Visual Interpenetration Tradeoffs in Whole-Hand Virtual Grasping

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ABSTRACT

We present the first experiment on tradeoffs involving visual interpenetration in whole-hand virtual grasping, with new findings that contrast prior interpenetration research and provide a stronger understanding of user behavior and beliefs. Most notably, preventing interpenetration reduced performance by increasing real hand closure and reducing release precision. Nonetheless, most users subjectively prefer interpenetration to be prevented and even expect this to perform better. Although reduced closure and true representation of real hand pose might help users anticipate a grasp release moment more precisely, most subjects believed release moment was better anticipated with virtual fingers constrained to object surfaces. Finally, we suggest how grasping techniques can resolve the tradeoffs.

KEYWORDS: Virtual grasping, visual interpenetration.

INDEX TERMS: I.3.6 [Computer Graphics]: Methodology and Techniques—Interaction techniques; H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities

1 INTRODUCTION

Visual hand-object interpenetration is an artifact where a virtual hand sinks into a virtual object due to lack of physical constraints. It can be visually prevented by keeping virtual hand segments outside of objects, but this misrepresents real hand state and could lead to detectable visual-proprioceptive discrepancy [1].

Prior interpenetration studies are not adequate for grasping, although they are important for some other tasks. Burns et al. [1] found visual interpenetration is more noticeable than visual-proprioceptive discrepancy and a tracker offset study showed offsets reduce aiming performance. Although they used a hand avatar, they did not consider grasp effects. Lindeman et al. [2] studied a finger on a virtual panel and found that a visual constraint improved preference, speed, and accuracy. These performance gains may hinge on a design feature (Section 5).

In contrast, we show benefits of visual interpenetration in addition to disadvantages (when compared to preventing it). Since visual interpenetration is unnatural, it may influence users to manually reduce interpenetration, which could help them learn better grasp behavior (lighter touch as mentioned in [3]). Our previous study [4] suggested that reduced real-hand penetration improves release performance in grasp techniques that require real fingers to exit an object's surface for release. So, we expected release may be better with visual interpenetration. Also, we considered that showing the real finger depth within a virtual object may improve a user's anticipation of release moment, especially for slow release.

2 RELATED GRASPING TECHNIQUES

Grasping approaches commonly require real fingers to be moved out of virtual objects for release (or some similar counterpart) and would benefit from better grasp behavior (light touch). Borst et al. [3] proposed a physically-based approach that coupled a dynamic virtual hand simulation to the tracked real hand configuration using virtual linear and torsional spring-dampers. Spring forces and torques provided virtual hand motion while collision response provided grasped object motion. Jacobs et al. [5] extended this with per-phalanx soft bodies to better model contact areas and forces. In a heuristic approach of Moehring et al. [6], a grasp was formed according to phalange-object collisions and friction cone rules, with grasp release based on either grasp release size or distance. Various other approaches [7, 8, 9] detecting grasp and release based on collision between the tracked hand and a virtual object require real fingers outside of objects for release.

To prevent hand-object interpenetration, a dynamically-simulated virtual hand can be constrained to stay outside of virtual objects via collision response that is also used for object motion [3, 5]. Other approaches include, e.g., searching for collision-free states [8, 9] or applying offsets to hand state data [10].

3 EXPERIMENT

We conducted within-subjects experiments comparing virtual grasping with and without hand-object interpenetration. An object-alignment experiment had 3 independent variables:
Grasp Approach – allowing and preventing interpenetration,
Object Shape (rigid) – bunny and cube,
Object Size – small (bunny length = 12 cm, cube edge = 6 cm), medium (15, 8 cm), and large (18, 10 cm).

Dependent variables were:
Grasp Size – finger-to-thumb tip distance,
Release Time – time spent releasing a grasped object,
Translation Error – object translation from grasp release,
Rotation Error – object rotation from grasp release.

We hypothesized that allowing interpenetration improves grasp behavior by inducing larger grasp size. We also expected to see corresponding grasp release performance differences.

We also conducted a subjective comparison experiment asking subjects to compare the two grasp approaches directly to indicate with which approach they better anticipated the release moment, and which approach they preferred overall. Subsequently, a written questionnaire asked subjects to explain their choices and how interpenetration influenced their grasp or release behaviors.

We hypothesized that allowing interpenetration is not preferred but allows better release moment anticipation.

We note that an object-drop experiment is mentioned only briefly here due to space constraints. It simply asked subjects to pick an object and drop it into a large pit, involving faster hand motions. Its findings were consistent with those reported here.

