Interacting With Grasped Objects in Expanded Haptic Workspaces Using the Bubble Technique

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Haptic force-feedback can provide useful cues to users of virtual environments. Body-based haptic devices are portable but the more commonly used ground-based devices have workspaces that are limited by their physical grounding to a single base position and their operation as purely position-control devices. The “bubble technique” has recently been presented as one method of expanding a 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 the end effector moves outside this volume, an elastic restoring force is rendered, and a rate is applied that moves the virtual accessible workspace. Publications have described the use of the bubble technique for point-based touching tasks. However, when this technique is applied to simulations where the user is grasping virtual objects with part-to-part collision detection, unforeseen interaction problems surface. Methods of addressing these challenges are introduced, along with discussion of their implementation and an informal investigation. [DOI: 10.1115/1.4031826]

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 indicating the interaction between grasped objects and the environment [1,2]. However, the limited physical workspace of ground-based haptic devices reduces the utility of these devices in large virtual environments. The bubble technique has been presented as one method of allowing a user to interact within a large virtual environment using a grounded haptic device with a smaller workspace. This technique holds great promise for expanding the potential of haptic interaction in virtual environments. This paper proposes improvements to the bubble technique to support force-feedback for users when they are manipulating grasped objects in large virtual environments. A discussion of current methods to increase the haptic workspace is followed by specific evaluation and algorithmic development of improvements to the bubble technique.

Increasing the Haptic Workspace for Ground-Based Devices

Ground-based haptic force-feedback devices result in a limited workspace. Some devices, such as the SPIDAR, are specifically designed for large workspaces without modification [3]. Other techniques involve physical modifications to the haptic device, which allow the device to travel within the virtual environment [4–10]. The focus of this paper is on increasing the haptic workspace of a fixed-base haptic device, such as the Haption Virtuose™ 6D35-45 in a CAVE with displays on two walls plus the floor as shown in Fig. 1. 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 that an entire virtual volume is reachable [11]. Scaling increases the reachable workspace and eases coarse manipulation, but makes fine manipulation more difficult.

Pioneered by Dominjon et al. [12,13], 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. The bubble is...
centered in the device’s physical workspace and sized to encompass the specific haptic device’s working volume. Movement of the haptic end effector outside of the bubble applies a velocity to the workspace, effectively moving the workspace to another position within the virtual scene. The user feels a slight elastic restoring force as he/she pulls the bubble to the new location. Once the bubble reaches its new location, the user freely operates the haptic device in that area of the virtual scene, feeling appropriate forces. For a device like the Haption Virtuose™ 6D35-45 that has a relatively large working volume, the bubble technique provides users with the ability to feel forces from interactions in areas of the virtual scene, which are beyond the device’s physical working volume. For smaller desktop-size devices like the Sensable Phantom Omni®, which has a limited working volume, this technique provides a valuable method to increase the overall haptic working volume, provided frequent movement outside the bubble is acceptable. The original research [12,13] discussed a number of variations on the original bubble technique. These include the presence or absence of a visual indication of the workspace, such as the wire-frame sphere shown in Fig. 2, the implementation of a small scaling factor to control the quality of fine manipulation incrementally, and the potential of moving the camera (the user’s viewpoint) with the bubble, effectively permitting navigation based on haptic interaction with the environment. Another related hybrid position-rate control technique, which is designed for a two-dimensional, nonhaptic input device, is RubberEdge [14].

In Dominjon et al. [13], the bubble technique is described and studied in the context of a point-touching application, without grasped objects or object-to-object interaction. The implementation as found in the VirtuoseAPI allows application of the bubble technique to both point-touching and grasped object simulations. However, we have found that the use of the bubble technique with grasped object manipulation presents interaction challenges. This paper outlines those challenges and describes proposed solutions.

