Nonuniform and Adaptive Coupling Stiffness for Virtual Grasping

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ABSTRACT

Recent virtual grasping approaches involve physical simulation and virtual couplings between tracked and virtual hand configurations. We introduce a nonuniform coupling in which the stiffness of thumb coupling is scaled relative to that of other digits. This shifts the position of grasped objects in the hand, which may impact grasp and release performance. We graphically illustrate the effects on grasped object position, and we experimentally measure impact on object motion during grasp release. In addition to basic nonuniform scaling, we propose adaptive scaling to account for the number and depth of digits involved in multi-finger grasps. We show that one particular choice of adaptive coupling results in a tradeoff of increased object position consistency and decreased release consistency. The knowledge gained from our study will enable researchers to optimize couplings in future work.

Keywords: Virtual grasping, virtual coupling, grasping forces.

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 AND RELATED WORK

Various recent approaches to physically-based grasping are based on virtual couplings between a tracked hand configuration and a simulation-driven virtual hand model (e.g., [1][2][3]). Couplings have also been made using point surface models that do not explicitly represent hands [4]. These works have not addressed the best balance of coupling stiffness (e.g., spring strength) between different digits, instead using either uniform or unspecified values. Uniform couplings result in grasped object position and hand configuration analogous to those for grasping soft deforming objects. However, for rigid virtual objects, this may not be ideal, and virtual grasping differs from real grasping because real fingers substantially penetrate virtual objects. Most recent virtual grasping techniques prevent visual interpenetration with constraints, as this is important for subjective experience [5].

We introduce nonuniform and adaptive coupling elements and we investigate their effects to provide a foundation for improving emerging grasping techniques. Specifically, we vary the stiffness of thumb-coupling springs in a spring coupling based on [6]. Increasing the stiffness of the thumb springs tends to shift grasped object position towards the fingers. The virtual thumb and fingers, constrained to remain on the object surface during grasp, are affected by object position changes. During hand opening or closing, object motion and hand configuration changes depend on relative spring strengths of the digits involved. Minimizing the penetration-related object motion during release is useful to increase release precision and to better match real-world release behavior for rigid objects. Understanding the effects of the nonuniformity is important for the following reasons:

- Effects on object position relate to interaction precision, e.g.,
  - We show a relationship between nonuniform coupling and accuracy (release motion) in a release task. Understanding such relationships is important for minimizing object motion imparted by coupling mechanisms rather than by a user's intentional manipulation.
  - Because a thumb tends to flex less than an index finger during grasping [7], minimizing object movement during pickup or release may require nonuniform stiffness.
- Effects on virtual hand configuration and grasped object position may impact perceived grasp quality.
- In case a special release mechanism is used to address release precision effects [3], motion discrepancy artifacts following release will depend on the impacted hand configuration.

We study two approaches. In fixed nonuniform coupling, thumb stiffness is simply scaled by a constant factor (multiplier). In adaptive nonuniform coupling, the factor changes depending on the number and depth of other digits in the grasp.

2 COUPLING METHODS

2.1 Spring-based Grasping Method

We use a grasping approach resembling that in [6], with a 16-segment virtual hand coupled to tracked hand configuration by linear and torsional spring-dampers. This coupling drives the virtual model to follow the tracked hand, subject to physical simulation and collision handling using the Nvidia PhysX SDK. Hand base (palm) springs are implemented as in [6]. Torsional springs at finger joints are implemented as PhysX revolute joints, with 4 total degrees of freedom per digit. Hand collision shape is set slightly larger than visual model shape, and a corresponding small overlap between collision shapes is allowed, to improve contact simulation. The approach prevents visual interpenetration, constraining virtual digits to grasped object boundaries.

2.2 Basic (Fixed) Nonuniform Coupling

The most basic nonuniform coupling that we consider simply scales the torsional thumb elements by a constant multiplier, m. The spring constant and damping constant of each of the 4 revolute joints for the thumb are scaled. We call this fixed nonuniform coupling, because the multiplier is constant during an interaction. The resulting effects appear mostly due to the spring constant, as our damping constants are set low and PhysX produces somewhat damped behavior regardless of low settings.

2.3 Adaptive Nonuniform Coupling

We also propose an adaptive coupling that varies the multiplier depending on the number and depth of digits opposing the thumb in the grasp. One motivation for this is to maintain a more consistent grasped object position: as more fingers enter the object, there tends to be more force opposed by the thumb. With a

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fixed coupling, this shifts object position towards the thumb, with the thumb penetrating more than any other digit (uniform case).