Apparatus and Software Notes: We used a mirror-based VR display with stereo viewing via CrystalEyes glasses (no tracked viewpoint), right-handed CyberGlove and miniBird 500 for hand tracking, and desktop speakers (Figure 1a). More details are given in our previous study [4]. Software ran on a Dell Precision T5500 with a Xeon W3680, 12GB RAM, and an NVIDIA Quadro 5000.

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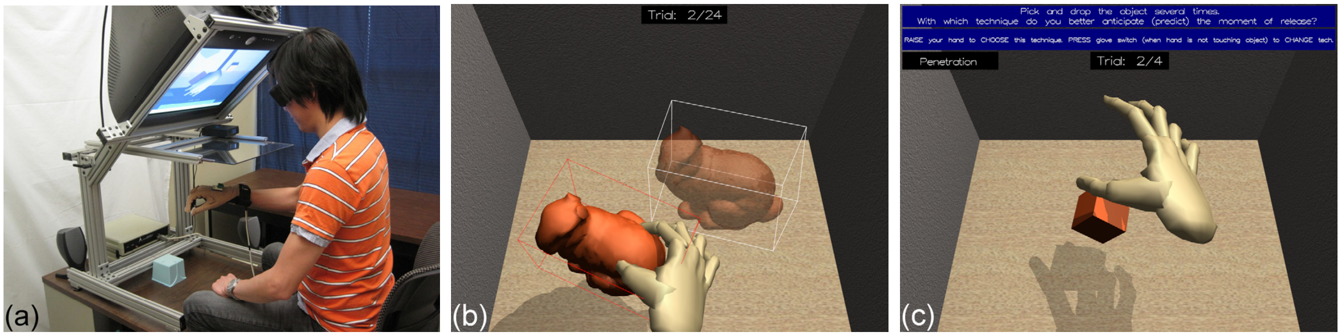

Pick and drop the object several times.
With which technique do you better anticipate (predict) the moment of release?
RAISE your hand to CHOOSE this technique. PRESS glove switch (when hand is not touching object) to CHANGE tech.

Figure 1. Experiment environment: (a) apparatus, similar to [4], (b) object-alignment experiment, (c) subjective-comparison experiment.

Both grasp approaches used Borst et al.'s spring model [3], which normally prevents visual interpenetration. The approach allowing interpenetration simply displays the tracked hand configuration instead of a spring hand configuration. Hand joint model and further software notes were as described in [4].

Subjects: 20 subjects participated: 19 males and 1 female, aged 20 to 30 years (average of 25), 18 right-handed and 2 left-handed. All subjects were students: 18 from computer science, and 1 each from mathematics and telecommunications. 7 participated in our previous grasping study [4], 3 others reported exposure to VR systems, and all of the remaining 10 played video games, watched 3D movies, or took a graphics course.

3.1 Procedure

To reduce possible effects of fatigue and short-term learning, we split experiments into 2 days, with a different grasp approach per subject's day (order randomized per subject). On both days, subjects completed tasks in this order: a learning task, the object-alignment experiment, and an object-drop experiment. Additionally, subjects completed the subjective comparison experiment and subsequently filled out a written questionnaire, only at the end of the second day. Experiments typically lasted 30 to 45 minutes per visit, including glove calibration.

Each experiment included: A 1-trial demo session with on-screen instructions to introduce subjects to the task; A 6-trial practice session without instructions (as an exception, the subjective comparison had no practice); The actual experiment session without instructions.

Learning Task: Subjects were asked to practice grasping and releasing objects well. There were 3 trials: ball, cube, and bunny.

Object Alignment: Subjects picked up an object from the floor to align it with a floating transparent target, with no gravity (Figure 1b). This task resembles scene arrangement, with objects staying in place after release. Bounding boxes were displayed temporarily after the object was lifted to aid the alignment. A 2-second countdown sound began after successful alignment. Subjects were instructed to hold the hand still while waiting for the countdown sound to end, and to release the object with precise alignment at the end of the sound. There were 24 trials: 2 shapes x 3 sizes x 4 trials. Condition order was randomized per subject.

Subjective Comparison: Subjects freely interacted with an object (Figure 1c), using a glove-mounted button to freely switch between grasp approaches, indicated on the upper-left screen as "penetration" and "no penetration". The initial approach was randomized per trial. A question at the top of the screen asked subjects to choose the approach that allowed better release moment anticipation by raising the hand for 2 seconds to indicate the current approach as the answer. A second question then asked them to indicate the approach preferred overall. There were 4 trials: small cube, large cube, small bunny, and large bunny. Condition order was randomized per subject.