Interaction Device Design and Bubble Restoring Forces

Zhai and Milgram [15,16] enumerated a few dimensions of the design space for input devices, of which transfer function, typically ranging from position to rate controlled, and controller resistance (isotonic through isometric) are most applicable to the current discussion. Isotonic devices allow muscle contraction and movement with low resistance: essentially the default mode of haptic devices as well as desktop computer mice. Isometric resistance refers to contraction with high resistance and little or no movement, e.g., Spaceball/SpaceMouse™-type devices or pointing sticks found on laptop computer keyboards. The range between these two extremes, in which the sensor provides some stiffness, includes elastic resistance (varying with displacement), viscous resistance (varying with velocity), and inertial resistance (varying with acceleration). Zhai and Milgram studied the performance of various devices in a two-dimensional design space. As the examples of desktop mice and laptop pointing sticks might suggest, isotonic resistance devices performed best for actions where position control was critical and isometric resistance devices performed best where rate or velocity control was most critical. Their data analyses showed a clear interaction of these two dimensions. Applying the bubble technique effectively turns a haptic device (typically an isotonic-position control device) into a device with both position and rate control transfer functions. It follows, then, that when rate control is active, the user would be well-served to feel isometric device resistance, which can be simulated by the force output capabilities of the haptic device. In the bubble technique, when the user moves the haptic end effector outside of the bubble, an elastic restoring force transforms the haptic device from an isotonic to an isometric device. This serves as an important purpose in not only signaling to users an exit from the bubble, but also pulling the user back out of rate control into position control. Though later discussion will reveal problems related to the inclusion of an elastic restoring force, it serves as an important function in the overall bubble technique and its removal is not a practical option.

Investigation of Interaction Challenges

Three interaction challenges were observed when applying the bubble technique in a virtual assembly application. Two challenges involved the experience of object–object collision while outside of the bubble. The elastic restoring forces of the bubble and the forces due to the manipulation of objects cannot be distinguished. This can confuse the user when object collisions occur when the end effector is outside of the bubble. In addition, the movement of the bubble when objects are colliding can result in a perceived “stickiness” when attempting to separate colliding objects. Finally, the visualization of the reachable workspace as a spherical volume or bubble can distract from the other visual feedback provided by the simulation.

Implementation Platform

The present work was implemented in SPARTA, the Scriptable Platform for Research and Teaching in Assembly [17]. This application, the successor to SHARP [18], provides a virtual reality environment where arbitrary CAD models can be loaded and manipulated using physically based modeling and haptic force feedback. It builds on the VR JUGGLER open-source virtual reality software framework to support a wide variety of hardware and software platforms [19]. Model loading, triangulated data structures, and graphics rendering are provided by the OpenSceneGraph library working in concert with VR JUGGLER. The VR JuggLua framework, which extends VR JUGGLER with Lua scripting capabilities [20], maintains the visual and audio feedback and provides rapid prototyping of immersive interaction in the simulation. SPARTA itself uses configuration scripts written in Lua code to load models, connect and configure devices, and launch the simulation. A run-time Lua console allows interactive reconfiguration of the simulation.

Collision detection and physically based modeling are based on the Voxmap PointShell™ (VPS) software developed by McNeely et al. [21,22] 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

Fig. 2 Wire-frame workspace display in virtual assembly application SPARTA
the scene-graph to be voxelized at run-time without a separate preprocessing step.

The implementation of interaction devices in SPARTA is modular [23] and polymorphic, with wand, glove, and haptic devices all presenting a generic device interface that hides the details of individual device types from the simulation. SPARTA also provides for objects that behave as virtual “filter” devices, modifying input and output rather than corresponding directly to physical hardware. Instead, while these filter objects present a device interface for use in the simulation, they also take a generic device object as input. The base class for such virtual filter devices provides method implementations that directly forward calls to the contained device, providing pass-through behavior by default. Derived implementations then selectively over-ride these default methods to produce specific effects as desired. For instance, SPARTA includes one such virtual filter device type that scales up position and velocity reports by a user-supplied coefficient and scales down forces correspondingly. These filter devices are akin to transformation 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 virtual filter device that takes as input an existing device object, the radius and center of the desired bubble with respect to the device’s workspace, the elastic stiffness for the bubble’s restoring force, 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 when working with desktop devices, such as the Phantom Omni in this research. Figure 2 is a screenshot of the SPARTA environment showing three geometry models, the bubble represented as a wireframe sphere and the location of the haptic end effector as indicated by the virtual cone object.