For adaptive coupling, we define a finger count n as follows:

$$n = \frac{\text{sum of finger penetration distances}}{\text{maximum of finger penetration distances}}$$

In this equation, "finger" does *not* include the thumb or non-penetrating fingers. When all relevant fingers penetrate equally, n is simply the number of fingers involved in the grasp. When penetration varies per finger, n varies continuously as fingers contribute in proportion to their relative penetration.

Furthermore, we calculate n using only the penetration amounts that oppose the thumb. For this, we first calculate penetration vectors per penetrating digit as the difference between its tip positions in the tracked and virtual hand models (the difference results from the collision response that constrains the virtual finger to the object surface). Thumb-opposing penetration distances are then computed using dot products between the finger vectors and the normalized thumb vector (i.e., we find the finger penetration distances parallel to thumb penetration direction).

One way to use n in an adaptive coupling is to scale the thumb's torsional elements by $n{\cdot}m$, where m is described in the previous subsection. The following sections show that this choice improves consistency of grasped object position at the cost of reduced consistency in object translation during release. Results presented there may be used to develop alternative adaptive couplings that vary with n to produce the opposite effect (e.g., reducing, rather than increasing, stiffness as n increases).

2.4 Effects on Grasped Object Position

To check effects of the proposed couplings on grasped object position, we captured grasps (tracked hand configurations) and varied m, coupling type, and finger flexion. Figure 1 shows the effects, and an accompanying video further demonstrates them. In each figure column, it is seen that as m increases (top to bottom), object position shifts more towards the fingers. In each row, fixed coupling is seen to result in a thumbward shift in position as more fingers enter the object, while adaptive coupling better maintains the object's vertical position. Consequently, the adaptive coupling also produces a more consistent virtual hand configuration. There is retained horizontal motion or "roll" as more digits enter with adaptive coupling, and vertical effects are more complex if maximum digit penetration increases during the entry. We note fixed and adaptive couplings are equivalent for 2-digit grasp.

3 Release Position Effects Experiment

3.1 Overview and Design

We measured grasped object motion during release to understand effects of the nonuniform couplings. This motion is important because it is a measure of positioning error from release: reduced object motion means increased release accuracy, and may also have a counterpart of reduced object motion during grasp.

Users performed a targeted release task under 24 condition combinations. The experiment had a within-subjects design with the following independent variables:

Multiplier m: values 1, 2, 4, and 8.
Coupling type: Fixed and Adaptive.
Grasp type: 2-digit (thumb and index), 3-digit (thumb, index, middle), and 4-digit (thumb, index, middle, and ring).

Note that a fixed coupling with m = 1 corresponds to standard uniform coupling.

3.2 Apparatus

Figure 2 shows the VR hardware. Users reached into a mirror-based "fishtank" display. An Acer GD235HZ LCD provided 1920 X 1080 stereo graphics viewed through Nvidia 3DVision glasses. A polarizing sheet on the mirror addressed view-dependent interactions between different polarizing elements (LCD and glasses). Viewpoint was not tracked. Hand configuration was sensed with an 18-sensor CyberGlove and a miniBird 500 tracker (distal finger joint angles were computed as two thirds of middle knuckle angles). Desktop speakers provided audio feedback. Software ran on a Dell Precision T5500 with a Xeon W3680, Nvidia Quadro 5000, and 12GB RAM.

