physically-based grasping approach by a virtual coupling applied to a kinematic hand. This approach consists in linking the tracked hand and the virtual hand by using a virtual linear and torsional spring damper. The coupling is applied to each joints of the kinematic hand. This addresses the problem of visual interpenetration and permits fairly good grasp and manipulation as well as force rendering for haptic application. However this approach engenders a "sticking object" feeling which affects the naturalness of the interaction.

Borst and Prachuyaded [2] address this issue by adding an adaptive coupling stiffness depending on the total penetration. This approach permits an unconstrained hand object interaction with some compliance. It is nevertheless still insufficient to overcome the problem of grasping and manipulation of small objects requiring more stability.

2.3 Other approaches

Other approaches deal with the high computational cost of the physic based approaches and the lack of realism of the hand gesture approaches. Borst and Prachuadech introduce for instance a visual feedback to their coupling hand [1] allowing the users to adapt their hand posture to the virtual hand colliding with the virtual objects. The visual information returns the colliding parts of the hand by coloring it but also the penetrating depth by the color intensity. Displaying both the colliding virtual hand and the penetrating tracked hand is also considered.

A non realistic physics is another trail in order to achieve this compromise. Thus, Oprea [28] proposes an approach where the object is fixed in the palm frame, then the fingers are fitted on the virtual object shapes. Nasim and kim [26] introduce a second proxy hand which is in interaction dynamically with the object and get frozen during the manipulating phase, the tracked hand being still displayed. But this method has restricted possibilities of interaction and doesn't allow precise grasp. Liu [19] proposes a caging based approach. When the algorithm detects that the object is overlapped by the colliding parts of the hand, the object is considered as caged by the virtual hand. Thus the physics properties of the object is disabled.

2.4 Contribution

Our paper makes two main contributions:

- We propose an assistance to precise grasping and manipulation that performs precise tasks with a certain degree of manipulability allowing relative movements of the object in the palm.
- We set up a method enabling to trigger a feasible grasp more accurately.

3 Virtual hand coupling and the Grasp Assistance

In this section we introduce the coupling architecture system of the hand and the grasp assistance used to improve stability.

3.1 Virtual hand

The first input on the manipulation system is the tracking system. Hand tracking systems available in the market place include some drawbacks but their main advantage is their accessibility. Some studies show the accuracy of some visual tracking systems like the LeapMotion Controller system [36]. One has to keep in mind that the Orion software developed right after the previously mentioned studies significantly improved the LeapMotion capacity. The benefit of a visual tracking system against a data glove for soft finger application is studied [14]. Furthermore, it provides accurate estimation of the fingertip positions, because its technology aims at tracking the phalanges comparing them to other data gloves systems [22]. Thus the morphological size of the user's hand is returned by the device while avoiding to calibrate the device in a data glove case, which also affects the repeatability. For all of these reasons we use a LeapMotion Controller even if another visual tracking system could be used.

The Borst and indulga approach [1] addresses the issue of non penetrating fingers and compliance between the real hand and the virtual one. Their method couples the kinematic joints with the torsional spring dampers except for the fingertips and the palm which are both linearly and torsionally coupled. Therefore we use a 26 Degrees Of Freedom (DOFs) kinematic model of the hand, being 2 DOFs for the metacarpal joint (MCP), 1 DOF for the proximal interphalangeal joint (PIP) and finally 1 DOf for the distal interphalangeal joint (DIP) Figure 3. The 6 remaining DOFs are for the palm. Because our tracking system allows an accurate tracking phalanx in the Cartesian space, we use a virtual proportional derivative coupling between the virtual phalanges and the tracked phalanges in the LeapMotion frame. The kinematic virtual hand configuration is calibrated via the LeapMotion output.

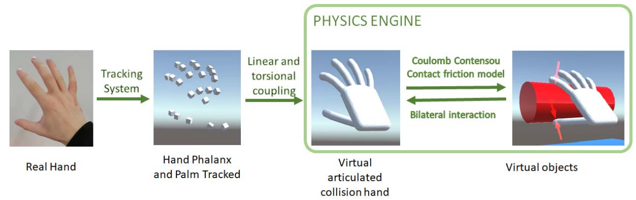

Figure 3: Virtual hand model

However, this coupling method has its limits such as the wrench produced by a huge gap between the tracked hand and the virtual one. This gap could imply a huge grasping contact force, generating a non robust grasping configuration. Therefore we add a rotation and translation effort saturation of the coupling.

