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A Conceptual Framework to Support Natural Interaction for Virtual Assembly Tasks

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Abstract
Over the years, various approaches have been investigated to support natural human interaction with CAD models in an immersive virtual environment. The motivation for this avenue of research stems from the desire to provide a method where users can manipulate and assemble digital product models as if they were manipulating actual models. The ultimate goal is to produce an immersive environment where design and manufacturing decisions which involve human interaction can be made using only digital CAD models, thus avoiding the need to create costly preproduction physical prototypes. This paper presents a framework to approach the development of virtual assembly applications. The framework is based on a Two Phase model where the assembly task is divided into a free movement phase and a fine positioning phase. Each phase can be implemented using independent techniques; however, the algorithms needed to interface between the two techniques are critical to the success of the method. The paper presents a summary of three virtual assembly techniques and places them within the framework of the Two Phase model. Finally, the conclusions call for the continued development of a testbed to compare virtual assembly methods.

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A CONCEPTUAL FRAMEWORK TO SUPPORT NATURAL INTERACTION FOR VIRTUAL ASSEMBLY TASKS

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ABSTRACT

Over the years, various approaches have been investigated to support natural human interaction with CAD models in an immersive virtual environment. The motivation for this avenue of research stems from the desire to provide a method where users can manipulate and assemble digital product models as if they were manipulating actual models. The ultimate goal is to produce an immersive environment where design and manufacturing decisions which involve human interaction can be made using only digital CAD models, thus avoiding the need to create costly preproduction physical prototypes. This paper presents a framework to approach the development of virtual assembly applications. The framework is based on a Two Phase model where the assembly task is divided into a free movement phase and a fine positioning phase. Each phase can be implemented using independent techniques; however, the algorithms needed to interface between the two techniques are critical to the success of the method. The paper presents a summary of three virtual assembly techniques and places them within the framework of the Two Phase model. Finally, the conclusions call for the continued development of a testbed to compare virtual assembly methods.

Keywords: virtual reality, virtual assembly, human computer interaction, assembly methods prototyping

INTRODUCTION

Virtual reality technology provides support for humans to interact with digital objects using natural human motions. Three-dimensional trackers and interaction devices are used to track human motion, stereo display devices render the virtual world as a three-dimensional spatial environment, and haptic devices provide force feedback to the user.

As applied to engineering tasks, the ability to reach out and touch or grab objects in the virtual world presents engineers with a novel interface for manipulating CAD models [1,2]. Instead of using the 2-D mouse to manipulate objects which are confined and displayed on a traditional 2-D monitor, virtual reality technology supports users who inhabit the digitally rendered 3-D scene and can select and manipulate objects using natural human motions of reaching and grasping. This ability has the potential to drastically change the product design process by supporting product evaluations within virtual environments prior to physical prototype builds. The result is that many more options can be explored and evaluated with the “human-in-the-loop” earlier in the design process, allowing for significant design changes to happen at less cost.

Physical prototypes are models created to represent design concepts. Prototypes are often built to varying levels of detail depending on the evaluation desired. Aesthetic prototypes will have detailed appearance but minimal functionality. Other prototypes are built to evaluate proof-of-concept or product functionality. Vandevelde [3] found that the use of physical prototypes supports the development of efficient product development process plans; provides designers with additional insights into their products; improves communication between design, manufacturing, engineering and customers; and results in superior product quality. He notes that iterative approaches to innovation rely on the need for quick, cheap and easy prototyping methods.

Concurrent engineering principles adopted by a wide variety of industries result in parallel consideration of product design and product manufacturing [4]. Here again, physical prototypes are used to evaluate assembly methods for assemble-ability, tooling, workstation layout and operator ergonomics (Fig. 1). Reduced scale prototypes are useful for evaluating entire facility layouts.

Since most product design is based on the use of 3-D CAD models, virtual reality techniques which support natural human interaction with CAD models has the potential for providing easy to create product prototypes for evaluation (Fig. 2). The key to realizing this vision is providing methods to facilitate natural interaction with CAD models in the virtual environment.

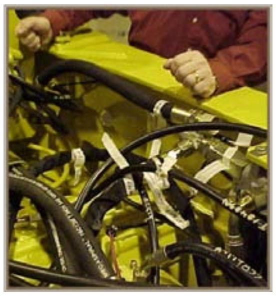

Figure 1: Physical prototype

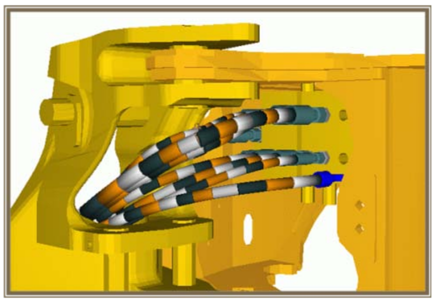

Figure 2: Virtual prototype

BACKGROUND

The goal of research in virtual assembly is to explore in the use of a 3-D immersive virtual environment to support user evaluation of virtual prototypes. There are several challenges to achieving this goal.