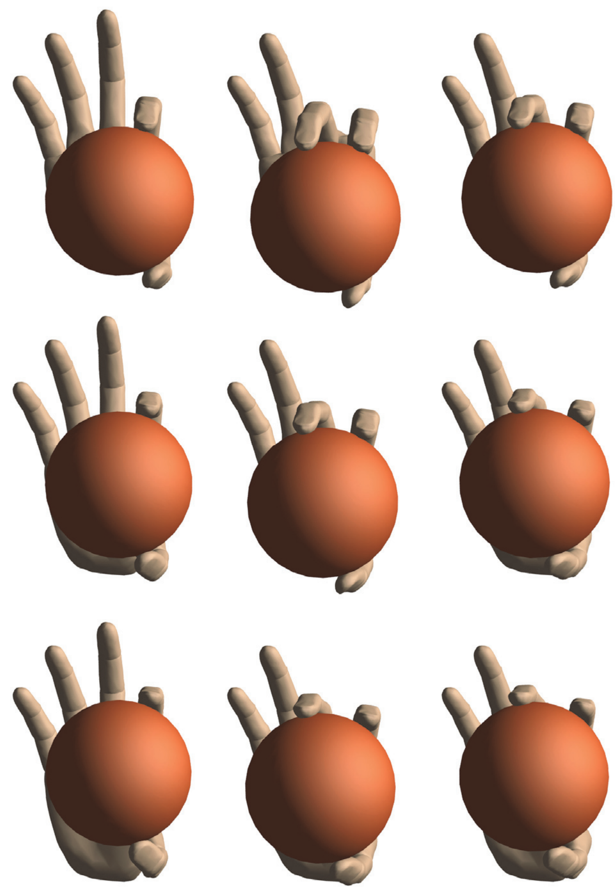

Figure 1: Grasped object positions and virtual hand behavior. *Columns, left-to-right*: 2-digit grasp, 3-digit with fixed coupling, and 3-digit with adaptive coupling. *Rows, top-to-bottom*: m = 1, m = 2, and m = 4. Viewpoint and tracked hand configuration are constant, except tracked middle finger configuration, which is identical for all 3-digit grasps.

3.3 Subjects

20 subjects participated, but 1 did not complete the experiment due to problems maintaining 4-digit grasp. Of the remaining 19, 17 were male and 2 were female, aged 18 to 36 years (average 25), all right-handed. All were students: 17 from computer science or engineering and 1 each from mathematics and communicative disorders. Subjects reported previous VR or 3D graphics exposure as follows: 6 participated in a previous grasping study, 1 mentioned VR development work, and the remaining 12 mentioned common experiences like video games or 3D movies.

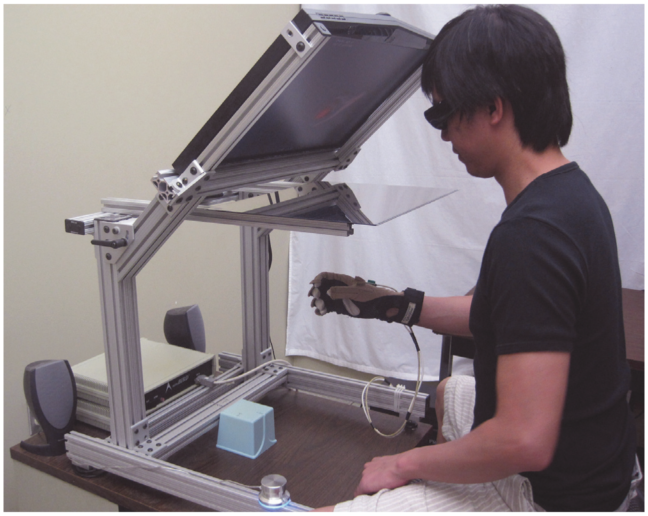

Figure 2: VR equipment with mirror-based display.

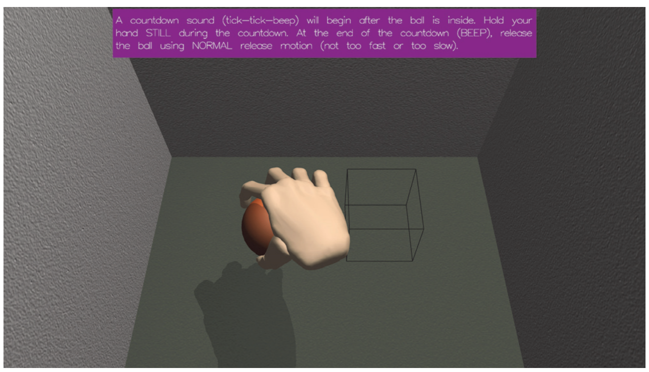

Figure 3: Experiment environment showing the hand grasping a ball. The user is moving the ball to the cubical outline target. On-screen instructions are only visible during a practice trial.

3.4 Procedure

Prior to the experiment, glove sensor gains and offsets were calibrated by having the subject move the hand to reference poses.

To introduce subjects to virtual grasping and to the three grasp types, they first completed a learning session where they freely practiced each grasp type until satisfied. There was no target in this session – subjects picked up and dropped the ball (with simulated gravity). In case of obvious calibration problems, slight manual adjustments were made to calibration in this session.

