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Expanding Haptic Workspace for Coupled-Object Manipulation

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Abstract

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EXPANDING HAPTIC WORKSPACE FOR COUPLED-OBJECT MANIPULATION

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ABSTRACT

Haptic force-feedback offers a valuable cue in exploration and manipulation of virtual environments. However, grounding of many commercial kinesthetic haptic devices limits the workspace accessible using a purely position-control scheme. The bubble technique has been recently presented as a method for expanding the user's haptic workspace. The bubble technique is a hybrid position-rate control system in which a volume, or "bubble," is defined entirely within the physical workspace of the haptic device. When the device's end effector is within this bubble, interaction is through position control. When exiting this volume, an elastic restoring force is rendered, and a rate is applied that moves the virtual accessible workspace. Existing work on the bubble technique focuses on point-based touching tasks. When the bubble technique is applied to simulations where the user is grasping virtual objects with part-part collision detection, unforeseen interaction problems surface. This paper discusses three details of the user experience of coupled-object manipulation with the bubble technique. A few preliminary methods of addressing these interaction challenges are introduced.

Keywords: Haptic feedback, bubble technique, hybrid haptic control, virtual assembly, virtual reality, human-computer interaction.

INTRODUCTION

Virtual assembly involves manipulation of computer-aided design (CAD) models to simulate assembly processes. Haptic force-feedback augments visual and audio feedback to provide physical feedback about the interaction of grasped objects and the environment [1, 2]. However, the limited physical workspace accessible to haptic devices reduces the utility of these devices in large virtual environments. The bubble technique has been recently presented as one method of allowing a user to access a large virtual environment with a haptic device with a smaller workspace. This paper focuses on improvements to the bubble technique when used to manipulate grasped objects.

Background on the virtual coupler, a common method of performing coupled-object manipulation, is presented to provide context for the interaction details later on. Techniques for expanding haptic device workspace are then discussed, as well as the limitations of existing literature in this area with respect to haptic object manipulation.

Haptic Object Manipulation

Haptic manipulation of grasped objects is performed using a "virtual coupler." Initially proposed by Colgate *et al.* [3] and further investigated by Adams and Hannaford [4], the virtual coupler connects the virtual representation of the device's position (also known as the haptic handle) to the grasped object by a critically-damped spring-damper system. The model of the virtual coupler contains both linear and torsional components, where a torsional spring may be envisioned like a clock spring or a beam pinned at one end. The virtual coupler is conceptually illustrated in Fig. 1. Stiffness values are assigned to the linear and torsional springs of the virtual coupler, which are determined empirically and related to the haptic device's capabilities and time step. Displacement of the haptic handle results in the calcula-

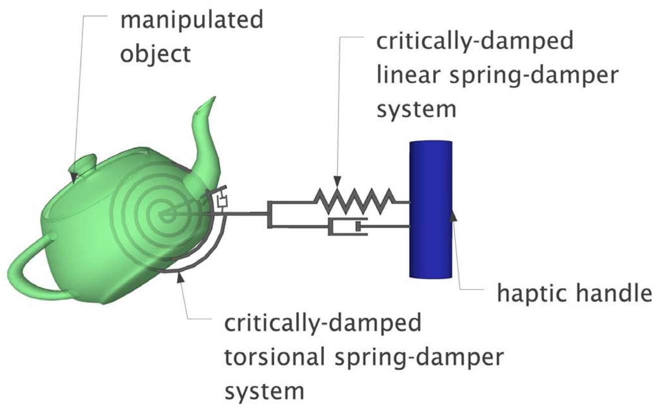

FIGURE 1. CONCEPTUAL VIEW OF VIRTUAL COUPLER

tion of a reaction force given the mass and inertia of the grasped object, which is then used to calculate the object's new position. The reaction force is also rendered to the haptic device, which conveys a sense of comparative mass. As a critically-damped system, the computed location grasped object tends to achieve the position and orientation of the haptic handle as rapidly as permitted by the specified stiffness, while not being prone to oscillations and other instabilities. Use of the virtual coupler helps ensure overall system passivity.