Questionnaire: The questions were:

1. Please explain why you chose one technique over another in the subjective comparison experiment:
   a. For the question: "With which technique do you better anticipate (predict) the moment of release?"
   b. For the question: "Overall, which technique do you prefer?"
2. Does seeing visual interpenetration artifacts influence or modify your grasping or releasing behaviors? Please explain.

4 RESULTS

Let:

t1 and *t2* be the time instants when the countdown sound ends and when no finger phalanges touch the object, respectively.

$\mathbf{d}_{t\text{-}i}$, $\mathbf{d}_{t\text{-}m}$, $\mathbf{d}_{t\text{-}r}$, $\mathbf{d}_{t\text{-}p}$ be distances between thumbtip and index, middle, ring, and pinky tips, respectively, at time *t1*.

$\mathbf{p}_{t1}$, $\mathbf{p}_{t2}$ be positions of the object center at times *t1* and *t2*, and

$\mathbf{q}_{t1}$, $\mathbf{q}_{t2}$ be quaternion orientations of the object at times *t1* and *t2*, respectively, so $\mathbf{q}_{t2}\mathbf{q}_{t1}{}^{*}$ describes the object rotation from *t1* to *t2* (* denotes quaternion conjugate).

Then:

Grasp size = $\min(\mathbf{d}_{t\text{-}i}, \mathbf{d}_{t\text{-}m}, \mathbf{d}_{t\text{-}r}, \mathbf{d}_{t\text{-}p})$,

Release time = $t2 - t1$,

Translation error = $\text{length}(\mathbf{p}_{t2} - \mathbf{p}_{t1})$, and

Rotation error = absolute value of an angle (adjusted to fall within $[-\pi, \pi]$) extracted from $\mathbf{q}_{t2}\mathbf{q}_{t1}{}^{*}$.

Figures 2 to 5 summarize grasp sizes, errors, and release times. We performed 3-way repeated-measures ANOVA per dependent variable. To focus on our hypotheses, we report only main effects and significant or near-significant interactions involving grasp approach (we use "near-significant" to denote $.05 <= p < .1$).

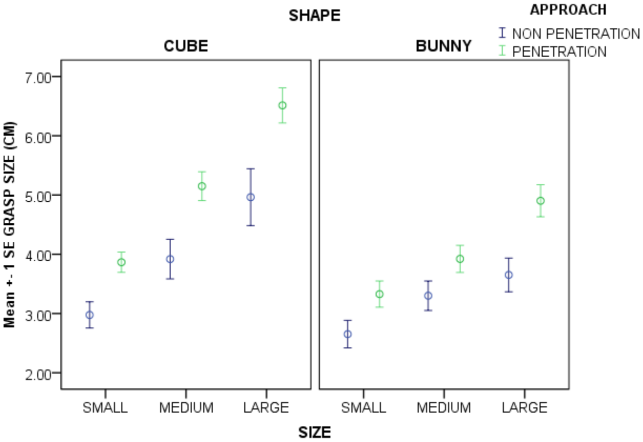

Figure 2. Grasp size (cm) in the object-alignment experiment.

For grasp size: There were significant approach (F(1,19) = 22.74, p < .001), object size (F(2,38) = 94.41, p < .001), and shape (F(1,19) = 72.65, p < .001) effects. There was a significant approach-size interaction (F(2,38) = 6.20, p < .01) and a near-significant approach-shape interaction (F(1,19) = 3.07, p = .096). Mean grasp size for the penetration approach was larger than for the non-penetration approach (p < .001) by 29%. The approach-size interaction can be explained by stronger effects of approach for larger objects than for smaller ones. The near-significant approach-shape interaction can be explained by possibly stronger effects of approach for the cube than for the bunny.

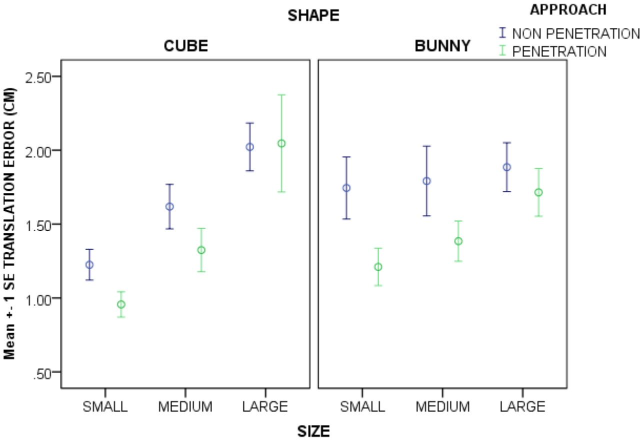

Figure 3. Translation error (cm) in the object-alignment experiment.