### Distinguishing Bubble Force From Collision-Related Force

Understanding the various forces that are calculated as a result of manipulation and/or collision is important in understanding issues that occur when using the bubble technique. When haptically manipulating grasped objects in a virtual environment, the primary source of forces rendered to the haptic device is the spring–damper system of the “virtual coupler.” Initially proposed by Colgate et al. [24] and further investigated by Adams and Hanford [25], the virtual coupler connects the virtual representation of the haptic end effector’s position (also known as the haptic handle) to the grasped virtual object by a critically damped spring–damper system 3. The model of the virtual coupler contains both linear and torsional components. Stiffness values are assigned to the linear and torsional springs of the virtual coupler. The stiffness constants are determined empirically and related to the haptic device’s capabilities and time step. When using the haptic device to perform free movement of objects in the virtual scene, displacement of the haptic handle results in the calculation of a reaction force based on 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. Because the system is critically damped, the new computed location of the grasped object tends to achieve the position and orientation of the haptic handle as rapidly as permitted by the specified stiffness, without oscillations and other instabilities. This presents to the user as if he/she was grasping the object with the haptic end effector and moving it in virtual space. Use of the virtual coupler helps ensure overall system passivity. The virtual coupler is conceptually illustrated in Fig. 3, with conventions that will be used throughout this work: a cylinder as the haptic handle, linked by a spring–damper system to a teapot as the grasped object. The distance between the haptic handle and grasped object is exaggerated for clarity in this figure.

![Fig. 3 Conceptual view of the virtual coupler](http://computingengineering.asmedigitalcollection.asme.org/)

The result of using the virtual coupler is that forces of collision are not directly transmitted to the haptic device, but are felt because of an increase in the virtual coupler spring displacement. Due to the high update rate, the virtual coupler can convey fairly detailed information about the shapes of colliding objects, such as initial contact and ridges.

In the bubble technique, when the end effector moves outside of the bubble, the haptic workspace moves in the direction of the end effector motion and an elastic restoring force is rendered to the haptic device as the device pulls the haptic handle back in the direction of the bubble. Recall that this restoring elastic force is desirable as Zhai and Milgram found that rate control using an isotonic (non-elastic) device resulted in poor performance [15]. When holding an object and moving outside of the bubble, as illustrated in Fig. 4, the grasped object moves in the same direction that the bubble moves. When the grasped object collides with another object, collision forces due to object-to-object interactions will be generated on the haptic handle. These collision forces will be in the same direction as the restoring elastic force. Since net forces are the summation of all forces acting on a body, forces due to collision and forces due to the bubble technique cannot be distinguished. This weakens the haptic cues provided by collision during assembly. When the haptic handle is already experiencing a force, the addition of a collision force appears incremental. Furthermore, current haptic devices do not have the ability to produce large reaction forces, so a collision may go entirely unnoticed by the user if the elastic restoring force saturates the device’s capabilities for force output. When the workspace velocity is proportional to the distance outside the bubble, users tended to seek high velocities by “pushing through” the bubble. This situation results in high velocities of movement and high elastic restoring forces which are likely to saturate the device’s output.

A combination of techniques can be used to convey to the user when a collision has occurred. One approach to distinguishing these two sources of forces is to decrease the elastic stiffness of the bubble itself by setting a low stiffness constant. By decreasing the intensity of the bubble forces, the user’s ability to move fast enough to saturate the force-rendering capabilities of the device during bubble movement will decrease, leaving capacity for rendering increased forces upon collision. However, this presents a tradeoff between available force capacity for collision and clarity of the elastic recentering cues during rate control. The use of additional sensory cues, both visual and audio, is a promising solution. Even a simple sound 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, yet it does not physically change the feel of the collision. The metallic clang sound effect used in SPARTA clearly indicates a change in the virtual environment, despite potentially unchanged or minimally changed force output. Similar visual...
changes, such as color or transparency, are effective cues that a collision has occurred.