Increasing Haptic Workspace

One technique of increasing the haptic workspace is to apply scaling in position control. As proposed by Fischer and Vance, the ratio of virtual workspace size to physical workspace size can be used to ensure an entire virtual volume is reachable [5]. Scaling increases the reachable workspace and eases coarse manipulation, but makes fine manipulation more difficult.

Pioneered by Dominjon *et al*. [6, 7, 8], the bubble technique is a hybrid haptic control technique for expanding the haptic workspace. It supports fine manipulation as well as access to a larger effective working volume by moving the workspace under some conditions. The bubble technique uses pure position-control within a spherical volume, referred to as the "bubble," located well within the working volume of the device. The bubble is sized to match the working volume of the specific haptic device. Movement of the device outside this sphere produces an elastic restoring force and applies a velocity to the workspace within the virtual environment. Described using Zhai and Milgram's model of the space of possible interaction devices [9], the bubble technique results in adapting an integrated, purely isotonic and positional device into one that moves along the Sensing-Mapping plane from isotonic and position control to isometric and rate control. For devices like the Haption Virtuose™ 6D35-45 that have a relatively large working volume, the bubble technique can permit one-to-one manipulation while being able to manipulate objects initially outside of reach. For smaller desktop-size devices like the Phantom Omni™ by Sensable, one-to-one manipulation in the more limited physical volume is possible if frequent movement outside the bubble is acceptable. Alternately, a smaller scaling factor can be used together with the bubble technique than when using scaling alone, increasing the quality of fine manipulation incrementally.

In Dominjon *et al*. [8], the bubble technique is described in the context of a point-touching application. The implementation as found in the VirtuoseAPI from Haption allows application of the bubble technique to both point-touching and object-manipulation simulations. However, the use of the bubble technique with coupled-object manipulation presents interaction challenges.

INVESTIGATION OF INTERACTION CHALLENGES

Three interaction challenges were observed when applying the bubble technique in a virtual assembly application. The visualization of the reachable workspace as a spherical volume or "bubble" interacts with the other visual feedback provided by the simulation. The other two challenges are both related to the experience of object-object collision while outside of the bubble. The forces associated with the bubble's elasticity and the manipulation of objects cannot be distinguished. Furthermore, movement of the bubble during collision can move the simulation into a condition that results in a perceived "stickiness" when attempting to separate colliding objects.

Implementation Platform

The present work was implemented in SPARTA, the *Scriptable Platform for Advanced Research and Teaching in Assembly.* This application, the successor to SHARP [10, 11, 12, 13], provides a virtual reality environment where arbitrary computer-aided design (CAD) models can be loaded and manipulated using physically-based modeling and haptic force feedback. It is tuned for use of real-world units throughout to investigate full-scale interaction. It builds on the VR Juggler open-source virtual reality software framework to support a wide variety of hardware and software platforms [14]. Model loading, triangulated data-structures, and graphics rendering is provided by the OpenSceneGraph library[1] working in concert with VR Juggler. The VR JuggLua framework, which extends VR Juggler with Lua scripting capabilities [15], maintains the visual and audio feedback, and provides rapid prototyping of immersive interaction. SPARTA itself uses configuration scripts that are actually executable Lua code that manipulates the simulation core to load models, connect and configure devices, and launch the simulation. A run-time Lua console allows interactive re-configuration

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[1] `http://www.openscenegraph.org`

of the simulation.

Collision detection and physically-based modeling is based on the Voxmap PointShell (VPS) software developed by McNeely *et al.* [16, 17, 18] and licensed from Boeing. VPS permits collision detection and force rendering involving arbitrary geometries at very high rates. It operates by performing discretization of input geometries into voxels, and performing voxmap sampling to detect collision and compute forces. SPARTA incorporates software that connects VPS to OpenSceneGraph, allowing arbitrary portions of the scene-graph to be voxelized at run-time without a separate preprocessing step.