This was followed by three trial sets: one per grasp type, in random order. In each set, the subject first practiced the experiment task four times: once with on-screen instructions and three times without. The task required subjects to pick up a 9-cm virtual ball from the virtual floor (registered with our table top), move it to a target, and release it on expiration of an audible countdown timer (Figure 3). Virtual gravity was turned off during this task, as we wanted to focus measurements on hand-related motion only. The target was a cube outline that changed color from black to bright green as the ball was centered in the box. The color switched on and off at a threshold distance of 1.25 cm between ball center and target center. This threshold distance also triggered the 2-second countdown timer (tick-tick-beep). The subject had to maintain the ball within 1.5 cm of centered for the timer to complete, otherwise the targeting had to be repeated. Grasp type was enforced: a trial was restarted if the subject did not maintain the correct digits in the grasped object between pickup and release sound.

Per grasp type set, after its practice trials, the subject performed 16 real trials, corresponding to 2 trials for each of the 8 possible condition combinations of *m* and coupling type, in random order.

3.5 Results and Discussion

We computed object translation amounts along a thumb-defined direction (line of action). Let:

t1 be the time when the countdown timer ends (release start),
t2 be the time when no fingers touch the object (release end),
$\mathbf{p}_1$, $\mathbf{p}_2$ be the object's center positions at times *t1* and *t2*, and
$\mathbf{d}$ be the thumb penetration direction at time *t1* (normalized tip difference as in Section 2.3, pointing inward)

Then, directed (projected) translation is $(\mathbf{p}_2 - \mathbf{p}_1)\cdot\mathbf{d}$. This estimates translation along the coupling's "line of action", similar to thumb-to-finger direction or thumb force direction. We note strong correlation between projected and full translations ($r(910) = .79$, $p < .001$) and between full translation and actual placement error amounts ($r(910) = .83$, $p < .001$). Projected results are in Figure 4.

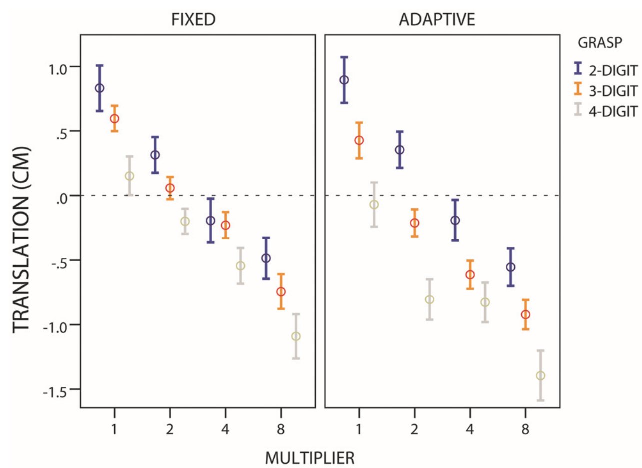

Figure 4: Object translation during release (mean with standard error bars for the 24 conditions). The plot shows translation component along a thumb "line of action". Negative translation is towards the thumb.

We checked for statistically-significant effects with 3-way repeated-measures ANOVA. Each variable had significant overall effect on the translation (*m* : $F(3,54) = 145.53$, $p < .001$; coupling type: $F(1,18) = 21.19$, $p < .001$; grasp type: $F(2,36) = 19.44$, $p < .001$). Furthermore, all possible pairwise comparisons between levels of each variable showed significant effect (2-digit vs. 3-digit: $p = .028$; 3-digit vs. 4-digit: $p = .002$; all other comparisons: $p < .001$; Bonferroni-corrected).

The clearest plotted effect is the change in object movement along $\mathbf{d}$ with changing multiplier *m*: The stiffer the thumb coupling, the more the object moves towards the thumb during release. This is a result of the stiffer thumb coupling causing the opposite motion during grasp, resulting in increased finger penetration and decreased thumb penetration relative to uniform coupling. The change in object position appears overall close to linear against exponentially increasing multiplier, especially for the fixed coupling.

The multiplier's effect confirms the utility of nonuniform coupling: the value of *m* minimizing translation (zero translation, maximizing release accuracy) is higher than 1. From the plot, we estimate optimal *m* for the fixed coupling to range from 1.7 to 2.4, depending on grasp type, or about 2.1 overall.