This coupling method (which is similar to the one introduced by Borst and Indugula [**?**, 1]) allows fine and precise hand movements tracking, and could be used for grasping tasks of small objects. However, the grasping efficiency and the robustness during the manipulation are still lacking especially when the object becomes smaller. Thus, a grasping assistance ensuring a stable precise grasp is implemented.

Even though this could allow fine and precise grasping tasks of small objects, the grasping efficiency and the robustness during the manipulation are still lacking especially when the object become smaller. Thus needed to ensure a stable precise grasp is implemented.

The soft tissue approach highlights the complexity of the interaction between the virtual object and the virtual hands [11], [16, 20, 29, 34]. This issue deserves to be pointed out especially for precise grasping cases where a certain compliance in the contact point is needed. In extreme cases, the computational cost and the non robustness change our approach by simplifying the problem. In that sense, we consider each phalanges of the virtual hand as a rigid body capsule implementing a Coulomb Contensou friction model Figure 5. All of the contact forces are monitored. The Coulomb Contensou model permits a rather soft finger contact while improving two fingers grasping. Nevertheless the fingers interactions are still limited and don't prevent the "releasing effect" and the "slipping effect" during the precise manipulation of a tiny object.

Our main hypothesis is that thanks to finger contact, the precise manipulation process allows degrees of freedom for the object related to the hand palm, all of this without slippage. So we need to prevent the possible "slipping effect" and "releasing effect" from happening. That's why we need a grasping assistance which will "anchor" the finger on the object during the manipulation with a certain compliance.

The resulting assistance consists in adding a linear coupling between the virtual fingertip and the object on the contact point. This coupling could be summed up by the following scheme Figure 4.

Thus the assistance principle is made up of four phases:

- P1: Contact Phase

  With the contact forces returned by the Coulomb Contensou model, we need to determine if the contact forces could respect the force closure condition. In other words we have to determine whether the grasping configuration is valid or not. This issue will be treated on the following section.

- E1: Grasping Event

  Once we trigger a good grasping configuration, the assistance can be activated. It involves bilateral spring-dampers applied to each contact points. Thus a proportional derivative coupling is

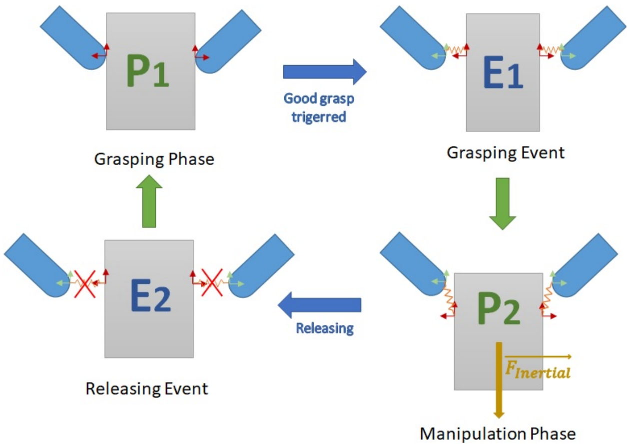

Figure 4: Assistance scheme

set between the contact base in the fingertip frame and the one in the object frame. We configure the proportional derivative coefficients according to the following phase.

- P2: Manipulation Phase

  During the object manipulation, the assistance needs to counterbalance the stiffness of the virtual hand tracking and the inertial effects applied to the object with a certain compliance. Then we define in a static case the minimal requiring stiffness to counterbalance the inertial effort in the worst case. As illustrated we consider the worst case as a two fingers manipulation where the less consistent direction effort resulting of the lack of force closure is described. The fingers are not in contact (due to a "releasing effect"), so the assistance remains the only interaction with the object supporting the inertial efforts during the manipulation. We consider the inertial efforts as the combined effects of the weight plus an acceptable acceleration that the hand could transmit to the object. We determine empirically this acceleration at 5 m/s². We deduce therefore the requiring stiffness to counterbalance this inertial efforts along the tangential component in order to constraint the spring deflection.