The implementation of interaction devices in SPARTA is modular, with wand, glove, and haptic devices all presenting a generic “Manipulator” interface. An interface for “ManipulatorEncapsulators” is supported, which presents a Manipulator interface allowing use in the simulation and that also takes as input another Manipulator object. Specific implementations of ManipulatorEncapsulators may selectively override default implementations of methods that directly forward calls to the enclosed Manipulator, to provide changes as desired. For instance, an encapsulator is included that scales up position reports and scales down forces by a user-specified amount. Encapsulators are akin to transform nodes in a scene-graph data structure, except that their more general formulation permits them to apply a range of effects beyond spatial transformations. In SPARTA, the bubble technique is implemented as a ManipulatorEncapsulator that takes as input an existing Manipulator, the coordinates of the device’s center, the radius of the bubble desired, the bubble stiffness for force rendering, and details of the rate control function. This permits a single implementation of the bubble technique to be used with all supported device types. It also permits the combination of scaling with the bubble technique, which has been useful in applying desktop devices like the Phantom Omni in this research. Figure 2 is a screenshot of the SPARTA environment with models loaded and the bubble technique enabled.

Display Options

The sphere-shaped volume of the workspace providing direct position-control has previously been visualized as a semi-transparent sphere [6, 7, 8]. Dominjon *et al.* note that dual-display of the spherical bounding volume (haptic and visual) supports association of the physical and displayed workspace. Three visualization modes were implemented in SPARTA: a semi-transparent sphere, a wire-frame sphere, and a no-visualization option. An ad-hoc, informal evaluation of these different visualizations of the bubble while assembling CAD models was performed. Display of the wire-frame bubble (Fig. 2) seems to serve as a useful tool to support explanation of the workings of the bubble technique. However, assembly of complex CAD geometry seems to be impeded by display of the bubble. The semi-transparent sphere obscures the geometry when opaque enough to clearly visualize the workspace volume. The wireframe sphere does not occlude the geometry, but it seems to be visually distracting and cluttered. In contrast, when display of the bubble was disabled, use of the haptic device to perform virtual assembly seems reasonably natural, and little conscious attention is paid to the detail of the hybrid control.

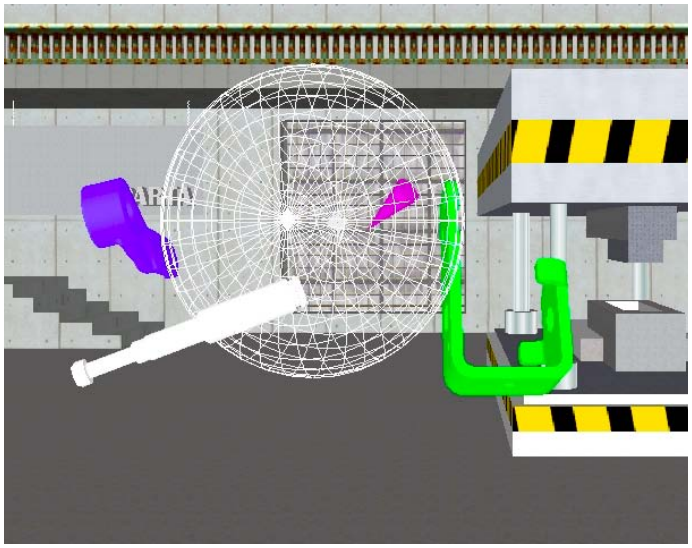

FIGURE 2. **WIREFRAME WORKSPACE DISPLAY IN SPARTA**

Two hypotheses may explain the seeming contradiction with existing results. A virtual assembly application may present a higher task load than point-touching applications. Visualization of the workspace may maintain awareness of the hybrid position-rate control scheme, presenting difficulties in completing the original task. A second hypothesis is that visualization of the bubble during object manipulation presents a challenge of divided attention, with the sphere visuals serving to distract from the features of the manipulated geometry that facilitate or impede assembly.