First of all, in order to obtain reliable prototype evaluations in the virtual environment, high fidelity interaction is essential. Intuitively, it would seem that moving from the 2D interface of the mouse to the 3D interface of position tracked human movement and haptic devices would support easier interaction with 3D CAD models. This is actually not the case. While the immersive environment does support a very intuitive understanding and natural investigation of the shape of 3D models, manipulating those models is challenging in an immersive environment. Tracker inaccuracies and drift combined with visual inconsistencies related to accommodation and occlusion present challenges to users of immersive environments. One further factor reducing the effectiveness of our ability to interact within 3D environments is the absence of physical affordances that restrict or contain movement between two objects [5]. The absence of these physical interactions not only makes it difficult to assemble parts, Mine et al. [5] also found that it results in increased fatigue.

Several existing immersive virtual assembly applications have been developed to overcome these challenges. One approach is to simulate the technique of 2D CAD "snapping to final position" when parts are in close proximity to each other [6-10]. Some applications enforce pre-defined geometric constraints that bring parts together and restrict full manipulation [11-13]. A full discussion of various approaches can be found in Seth et al. [14]. While these approaches can be used to validate facilities and operator workstation layout, they remove the human-in-the-loop from the final assembly step.

Research by Bowman et al. [15] suggests that reducing the number of degrees-of-freedom controlled by the user will support highly accurate manipulation of objects in an immersive virtual environment. This supports the observation that in the real world, physical affordances act to reduce the number of degrees-of-freedom that users feel when assembling parts [16].

Multimodal rendering is also important to support user perception, especially during object manipulation [17]. Humans perceive their environment through their physical senses of sight, touch, hearing, smelling and tasting. Over the years, the field of virtual reality has concentrated on stimulating the senses of sight, touch, and hearing with little work being performed in the area of smelling and tasting. Stereo viewing, either through head mounted displays or projection surfaces, is a common interface for viewing CAD models. Sreng et al. [18] presented research which superimposed rendering techniques for improving perception of collision and sliding during virtual assembly. Visual cues as well as spatial audio and haptics were combined to provide multimodal feedback about collisions in the virtual environment.

Six degree-of-freedom (6-DOF) haptic devices provide force and torque feedback to the user as objects are manipulated. Full 6-DOF forces and torques provide the most realistic feedback for virtual assembly. However, there are significant challenges with implementing haptics for virtual prototyping. Interaction between 3-D objects consists of contact and reaction forces. The reaction of objects to forces and torques is governed by differential equations of motion that are classically derived from Newton's laws of motion or in the form issued of the Lagrange method as proposed in (Eq.1).

$$M(q)\ddot{q} = Q(q,\dot{q},t) \qquad (1)$$

Where $M(q)$ is the matrix that represents the inertia properties of the set of objects, t is the time, q is a vector of the generalized coordinates (representing the position), $\dot{q}$ is a velocity vector (first time derivative of the q vector), and $\ddot{q}$ is the acceleration vector. Q is the external force acting on the set of objects (gravity, haptic control…). In case of contact or impact, the constraints resulting from the interaction induces a reaction force R that act as an additional force (Eq.2)

$$M(q)\ddot{q} = Q(q,\dot{q},t) + R \qquad (2)$$

The challenge lies in solving equation (2) for complex CAD models in virtual environments that potentially could consist of a collection of many CAD models. Equation 2 implies the use of complex computational methods to arrive at a solution [19]. The update rate of the simulation has a great influence on the force feedback perception. The commonly accepted rate for a good perception of stiff contact between solids considered as rigid bodies is 1000 Hz [20].

Embedded in these equations is the need to model the contact of objects. When CAD models are tessellated for display, an approximate geometry replaces the exact geometry. The tessellation results in polygonal approximation of smooth curves. This limits the number of DOF that are possible between the contacting parts. The example in Figure 3 demonstrates an idealized insertion that allows both rotation and translation, and a tessellated insertion that results in only free translation.

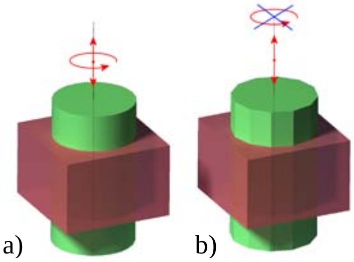

Figure 3: a) Idealized insertion, b) Tessellated insertion [21]

A considerable amount of research has been performed in the area of collision detection and force rendering. An excellent overview can be found in Lin and Otaduy [22].