- E2: Releasing Event

  The spring dampers function is mainly present to prevent slipping along the tangential component of the contact point and unintentional release along the normal component of the contact point. However this assistance must be deactivated separately for each finger when they tend to release the object intentionally. That's why we implement an assistance effort threshold along the normal component in order to deactivate the assistance. This threshold is established manually according to a trade off between the sticky effect of the assistance and the unintentional release.

4 Detection of a Feasible Grasping State

We need to activate the assistance when it's necessary. In that way we had to discriminate a good grasp configuration from other hand object contacts. According to Liu [19], this event corresponds to the detection of a "caging" configuration where the geometry center of all the collision points of the hand are overlapped with virtual objects. However this approach doesn't allow to detect a good grasp configuration with two fingers and is limited with some objects like hollowed objects or curved ones. Roa [32] proposes an exhaustive review of some grasp criteria used in robotics. Many of them are based on simple geometric properties like the area of the polygon formed by the contact points, yet they are limited. Moreover most of them do not allow a two fingers grasping criteria. Ullmann [35] propose a geometrical detection with two fingers but this method is limited by the object geometrical shape and doesn't discriminate some bad grasp configuration.

Other grasp criteria described by Roa [32] implement a better description of the interaction between the virtual hand and the object including the contact friction model. In that sense, we have to build the usual grasp Matrix which allows to determine the effect of the contact forces on the object and the Hand Object Jacobian which takes into account the hand configuration.

4.1 Grasp Matrix and Hand Object Jacobian

The interaction between the virtual hand and the object is performed via the collision detection and the friction contact module computed by a specific physics engine. Generally, the wrench applied to the object by the finger uses a simple friction cone model, however for some precise manipulation tasks requiring only two fingers, it is an inadequate model. Instead, a soft-fingers contact model is used. It includes a Coulomb Contensou contact model [25], which takes into account torques around the normal component of the contact point Figure 5.

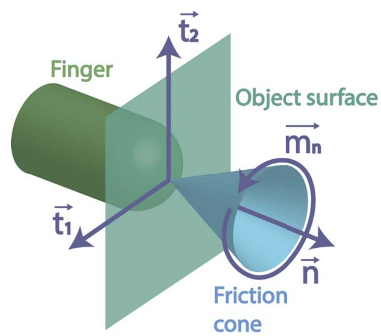

Figure 5: Coulomb Contensou scheme of the model, the moment normal component $\overrightarrow{m_n}$ is taken into account.

The action of the hand on the object is denoted by $f_{c_i} \in R^6$ [25]. Only the degrees of freedom required for the Coulomb Contensou model are needed, which is done by introducing the wrench basis matrix B_{c_i}. The following equation defines the reduced force $F_{c_i} \in R^4$.

$$F_{c_i} = B_{c_i} f_{c_i}$$

B_{c_i} is the wrench basis associated [25] :

$$B_{c_i} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Thus we obtain the resultant of force contact F_0 for each finger transformed into the object coordinated:

$$F_0 = \sum_{i=1}^{n} Ad^T_{g^{-1}_{oc_i}} F_{c_i} = \sum_{i=1}^{n} Ad^T_{g^{-1}_{oc_i}} B_{c_i} f_{c_i} = \sum_{i=1}^{n} G_i f_{c_i}$$

With $Ad^T_{g^{-1}_{oc_i}}$ the wrench transformation matrix in the object frame for the ith contact, thereby introducing the contact map G_i as the linear map between contact forces with respect to B_{ci} and the object wrench. This contact map enables to introduce the Grasp Matrix as the map between the n contact forces and the total wrench applied to the object. Then Grasp Matrix G can be written:

$$F_o = \begin{bmatrix} G_1 \dots G_n \end{bmatrix} \begin{bmatrix} f_{c_1} \\ \vdots \\ f_{c_n} \end{bmatrix} = G f_c$$

It may be noted that the grasp matrix is also the map between velocities v at the contact point and the twist $\dot{x}$ of the object.

$$v = G^T \dot{x}$$

By using the jacobian matrix J_h which links the velocity in the joint space of the kinematic hand to the twist of the object [25], we can obtain:

$$J_h \dot{\theta} = G^T \dot{x}$$

That leads us to the relation between the joint space of the kinematic hand and the object space:

$$\dot{x} = (G^T)^+ J_h \dot{\theta} = H \dot{\theta}$$

Where $(G^T)^+$ is the pseudoinverse of G^T. We call H the hand-object Jacobian.