In light of these findings, run-time-switchable display of the workspace bounding sphere has been implemented. This allows explanation of the workings of the bubble technique, and subsequently allowing actual completion of assembly tasks to proceed unobstructed.

Distinguishing Bubble Force from Collision-Related Force

In the described haptics-enabled virtual assembly application, the primary source of forces rendered to the haptic device is the virtual coupler. Forces of collision are not directly transmitted to the haptic device. However, forces are felt associated with collision because collision prevents the grasped object from moving and increases the spring displacement. Due to the high update rate, the virtual coupler can convey fairly detailed infor-

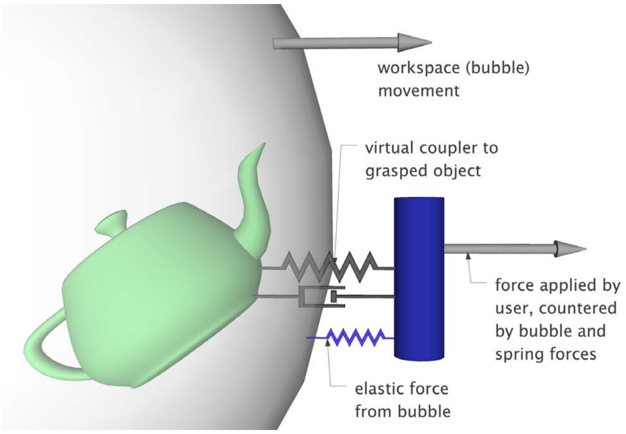

FIGURE 3. **GRASPING OBJECT WHILE MOVING BUBBLE**

mation about the shapes of colliding objects, such as initial contact, ridges, etc.

An implementation of the bubble technique provides another source of force: the elastic force associated with movement out of the bubble to simulate an isometric device. This is desirable as Zhai and Milgram found that rate control using an isotonic (non-elastic) device resulted in poor performance [9]. This may be due to the lack of self-centering effect: the user must remember where the neutral area is in order to stop movement [8]. Furthermore, it is desirable to be able to grasp an object while moving the bubble. After all, if object manipulation was only permitted in the pure position-control zone, taking advantage of the expanded workspace would require the user to perform an indexing operation, first moving the workspace, then the object. When holding an object and moving outside of the bubble, as illustrated in Fig. 3, the workspace is moved in the direction of the device's movement outside of the sphere, while an elastic force opposes this direction. Because a grasped object also moves in the direction of movement out of the bubble in this instance, it is likely that collision forces, and by extension, virtual coupler forces, also oppose this direction. However, a user cannot sense individual forces, but rather the summation of all forces acting on a body. Thus, to a user, collision and bubble forces feel the same, weakening the haptic cues provided by collision during assembly.

Collision and bubble movement can be distinguished by adding audio, an additional sensory cue. Even a simple audio effect played upon starting collision draws attention to the transition between free-space movement and collision when manipulating an object in the rate-control area of the workspace. It does not physically change the feel, but the metallic clang effect used in SPARTA noticeably increases awareness of collisions. Another way of distinguishing these two sources of forces is to decrease the elastic stiffness of the bubble itself. By decreasing the intensity of the bubble forces, the user hopefully does not saturate the force-rendering capabilities of the device during bubble movement, leaving capacity for rendering increased forces upon collision.

Bubble Movement During Collision

In a purely position-control system, moving the haptic device away from a colliding object quickly moves the grasped object. In turn, this decreases forces rendered because no collision impedes the restoration of the grasped object to the pose of the haptic handle.