For translation error: There were significant approach (F(1,19) = 5.22, p < .05) and object size (F(2,38) = 35.62, p < .001) effects. No significant shape effect was detected (F(1,19) = .95, p = .342). Mean translation error for the penetration approach was smaller than for the non-penetration approach (p < .05) by 16%.

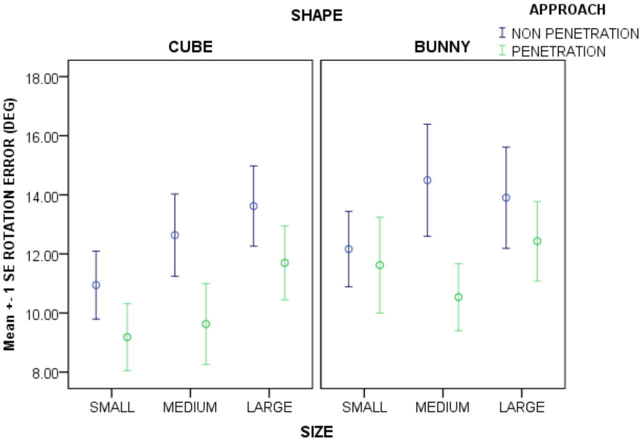

Figure 4. Rotation error (deg) in the object-alignment experiment.

For rotation error: There was a near-significant approach trend (F(1,19) = 4.09, p = .057) and a significant object size effect (F(2,38) = 3.71, p < .05). No significant shape effect was detected (F(1,19) = 2.63, p = .121).

For release time: There was a significant object size effect (F(2,38) = 15.70, p < .001) and a near-significant approach-shape interaction (F(1,19) = 3.87, p = .064). No significant effects were detected for: approach (F(1,19) = .78, p = .388) or shape (F(1,19) = .17, p = .686). The near-significant approach-shape interaction can be explained by possibly stronger effects of approach for the cube than for the bunny.

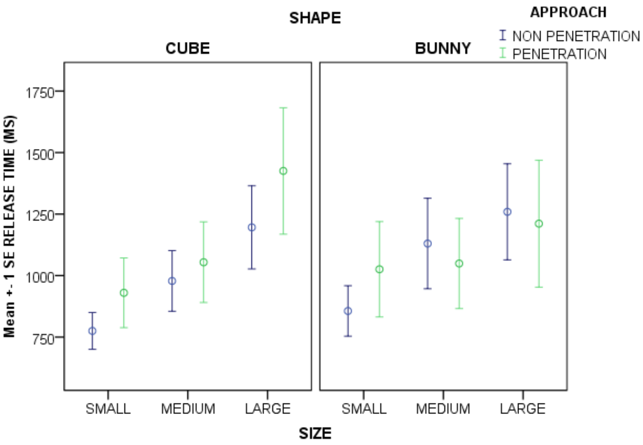

Figure 5. Release time (ms) in the object-alignment experiment.

Subjective Comparison: For each condition, each subject was given a score of zero or one depending on the approach selected. We used one-parameter two-tailed z-tests to detect difference in response proportion from 50% (the no-preference score). 15/20 is the threshold proportion for significance (Z(20) = -2.24, p < .05).

For the release moment anticipation question: Significantly, 15, 16, and 15 subjects chose the non-penetration for the small cube, the small bunny, and the large bunny, respectively. Near-significantly, 14 subjects chose the non-penetration for the large cube (Z(20) = -1.79, p = .074).

For the overall preference question: Significantly, 17, 19, 16, and 16 subjects preferred the non-penetration for the small cube, the small bunny, the large cube, and the large bunny, respectively.

Questionnaire: For Question 1a, 17 subjects gave responses favoring non-penetration and 4 subjects gave responses favoring interpenetration (a subject giving a mixed response was counted twice). The most common reasons for preferring non-penetration were that natural visuals help anticipation or that penetration visuals are confusing. Also, 7 of the responses favoring non-penetration explicitly described perceived behavior that contradicts grasp size results or actual release requirements. Subjects believed more finger extension was required with interpenetration. Of the 4 responses favoring interpenetration, 2 noted that large objects could stick on release attempts with non-penetration. The remaining 2 stated: penetration helped to not grasp into the object unintentionally, and interpenetration helped anticipation when overgripping.

For Question 1b, 18 subjects gave responses favoring non-penetration and 3 subjects gave responses favoring interpenetration. Most described non-penetration as more natural or visually pleasing. One atypical response stated non-penetration helped interpret object mass and shape. Another response stated that the amount of real hand closure with non-penetration better approximated object dimension, contrary to real grasp size differences. The 3 explanations for preferring penetration were: it was useful for releasing large objects; it was more intuitive during release since virtual hand motion matched real hand motion while the non-penetration hand only opened after some amount of real hand motion; it was easier to grasp/move large objects when grasps did not have to obey object shape.