**Bubble Movement During Collision**

There is another issue that occurs when the grasped object collides with another object in the virtual environment. In a pure 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, so the spring displacement (due to the virtual coupler) between the object and handle can quickly approach zero. However, when using the bubble technique to move the workspace, a stickiness occurs during object-to-object collisions when the end effector is outside of the bubble.

As the bubble and the grasped object move, the object may collide with other objects in the scene. Collision forces on the object prevent it from moving through the obstruction, normally generating a haptic cue by rendering increased forces through the haptic device. However, as discussed earlier, sustained, swift movement of the bubble may actively produce large bubble restoring forces that mask the forces related to the collision. When users fail to feel the collision of objects, they 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 continuing to move the effective position of the haptic handle in the virtual environment, as illustrated in Fig. 5.

Moving the end effector back within the bubble is expected to produce a decrease in forces felt due to the elimination of bubble restoration forces. The user also expects that the grasped object will move away from the colliding object. In fact, neither takes
place. While bubble restoring forces are eliminated, the large
displacement between the handle and the grasped object, resulting
from bubble movement, continues to provide collision forces. Fur-
thermore, since the virtual location of the workspace has moved,
the user now must move the end effector in the opposite direction
(and of equal magnitude of the bubble’s movement during collis-
ion) before the colliding objects are pulled apart. These two con-
ected phenomena are illustrated in Fig. 6. The subjective
experience of this situation is of a stickiness that prevents a user
from being able to easily separate objects once they have collided.
Attending to the displayed location of the haptic handle and its
changed relationship with respect to the grasped object would
reveal the true state of the simulation and how to disentangle the
objects. However, since the handle’s visual representation is gen-
erally less prominent and less subjectively meaningful than the
visualization of the grasped object itself during manipulation, 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. This is not a very viable option. The
nature of the collision-detection computation actually results in
oscillation between states of collision and noncollision. This
requires developing a state rule to determine when to stop bubble
movement yet avoid oscillation. One solution would be to deter-
mine a new collision by comparing the current collision count to a
short-term maximum collision count. Usually, this will avoid the
cycle problem. However, stopping the bubble during collision
poses new problems (when and how should it be restarted?) and
reduces a worthwhile aspect of the bubble’s effect: 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.

Another approach is to change the rate control law governing
the bubble displacement such that large movements outside the
bubble are discouraged, and therefore, force saturation is less
likely to occur. The bubble rate and elastic force are along the
same direction as the vector from the center of the bubble to the
distance that the user must move the
effective handle “back” (toward the object) to
“unstick” it from the collision

The restoring force, \( F \), is modeled as a linear spring force as given
in Eq. (2), where \( k \) is a constant

\[
F = -k \cdot x
\]  

(2)

Dominjon et al. proposed a cubic, monotonic relationship between
distance outside the bubble and rate of bubble movement as illus-
trated in Eq. (3), where \( V \) is the bubble velocity and \( K' \) is a
constant

\[
V = K' \cdot x^3
\]  

(3)

A quadratic, monotonic relationship has also been implemented
which produced similar results as the cubic relationship of Eq. (3).

An alternate rate control law that reduces the workspace rate
after reaching a peak has been implemented and evaluated. This
control law is referred to as a “peak ring” function. In essence,
the function allows increasing velocity beyond the surface of the
bubble until a predefined distance is achieved. At this “peak” dis-
tance, the peak velocity of the bubble is achieved. When a user
pushes the end effector beyond this peak distance, the velocity of
the bubble is reduced so that no additional advantage is gained by the user by moving farther away from the bubble. 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, the greatest bubble movement that a user will encounter will be confined to the area where the bubble renders a relatively small elastic force. This method reduces the user’s tendency to continue to push harder against the bubble.