4.2 Grasping Criteria

According to the grasping criteria review of Roa [32], this grasp matrix allows grasps criteria based on the grasp wrench space (GWS) which denotes the set of wrenches that can be applied to the object [10]. However the exploration of this GWS or the related metrics require to define physically meaningful limits on the contact forces. In that way, knowing the physical properties of the task in order to match them with this metrics is important [18], likewise the hand configuration during the manipulation has to be taken into account. This is not the case for us where users could freely move the object. In that way assuming large force contact limits independently imply an expensive computational cost of the full GWS [18, 23].

However Roa [32] also mentions criteria based on algebraic properties of G and H which denotes properties of the grasping state only by taking into account the geometric object properties (shape,size). These criteria don't depend on the weight nor the friction value but is still meaningful enough to describe a feasible grasp configuration.

According to Roa [32], when a grasp is in a singular posture, one of the singular values of G (here $\sigma(G)$) goes to zero.

- So the minimum of the singular values indicates the "distance" between the actual configuration and a singular configuration. We call G_{min} the grasping criteria associated:

  $$G_{min} = \sigma_{min}(G)$$

- By using the product of all singular values of G we consider all of them in the description of the grasp configuration.

  $$G_{det} = \sqrt{det(GG^T)} = \sigma_1 \dots \sigma_6$$

- In order to describe the uniformity of the contribution for each contact point in the total wrench applied to the object, we use the ratio of the minimun singular value to the maximun singular value.

  $$G_{rat} = \frac{\sigma_{min}(G)}{\sigma_{max}(G)}$$

According to Roa [32], the same idea can be applied to the hand-object Jacobian Matrix H resulting in:

- $$H_{min} = \sigma_{min}(H)$$

- $$H_{det} = \sqrt{det(HH^T)} = \sigma_1 \dots \sigma_6$$

  We consider these criteria as the maniability combined with the effort applied to the object.

- $$H_{rat} = \frac{\sigma_{min}(H)}{\sigma_{max}(H)}$$

4.3 Implementation

Feasible grasps are defined as those for which all relevant criteria values are within a certain threshold. However we have to determine the ones that are relevant. According to Hussein [23], there is a huge correlation between the G_{min} and G_{rat} criteria. This correlation is confirmed in our implementation of the grasp criteria in our environment, so we reject the G_{rat} criterion in our analysis.

After an analysis of different grasping criteria in an exhaustive objects set with two fingers grasp and three fingers grasp, we can determine that the G_{det} and H_{rat} are useless for the discrimination of feasible grasps. The H_{min} criterion is also useless in a three fingers grasping case.

As these criteria depend on the number contact, we consider the best contact configuration as a three contact type, the other contacts can be considered as perturbations in the grasp process which could be solved by deactivating their contact module during the manipulation. We nonetheless have to choose the best three contact points configuration from the four or five contact points set. Here we decide to choose the set of 3 which is accepted by the "grasp threshold" and that maximises the manipulability. We note that the choice of maximising the manipulability determined by H_{det} is made regarding the G_{min} criterion. So we decide to choose the contact point set which maximises $H_{det} * G_{min}$.

This analysis work is included in a further analysis taking into account the variability of the object dimension and will be introduced in a future publication.

5 Determination of Grasping activation

In order to test the efficiency of the grasping assistance, especially for fine manipulation, we refer to the precision grasp type in GRASP taxonomy generalized in [9] (Figure 1). We can confirm that the assistance could nevertheless perfectly work for power grasp.

In that way we decide to choose a set of objects that satisfy all kind of precision grasp and also allow some power grasp (Figure 1). Thus, according to Feix [8, 9], we take a set enabling this trade off which represent the most commonly used type too. Moreover these objects are sized in order to make precise grasp type a little bit tricky without assistance.