However, using the bubble technique to move the workspace while coupled to an object can lead to a subtle problem. As the bubble and the object move, the object may collide with other objects in the scene. This prevents the object from moving, and by extension is expected to cause an increase in forces rendered. However, sustained, swift movement of the bubble may actively produce large forces even before the coupling begins to transmit collision. As such, an increase in forces due to collision might not always be felt or felt as clearly. This failure to feel and react to the start of collision is further aggravated by the indistinguishable nature of bubble forces and coupling forces as discussed above.

When users fail to feel the collision of objects, they may continue to apply enough force to the device to counter all forces rendered, keeping the haptic handle outside of the bubble. As a result, the bubble continues to move, thus moving the effective position of the haptic handle in the virtual environment, as illustrated in Fig. 4. When the user moves the device back within the bubble, they expect a decrease in forces due to the discontinuation of bubble forces, as well as the movement of the grasped object back away from the colliding object. In fact, neither takes place. While bubble forces are eliminated, the large displacement between the handle and the grasped object leads to substantial continuing forces. Furthermore, since the virtual location of the workspace has moved, the user now must physically move the same distance in the opposite direction within the position-control area of the bubble before the colliding objects are pulled apart. These two connected phenomena are illustrated in Fig. 5. The subjective experience of this situation is of a "stickiness" that prevents a user from being able to separate objects once they have collided. Of course, attending to the location of the haptic handle's visual representation would reveal the true state of the simulation and how to disentangle the objects, but as this visual representation is generally less prominent and meaningful than the visualization of the grasped object itself, this remains a frustrating challenge to users.

Addressing this problem is complex. One technique is to stop the bubble from moving during collision, even if the haptic handle is outside of the bubble. The nature of the collision-detection computation actually results in oscillation between states of collision and non-collision. This requires a rule to de-

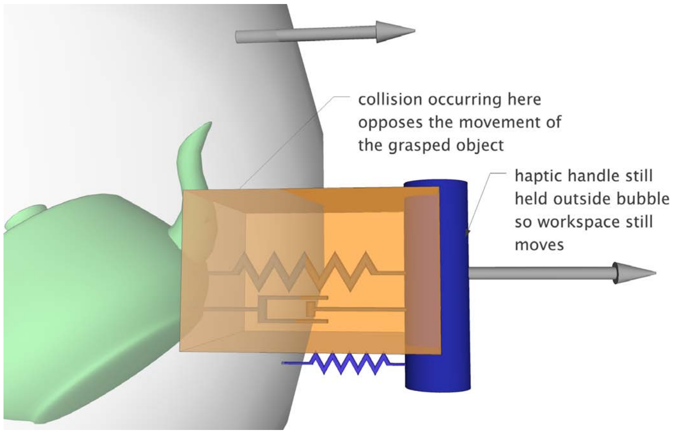

FIGURE 4. **COLLIDING OBJECTS WHILE MOVING BUBBLE**

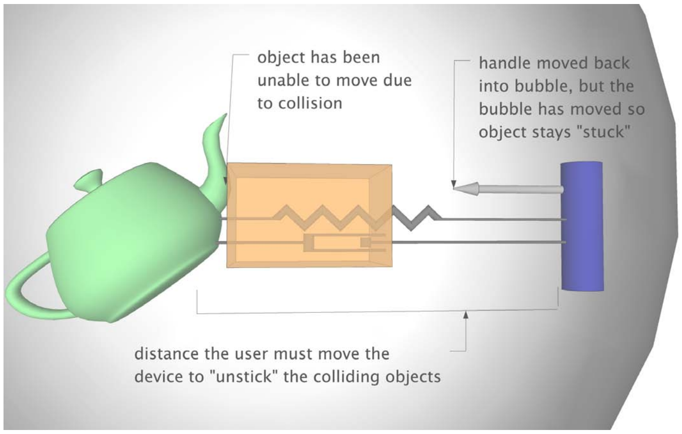

FIGURE 5. **HANDLE RETURNS WITHIN BUBBLE**

termine when to stop bubble movement without being prone to oscillation. The audio system implemented in SPARTA determines new collision by comparing the current collision count to a short-term maximum collision count, which can usually avoid the cycle problem and produce the collision sound only when expected. Such an approach is worthwhile, but not fully complete as the bubble also represents the region of the device with the highest fidelity feedback so keeping the handle within it has merit on its own. Stopping the bubble can be applied in combination with other techniques to improve this situation.