For Question 2, concerning grasp behavior for penetration, 3 subjects reported lighter grasps, with one explicitly stating that it was due to interpenetration visuals, and 6 subjects reported tighter grasps contrary to grasp size results. Concerning release behavior for penetration, 6 subjects reported they required more hand opening or more abrupt grasp release due to seeing visual sink-in, making sure the fingers exited the object, or object sticking. The remaining responses did not reflect on behavior change.

5 DISCUSSION

The object-alignment results confirm our hypothesis that interpenetration improves behavior by reducing real hand closure. The questionnaire responses suggest that this was transparent to many subjects in that they felt fingers were further apart without interpenetration. Possible reasons for lighter grasp with interpenetration include attempts to mimic more natural grasping or mitigate undesirable visual artifacts, and some understanding of grasp release requirement (for at least a few subjects).

Grasp release was also more accurate with interpenetration. This can be explained by less required finger extension for grasp release, due to reduced real hand closure, resulting in less object movement [4]. Another possibility is that although less motion was required, subjects might extend fingers more slowly or carefully due to some influence from interpenetration visuals, with no net detected time effect. In terms of release time, we did not find a significant effect of interpenetration. Considering that reduced real hand closure from interpenetration could speed up grasp release due to less required finger extension [4], we suspect our experiment was less sensitive to such performance differences because reaction time in the release time results may blur the difference between approaches. This, or inter-subject difference, is reflected in relatively large variances.

The subjective comparison confirms our hypothesis that interpenetration is not preferred, with the main reason from questionnaire results being that it was less natural and less visually pleasing. However, results do not support our hypothesis that interpenetration allows better release moment anticipation. Responses suggest subjects believed what they saw (visual capture [11]), and preventing interpenetration led them to (incorrectly) believe minimal finger movement releases a grasp (interpenetration was perceived to require more extension, contrary to objective results). As an exception, a few subjects did describe improved anticipation, particularly for large objects.

Our results contrast Lindeman et al.'s performance drop for interpenetration [2]. In [2], virtual finger penetration into a panel cancelled object drag. But, grasp approaches retain grasp during interpenetration. Our results nonetheless confirm subjective preference for preventing interpenetration and demonstrate subject beliefs that support the finding that visual-proprioceptive discrepancy is less detectable than visual interpenetration [1].

6 CONCLUSION AND IMPLICATIONS

Our study provides new knowledge about tradeoffs involving visual interpenetration and demonstrates them in the new context of virtual grasping. Unlike prior studies, this showed how preventing interpenetration with visual constraints (rubber band metaphor [8]) can reduce performance: real hand closure was increased and release precision was reduced. Preventing interpenetration is still subjectively preferred as it appears more natural. To deal with this tradeoff, we suggest that grasp approaches prevent interpenetration and consider the following:

When interpenetration is substantial but visually prevented, grasp methods should not require the real hand to move outside of objects for release. To match user expectations, small grasp opening motions should release objects. We presented such a technique in [4] and showed release performance gains exceeding interpenetration effects reported here. However, even with such methods, encouraging "light touch" can remain useful for stability of physical simulation and for reducing detectable visual-proprioceptive discrepancy.

Secondarily, grasp techniques can incorporate various mechanism that may encourage lighter or more realistic grasp closure for improved performance and learning. However, it is not yet known if any non-force approaches are as strong as showing the real hand penetration. Force feedback can improve grasp control [12] and provide some motion constraints, but whole-hand force-feedback is expensive and cumbersome. Lightweight tactile elements [13] may aid grasp control but would not provide actual motion constraints. Finger closure (interpenetration) may be represented indirectly, without showing actual interpenetration. Moehring et al. [13] showed that changing color of finger segments defining a valid grasp improved grasp judgment. Lindeman et al. [2] changed virtual finger color to alert the user of real finger interpenetration. Techniques with finger deformation [5], object deformation [12], or rendered grasp force vectors [3] can represent the interpenetration depth indirectly. Visual and auditory force-level indicators can improve grasp control [12].

Finally, there are some grasp methods that cannot readily prevent interpenetration (e.g., in augmented reality systems where the real hand is visible, or optical capture of arbitrary real hand and tool geometry without modeling joints). Our experiment suggests their user experience would not be pleasant, but fortunately that we can expect interpenetrating visuals do not reduce grasp performance.

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