It results in a set of two shapes (cylinder and parallelpipoid) for three dimension :

- Small types:

  A width of 1 cm and a length of 2 cm (Figure 6). This type of object don't appear that frequently in the literature [8]. However they are related to some particular cases like manipulating a screw or a dice. Moreover, they enable some precision grasp type like tip or palmar pinch. We add a little support in order to facilitate the grasping during the following user experience.

- Flat types:

  A width of 8 cm and a length of 1 cm, Figure 7. Their shapes are related to some particular grasp type present in [8, 9], such as parallel extension, precision disk and lateral pinch.

Figure 6: Small Objects, the cubic one in yellow and the cylinder in red. The support is present in brown only for grasping convenience during the user experience phase

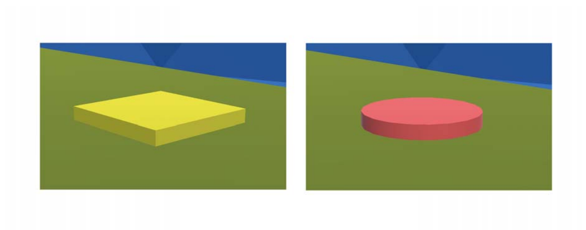

Figure 7: Flat Objects, the cubic one in yellow and the disk in red

- Slim types:

  A width of 2 cm and a length of 15 cm, Figure 8. They represent the most frequent uses according to Feix [8,9], consisting in the cylinder and long prism object type. They are related to some pinch grasp like the small object but also prismatic grasp and even tripod grasp.

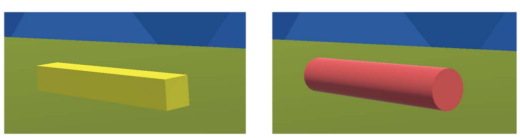

Figure 8: Slim Objects, the cubic one in yellow and the disk in red

The grasping criteria threshold are determined heuristically by applying good grasp configurations ([8,9]) and unfeasible grasp configuration for each object type. The resulting threshold is resumed in the table 1:

Table 1: Resulting grasping criteria threshold

Grasping Criteria Threshold		Slim Cubic	Slim Cylinder	Flat Cubic	Flat Cylinder	Small Cubic	Small Cylinder
2 Fingers	Gmin	0.01	0.02	0.045	0.05	0.008	0.008
	Hmin	0.2	0.2	0.2	0.2	0.2	0.2
	Hdet	$1.5e^7$	$6e^6$	$2e^5$	$2e^5$	$2e^6$	$2e^6$
3 Fingers	Gmin	0.017	0.022	0.06	0.06	0.01	0.01
	Hdet	$1.5e^7$	$6e^6$	$1e^7$	$1e^7$	$2e^6$	$2e^6$

6 User Study

We demonstrate the qualitative performance of our approach by conducting within-subjects experiments which compare grasping and manipulation of the objects above-mentioned with and without the assistance.

6.1 Design

The experiment consists in a pick-and-place task for the 6 objects mentioned previously. There are two tests with assistance and two tests without for each object, which represents four tests per object. Each test comprises 3 ”pick and place” tasks consisting in placing the object on targets to reach (targets set depend on the dimension type object).

The objects order and their associated test order are created by a pseudo random process, reducing the transfer and learning bias during the session. Each pick and place task comprises 3 stages:

- 1) Manipulation phase: This starts with the appearance of the object and its associated target. The target is in see-through blue and linked to the object by a see-through blue guiding line.
- 2) Maintaining phase : Once the target is triggered, participants have to maintain the target position during 1 second. The target becomes opaque blue.
- 3) Releasing phase: The target turns into purple. The participant has to drop the object.