Another approach is based on how the user tends to apply the bubble technique in context. A user learns that pushing harder against the elastic force of the bubble results in faster movement of the workspace. Once this realization is made, a user tends to alternate between working entirely within the bubble to assemble parts and pushing hard against the perimeter of the bubble to access the full workspace. The high elastic forces produced in these coarse-grained movements by the bubble alone tends to saturate the capabilities of the device, inhibiting the user's ability to recognize and respond to collision, as discussed above. However, if the control law relating distance outside the bubble and the bubble's velocity is not monotonically-increasing, pushing hard against the bubble force would not result in optimum bubble velocity. Earlier work in the bubble technique proposes a cubic, monotonic relationship between distance outside the bubble and rate. A quadratic, monotonic relationship has also been implemented but it produces the same user behavior. A rate control law that reduces the workspace rate after reaching a peak is proposed as an alternative.

In the previous work as well as the current proposal, the bubble rate and elastic force are along the same direction as the vector from the center of the bubble to the device. Thus, the device position, elastic force, and bubble rate will be discussed as scalar distances, forces, and rates along this vector. As previously formulated [6], R is the radius of the bubble, and D is the distance between the center of the bubble and the device. For clarity, the equations from previous work will be reformulated by denoting the distance of the device outside of the bubble as

$$x = D - R \tag{1}$$

The elastic force rendered to the device upon leaving the bubble is thus as follows, where k is a constant stiffness:

$$F = -k \cdot x \tag{2}$$

The bubble rate as originally proposed in [6] can be re-written as follows, with a constant coefficient K':

$$V = K \cdot F^3 = K' \cdot x^3 \tag{3}$$

An alternate rate function, combined with the original elastic force function, has been implemented and evaluated. This function is referred to as "peak ring" as a ring of peak velocity surrounds the bubble in a two-dimensional rendering. Let α specify the distance outside the bubble at which the peak rate v^* is achieved, as a factor of the bubble radius, and let $0 < \beta < 1$ specify the velocity when past the ring as a factor of v^*. As an initial approximation of a non-monotonic rate control, the following rate control law is proposed. Define a quadratic function of x with its global maximum of $v^* = f(\alpha R)$ as follows:

$$f(x) = -\frac{v^*}{\alpha^2}(x)(x - 2\alpha R) \tag{4}$$

The region described by the interval $x \in [0, 2\alpha]$ can be called the "peak zone." In the tested implementation, parameter values of

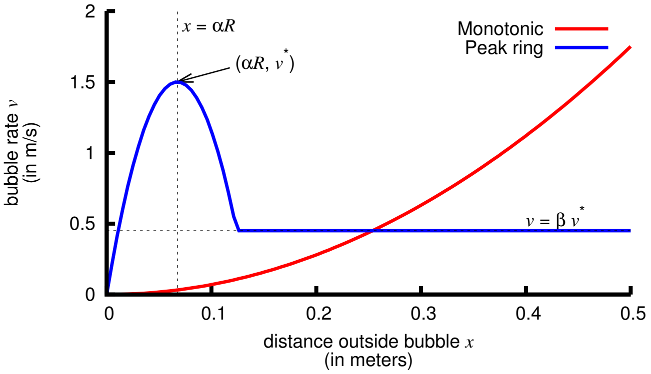

FIGURE 6. CONTROL LAWS AS INVESTIGATED

$\alpha = .15$ (in meters), $\beta = .3$, and $v^* = 1.5$ were chosen. The bubble rate for some distance outside of the bubble x is a piecewise function defined as

$$V = \begin{cases} f(x) & \text{where } x < \alpha R \text{ or } x > \alpha R \text{ and } f(x) > \beta v^* \\ \beta v^* & \text{otherwise} \end{cases} \tag{5}$$