Choose $x^+$ as the distance outside the bubble at which the peak rate, $v^+$, is achieved. This distance can be a function of the bubble radius, $R$. Let $0 < \beta < 1$ specify the percent of the total peak velocity that is achievable at all distances farthest away from the bubble surface. Define a quadratic function of $x$ with its global maximum of $v^+ = f(R \cdot x^+)$ as follows:

$$ f(x) = -\frac{v^+}{x^+} (x - 2R \cdot x^+) $$

In the interval $x \in [0, 2x^+]$, $f(x)$ is positive. The velocity is determined by $f(x)$ in what can be called the “peak zone,” a subset of $x \in [0, 2x^+]$ defined by the predicate

$$ P(x) = (x < R \cdot x^+) \vee ((x > R \cdot x^+) \wedge (f(x) > \beta \cdot v^+)) $$

In the tested implementation, parameter values of $R = 0.45$ (in meters), $x^+ = 0.15$, $\beta = 0.3$, and $v^+ = 1.5$ were chosen. The bubble rate for some distance outside of the bubble $x$ is a piecewise function defined as

$$ V = \begin{cases} f(x) & \text{if } P(x) \text{ is true} \\ \beta \cdot v^+ & \text{otherwise} \end{cases} $$

Figure 7 shows a monotonic quadratic control law ($V = K' \cdot x^2$ with $K' = 7$) and this peak ring with parameters set as above. The specific values are not as relevant as the overall trends. 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 by touching just outside the bubble.

This contributes to resolving the issues with grasped object manipulation in two ways. Since the most efficient movement occurs at a slight distance outside the bubble, the elastic restoring force is relatively small. 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. Second, 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 stopping the movement of the bubble once collision occurred. This simple sample control law demonstrates the principle of finite peak velocity for the bubble technique in grasped object manipulation.

**Bubble Visualization**

The sphere-shaped volume of the workspace providing direct position control has previously been visualized as a semitransparent sphere [12,13]. Dominjon et al. asserted that dual-display of the spherical bounding volume (haptic and visual) is important and supports association of the physical and displayed workspace. SPARTA’s bubble technique module includes three visualization modes: a semitransparent sphere, a wire-frame sphere, and a no-visualization option. An 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 how the bubble technique works. However, assembly of complex CAD geometry appeared to be impeded by display of the bubble. The semitransparent sphere obscures the geometry when opaque enough to clearly visualize the workspace volume. The wire-frame sphere does not occlude the geometry, but it appeared visually distracting and cluttered. In contrast, when display of the bubble was disabled, use of the haptic device to perform virtual assembly was natural with little conscious attention paid to the detail of the hybrid control.

Dominjon et al. [13] concluded that visual display of the sphere aided users in interacting in the virtual environment. Two hypotheses may explain the seeming contradiction with the assertion of the sphere display’s importance. A virtual assembly application may present a higher task load than point-touching applications such as the one studied in Ref. [13]. Visualization of the workspace may impose a continued cognitive 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, which 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 bubble technique with the workspace clearly visualized and subsequently allows actual use of the environment and completion of assembly tasks to proceed unobstructed with the bubble display disabled.

**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 ground-based haptic devices is to implement a hybrid position-rate control scheme rather than purely position control. Investigation into extending the haptic workspace during grasped object manipulation, as needed for virtual assembly tasks, has identified several additional challenges. The lack of distinction between bubble and collision forces, and the fact that bubble movement may proceed even during collision, can result in inaccurate perceptions of force and an uncomfortable perceived stickiness between the colliding objects. A promising approach for addressing these issues is to use a nonmonotonic rate control scheme for the bubble movement. A user can be discouraged from pushing too hard/fast against the bubble force by creating 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 implementation of such a peak ring

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**Fig. 7 Control laws as investigated**

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control has been devised which combines quadratic and constant functions. Initial investigation of this method shows promise.

In the future, other methods of improving the bubble technique will be explored. An additional technique for distinguishing bubble and collision forces is to render an augmented “bump” effect 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. Implementing an augmented bump would affect the user’s hand position during subsequent time-steps, leaving less margin for error in determining the start of collision. Implementing and evaluating this force augmentation are planned.

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