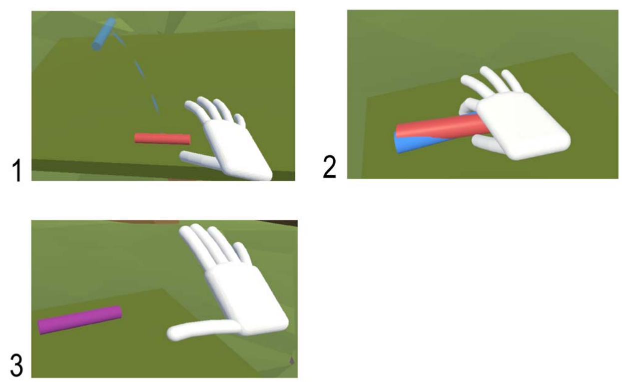

Figure 9: Different pick and place steps with 1: before grasping in the placing phase, 2:During the maintaining phase (as we can see the gap between the target and the object), 3: After the releasing phase (the user has to wait for the next placing task)

After that, the participant waits for the following target to be reached until the target set is finished. Every time the object slips through the user’s fingers during the placing phase, we reset the object state and count this attempt. We measure both quantitative and qualitative aspects of the manipulation summarised as follows.

For the quantitative aspect we record the precision of the alignment to the target, the time needed to perform the task and the number of failed task attempts. So, for the study we take into account the following dependent variables:

- 1) Error in translation: the average distance between the target and the object during the maintaining phase.
- 2) Error in rotation: the average angle between the main axis of the target and the object.
- 3) Manipulation Time: the amount of time required to place the object.

- 4) Number of fails: all fails are counted. We consider an attempt as failed when the object dropped during the manipulation phase.

The independent variables considered are:

- 1) Grasping Mode: with or without assistance
- 2) Object Dimension: Small, Flat and Slim

For the qualitative aspect, for each test we ask participants to rate two sensations on a 11-point Lickert scale :

- Naturalness: "How natural the sensation of the average pick and place experience was?" (0: Extremely unnatural, 10: Extremely natural)
- Efficiency: "How the efficiency of the average pick and place experience was?" (0: Extremely inefficient, 10: Extremely efficient)"

6.2 Procedure

The procedure is described to the participant, after a short introduction to the fine grasping objective. We asked participants to perform primarily two or three fingers precise grasping task. If the participant seems to be experiencing difficulty reaching the target after several unsuccessful attempts, power grasp is allowed.

The participant starts with a training session where the 6 objects appear in a random order and two pick and place tasks have to be performed for each object. Thus he could practise freely the grasping task in order to learn and to get used to the grasping without force feedback. If the object drops, the user is allowed to retrieve it. Moreover this session permits to determine the user's grasping skills level.

After that, the participant starts the experience session.

6.3 Apparatus

We used a HTC vive headset to display the virtual environment. The hand is tracked via a LeapMotion system in a head-mounted mode, therefore the viewing angle could impact the hand tracking. All the tests were run on a PC assembled with a i7 processor, 16 GB RAM and a NVIDIA 1080p graphic card. Participants were sitting during the session.

6.4 Participants

25 subjects were recruited for the study: 20 males and 5 females aged 20 to 40 years old. 3 participants were left-handed. 8 participants had no previous VR experience and 9 had previous LeapMotion experiences.

6.5 Quantitative Results

As to the quantitative aspect, we run a two-way repeated-measures ANOVA per dependent variable. Thanks to the interaction, we make one way repeated measures ANOVA per object dimension. The sphericity assumption was not violated for any dimension or dependent variable. All p-value of the pairwise post-hoc comparison are Bonferroni corrected.

For the number of failed attempts:

- 1) There was a significant effect of grasping mode, $F(1,24) = 83,39, p < .001$
- 2) There was a significant effect of object dimension, $F(2,48) = 24.64, p < .001$
- 3) There was a significant mode/dimension interaction, $F(2,48) = 28.02, p < .001$