Figure 6 shows a monotonic quadratic control law compared against this "peak ring" with parameters set as above. The specific values are not as relevant as the overall trends. By producing the highest rate of bubble motion at a single peak just outside of the position-control region of the bubble, and quickly tapering off to a constant rate beyond this peak, a user's most efficient coarse motions will be when the bubble renders a relatively small elastic force. It reduces the tendency to push hard against the bubble, since pushing harder than the elastic force at this peak,

$$f^* = f(\alpha R) \tag{6}$$

will result in decreased bubble rate. Whereas the original bubble technique produces workspace movement in response to pushing out of the bubble, this modified control law can be described as producing movement in response to touching the inside of the bubble.

This contributes to resolving the issues with coupled-object manipulation in two ways. Since the most efficient movement occurs with a small elastic force from the bubble, the device is less likely to be saturating its force-rendering ability with just the bubble force alone. If the manipulated object collides with another object, the collision effects transmitted through the virtual coupler will be more clearly felt with a lower "background level" of force from the bubble. Secondly, as this peak rate is located physically near the pure position-control area of the workspace, a user's action to move a grasped object away from a collision will result in the device leaving the rate-control zone in a short distance and short time. As implemented, this "peak ring" bubble rate function anecdotally improved the perception of collision forces during bubble movement, often resulting in the user ceasing moving the bubble once collision started. While this sample control law does not have C^1 continuity, it demonstrates the principle of finite peak velocity for the bubble technique in coupled-object manipulation. A more sophisticated function could be devised that blends smoothly from the peak zone to a nonzero horizontal asymptote, while providing a fundamentally equivalent effect on the interaction. When combined with stopping bubble movement during collision, this technique holds promise of improved user interaction with coupled object manipulation when using the bubble technique.

CONCLUSIONS AND FUTURE WORK

Haptic interaction devices provide valuable cues in virtual reality simulations, but their physical workspace is often limited by the mechanics required to render stiff, realistic forces. One particularly promising way of extending the workspace of haptic devices is to implement a hybrid position-rate control rather than purely position-control. The bubble technique has been primarily examined in touching and exploration tasks. Investigation into extending the haptic workspace during coupled-object manipulation, such as in virtual assembly tasks, has identified distinctions from the experiences noted in earlier work on the bubble technique. Furthermore, coupled-object manipulation leads to complications in the experience of using the bubble technique. The lack of distinction between bubble and collision forces, and the fact that bubble movement may proceed even during collision, can result in an uncomfortable perceived stickiness between the colliding objects. A promising approach for addressing these issues is a non-monotonic rate control for the bubble. A user can be encouraged to not push hard against the bubble force by locating a peak bubble velocity a short distance outside of the position-only area of the bubble, rather than having the velocity continually increase with increased distance from the bubble. A rudimentary implementation of such a "peak ring" control has been devised by combining quadratic and constant functions.

Based on this work, a number of empirical user studies are planned. The effect of the different visualization modes for the bubble during virtual assembly tasks will be formally evaluated. Empirical measurements of the peak ring bubble rate function will be performed to evaluate how well it achieves the goals of reducing object stickiness and improving collision force display during bubble movement.

An additional technique for distinguishing bubble and collision forces is to render an augmented "bump" effect above and beyond the physically-modeled forces upon the start of collision. The nature of penalty-based physics, where an object in collision is modeled as cycling in and out of collision rapidly, requires a careful detection of the start of a high-level collision event. As an augmented bump would also feed back in to the overall simulated system by affecting the user's hand position during subsequent time-steps, there is less margin for error in determining the start of collision. Implementing and evaluating this force augmentation is planned.

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