There is also more thumbward release translation for an increased number of fingers in the grasp (grasp type effect), even for the fixed coupling. This is counter-intuitive considering the effects in Figure 1: as the number of fingers increases, we expect the object is already more towards the thumb during grasp (with decreased individual finger penetration but increased total penetration), so less thumbward translation might be expected during release. So, the observed increase is due to some effect other than grasped object position, such as different hand base motions or grasp apertures for different grasp types. For example, in the 2-digit grasp, the middle finger remains more extended than in the 3-digit grasp, and this may stabilize palm motion relative to a 3-digit grasp that causes more palm motion. Increased palm motion could speed up thumb exit and impart overall hand movement towards the thumb. We checked for tracked palm rotation difference in our data by computing a palm rotation angle during release, analogous to translation during release. Palm rotation amounts differed significantly between grasp types ($F(2,36) = 3.44$, $p = 0.043$) with a detected increase in palm rotation for the 3-digit grasp compared to the 2-digit grasp ($p = .015$, Bonferroni-corrected). Mean increase was 2 degrees rotation about a point near the wrist, which can produce digit tip motion of about 5 mm during release, depending on hand configuration. We expect there are additional factors contributing to the grasp type effect, such as more complex hand motions or user behaviors.

The most important result from the coupling type variable is that the adaptive coupling has a more pronounced grasp type effect than the fixed coupling: There was significant interaction between grasp type and coupling type effects ($F(2,36) = 9.81$, $p < .001$). The adaptive coupling, designed to improve grasp object position consistency, has the side-effect of decreasing release translation consistency. This is counter-intuitive with respect to the adaptive coupling's effect on grasped object position, but it can be understood with respect to fixed coupling results: the adaptive coupling increases spring stiffness as more fingers are used, and the basic effect of increasing stiffness, seen in the fixed coupling, is increased thumbward release translation. In the release translation metric, this effect outweighs the improved consistency of grasped object position from the adaptive coupling.

The results can be used to design other adaptive couplings with more consistent release translation, if desired. Results suggest that this requires decreasing, rather than increasing, thumb coupling stiffness as a function of increasing finger count n. Such an approach would produce less consistent grasped object position with respect to the palm (Section 2.4), but release translation results suggest that this actually corresponds to reduced object movement during interaction, possibly due to hand motion differences for different grasp types. In general, a promising initial approach is to first estimate the optimal fixed m per grasp type, then find the average corresponding n for each estimated m, and finally fit a function that can be used to compute an adaptive m from n. The average values of n during our user study were between 1.45 and 1.67 for 3-digit grasps and between 1.85 and 2.10 for 4-digit grasps, with lowest value when $m = 1$ and highest when $m = 8$. 2-digit grasp always gives $n = 1$. Preliminary inspection of data suggests fitting to (m,n) pairs of about (1.7, 2.0), (2.2, 1.6), and (2.4, 1.0).

4 Additional Subjective Experiment Summary

We briefly summarize an additional study. The 19 subjects returned to the targeted release environment and subjectively tuned m for the two coupling types and for 2-digit and 4-digit grasps. They were asked to turn a knob to "tune for BEST overall release precision". Additionally, we included trials with a release mechanism from [3]. This mechanism lifts virtual fingers from the object when a heuristic detects release motion, and subsequently adjusts fingers to return to their tracked configuration. Because this may negate release motion effects but add motion discrepancy after release [3], these trials asked subjects to adjust the knob for "preferred hand motion after release".

The main result was that subjects tuned m to high values, with large variation. Mean tuned values of m were 13.9 (SD 5.45) with the normal grasping system and 9.1 (SD 5.93) for the version with an added release mechanism. High m keeps the virtual thumb close to the tracked thumb. For the normal grasping method, such high values would result in low thumb penetration during grasp but substantial positioning error during release. For the method with an added release mechanism, a high value reduces post-release thumb motion artifacts in exchange for increased finger motion artifacts. In both cases, subjects may have been sensitive to thumb artifacts at very low values and tuned high to avoid them, while being less sensitive to finger artifacts and release precision. Results suggest that preferred values may be much higher than the values minimizing release translation (Section 3.5), but high variances suggest there is not a clear best value.

5 Conclusion

We demonstrated impacts of nonuniform coupling stiffness on grasped object position, virtual hand configuration, and object motion during release. An adaptive version showed a tradeoff of increased grasped object position consistency and reduced release motion consistency. Our results can be used to design more precise virtual grasping systems.

The benefits of increased thumb coupling stiffness (relative to finger stiffness) are likely related to less thumb motion than finger motion in real grasps. Basing coupling element stiffness on studies of hand motion on a per-joint basis may lead to generalization of results and additional improvement.

Forces or offsets in a hand coupling can be used to render force feedback (e.g., [6]). So, the impact of the nonuniformity on force feedback should also be considered. If force feedback is rendered by simply mapping coupling element forces to a device, overall computed force may increase as coupling elements are stiffer, but relative strength of force between fingers would be preserved because object position shifts to maintain force balance. Future work can include techniques to make nonuniformity transparent and to consider effects on other force rendering techniques.

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