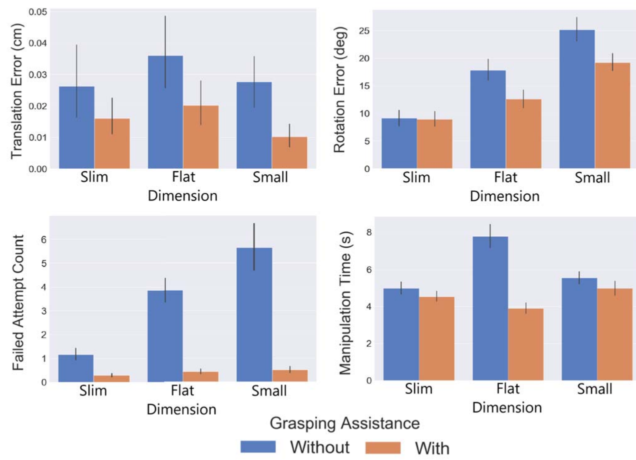

Figure 10: Effect of assistance on translation error (top-left), rotation error (top-right), failed attempts count (bottom-left) and manipulation time (bottom-right)

Post-Hoc analysis show a significant impact on the assistance. Indeed, the average failed attempts without assistance mode are approximately 90,4% higher than the ones with assistance for small objects (p<.001), 92.3% for flat objects (p<.001) and 84.7% (p<.001) for slim objects. The per-grasping mode test shows a significant effect on the object dimension for the non-assisted grasping mode ($F(2,48) = 26.73, p < .001$) but no significant effect for the assisted grasping mode ($F(2,48) = 2.53, p = .183$).

For the translational error:

- 1) There was a significant effect of grasping mode, $F(1,24) = 24.05, p < .001$
- 2) There wasn't a significant effect of object dimension, $F(2,48) = 2.14, p = 0.1302$
- 3) There wasn't a significant mode/dimension interaction, $F(2,48) = 0.66, p = 0.5210$, consequently no per-grasping mode test was made.

Post-Hoc analysis show significant impact on the assistance for small objects (nearly 3 times more accurate with p<.001) and flat objects (2 times more accurate with p=.0452). For the large objects, the mean difference is non significant (p=.218). No significant effect of the object dimension was revealed.

For the rotational error:

- 1) There was a significant effect of grasping mode, $F(1,24) = 33.80, p < .001$
- 2) There was a significant effect of object dimension, $F(2,48) = 101.21, p < .001$
- 3) There was a significant mode/dimension interaction, $F(2,48) = 10.42, p < .001$

Post-Hoc analysis reveal significant impact on the assistance for small and flat objects. The average rotational errors are in fact 22% lower with the grasping assistance for small objects (p<.001) and 28% for flat objects (p<.001). No differences are observed for slim objects. The per-grasping mode test shows a significant effect of object dimension for both of the grasping modes: ($F(2,48) = 41.80, p < .001$ for assisted mode) and ($F(2,48) = 94.00, p < .001$ for non assisted).

For the manipulation time:

- 1) There was a significant effect of grasping mode, $F(1,24) = 78.34, p < .001$
- 2) There was a relatively significant effect of object dimension, $F(2,48) = 6.8, p = 0.0027$
- 3) There was a significant mode/dimension interaction, $F(2,48) = 44.67, p < .001$

Post-Hoc analysis reveal significant impact only for flat objects (49% faster with assistance, p<.001). No significant differences are observed for the others. The per-grasping mode test shows a significant effect of object dimension for both of the grasping mode: ($F(2,48) = 8.82, p < .001$ for assisted mode) and ($F(2,48) = 22.72, p < .001$ for non assisted).

Overall the number of failing attempts is the most significant performance improved by the assistance. This could be explained by the relative complexity of object grasping without force feedback. Indeed, slim objects are less tricky to manipulate (the force closure configuration could be made easier by default) and so the performance of the assistance is less noticeable for them. For the positioning errors, both are impacted by the assistance. This demonstrates the dexterity afforded by the assistance, as the user can adjust more efficiently the object position. Regarding the time necessary to proceed the manipulation task, only flat objects are impacted by the assistance. This could be explained by the fact that flat objects are particularly tricky to manipulate, forcing the user into manipulating carefully when there is no assistance. For the other objects dimension, once a good force closing grasp configuration is performed, the object manipulation can be made without assistance as well (relatives to the Liu's caging based configuration [19]).

6.6 Qualitative Results

For the qualitative aspect, we report the response to naturalness and efficiency questions for each object dimension. The p-values were Bonferonni corrected for the 3 object types comparison.

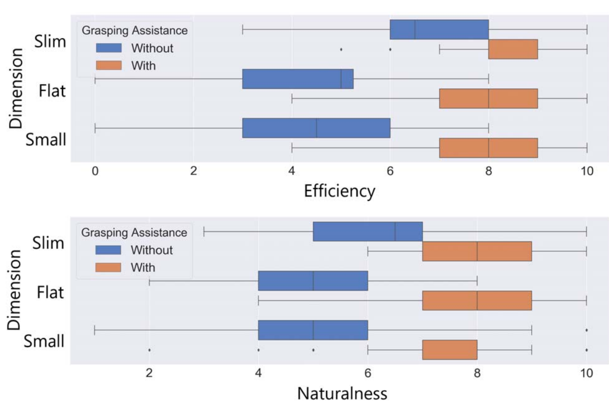

Figure 11: Subjective feedback on 11-points Likert scale

Overall the mean score for the naturalness and efficiency questions significantly show that the feeling of grasping seems more natural thanks to the assistance, and this for each object dimension independently. For the naturalness, the mean score with the assistance is indeed above 3 points for small objects ($t(24) = 17.85, p < .001$) and flat objects ($t(24) = 25.43, p < .001$). For slim objects the mean score with the assistance is above 2.5 points ($t(24) = 11.67, p < .001$). For the efficiency, the mean score with assistance is significantly higher than 1.5 points for slim objects ($t(24) = 14.80, p < .001$), 3 points for flat objects ($t(24) = 30.58, p < .001$) and 3.5 points for small objects ($t(24) = 27.31, p < .001$).

7 Discussion

Regarding the positioning error studies, the user experiences confirm the accuracy improvement thanks to the assistance. This can be explained by the spring anchoring compliance of the assistance. Thus the users can rely on the dexterity improved by the assistance and therefore move freely the object against his palm in order to adjust the object position. This is very helpful for precise tasks like screw manipulation. The quantitative results also show a significant slipping object prevention brought by the assistance. Indeed the number of failed attempts is practically null with the assistance and not negligible without the assistance. This number grows with the dexterous and precise manipulation requirement, such as small objects manipulation.

Thus the grasping assistance alleviates the dexterity problem and so is less significant in manipulation cases requiring less dexterity. In that respect, there is less performance discrepancy for slim objects, their quantitative results being already good. Moreover, in some cases, slim objects are intentionally grasped with a power grasp configuration because of their very aspect inciting that kind of grasping. In other cases they are not: the object sometimes slips out inside the hand and is overlapped by the palm.

The qualitative results provide some evidence that the assistance doesn't disturb the feeling of naturalness during the manipulation. This natural feeling aspect is even improved by the assistance. This can be explained by the fact that the assistance prevents the object from slipping out of grasp. Most of the subjects reported this inconvenience during the tests not implying the assistance. However, some subjects sometimes reported a sticky situation during the releasing phase when the assistance was activated. This can be a problem under discussion in the future. As to efficiency questions, the subjects are also unanimous about the fact that the efficiency of the manipulation is improved by the assistance. Sometimes, some subjects struggled to grasp the small or flat objects when the assistance was deactivated. In that way, the following test involving the assistance is perceived as a relief and the following score is high rated.

However our assistance actually depends on the tracking system, especially for small objects cases. Indeed, during the manipulation, the LeapMotion system couldn't track accurately in certain viewing angles, sometimes hopping the tracking input. Moreover, some subjects' hands weren't tracked very well. Yet this inconvenience is absorbed quite well by the assistance.

8 Conclusion

In this work, we proposed an efficient grasping assistance allowing dexterous grasping of small objects in a virtual environment. We suggested a method to detect a feasible grasp configuration with a low computational cost thus enabling activation of this assistance. However the grasping criteria depends strongly on the object dimensions and a future work on a more complete grasp criteria analysis is in progress. This work will try to generalize this approach to more complex objects by taking into account the correlation between the dimension, the shape and the grasp criteria.

This approach improves nevertheless greatly the manipulation in virtual environment and expands the coupling approach to complex manipulation. We want to go further in our approach by minimizing the difference between the virtual and the real hand regarding the type of dexterous movement applied to the object. Some hand-tracking filtering using machine learning approaches could be considered.

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