In 1997, Bowman and Hodges [23] described the object manipulation task as having two phases: grabbing or selection, and manipulation. Over a century ago Woodworth [24] presented the Two-Component Model which characterized goal directed aiming as a relationship between human speed and accuracy of performing an aiming task. We build upon this work to propose the following classification of the two phases of virtual object manipulation: free movement and fine positioning movement. This approach, the Two Phase Model, facilitates interaction with large, complex CAD environments, yet also supports 6-DOF contact and haptic rendering of precise part collision. One of the major challenges of this approach is the need to model the transition from one phase to the other phase as the user moves objects within the environment.

The next section will describe three methods, based on the Two Phase Model, that have been developed to support 6-DOF haptic assembly: Automatic geometric constraints, virtual constraint guidance and dynamic decomposition of degrees of freedom.

METHODOLOGY

The Two Phase Model, as applied to virtual object manipulation, divides the assembly process into two stages. The free movement phase spans the interaction time from object selection until a collision is detected. The final insertion or fine positioning movement is phase two. Various algorithms have been developed to smoothly transition between phase one and phase two. The following sections describe three approaches to virtual assembly based on the Two Phase Model.

Automatic geometric constraints (AGC)

Seth et al. [25] initially investigated virtual assembly modeling based purely on physically-based modeling. The result was a software application called SHARP: System for Haptic Assembly and Realistic Prototyping. Their work used Voxmap Pointshell (VPS) collision and physics based modeling algorithms to calculate the physical interaction of parts as they were assembled. This work concluded that the use of an approximate geometry model was not sufficient to support the assembly of low clearance parts.

In 2010, Seth et al. [26, 27] approached the low clearance assembly problem by dividing the task into two phases: moving an object in free space and guiding the assembly of two objects. To overcome the limitations of assembling models represented by approximate geometry, they turned to B-rep based models to represent the geometry during the second phase of assembly. Therefore, two distinct geometry models were utilized in the method: tessellated models for visualization, and B-rep models for low clearance assembly.

The method relies on collision detection between B-rep surfaces during free movement of parts in the virtual environment. Contact between B-rep elements signals a switch to the second phase of the assembly simulation where geometric constraints are used to guide the assembly process. These geometric constraints are easy to define based on the B-rep geometry. For example, for the pin-in-a-hole insertion task, when the cylindrical surface of the pin and the cylindrical surface of the hole intersect, a logic sequence can identify a feasible constraint (axis alignment) between these two surfaces. These constraints can be identified automatically. Once a constraint has been identified, the two parts are aligned and the degrees of freedom allowed for the user motion are reduced to correspond to the allowable motion that results from the geometric constraint (Figure 4). When the parts are no longer in contact, the constraint is removed and the user is returned to operating within a phase one algorithm (free movement).

Figure 4: Assemble of a pin-in-a-hole using automatic geometric constraints [26]

Virtual constraint guidance (VCG)

Tching et al. [21,28] proposed to divide the human interaction during an assembly task in two parts: an exploration phase and an assembly phase. Within the exploration phase, non-smooth dynamics provides the underlying physics engine for computation of collisions and 6-DOF force rendering.

During the assembly phase, virtual constraint guidance (VCG) assists the user in precisely positioning the CAD model into the assembly. The VCG method relies on virtual fixtures to guide the moving object to a specific position. These virtual fixtures are created as 3D geometric entities before the assembly process takes place. No changes to the underlying CAD model geometry are required.

Once the exploration step is complete, the collision detection is disabled at the time and at the place where collisions between the moving object and the virtual fixtures occur. Disabling this collision detection during the insertion task facilitates overriding the limits of collision algorithms (time consumption and geometric approximations). During the assembly phase, an assembly task is modeled as motion between simple mechanical linkages (prismatic, ball, hinge joints, etc.). Figure 5 shows the virtual constraint guides (planes) associated with a peg-in-a-hole insertion task as well as the simple cylindrical joint which guides the insertion.

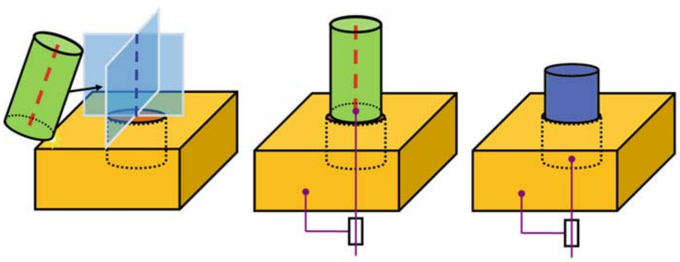

Figure 5: Peg-in-a-hole insertion task using VCG [28]

The transition between the exploration phase and the assembly phase is triggered by collision of the virtual constraint guides of the moving object with the virtual constraint guides of the fixed object. In the case of the insertion task, the axis of the pin collides with the intersection of the virtual constraint planes aligned with the hole. This "idealized" collision handling between "idealized" guides is much quicker than determining the collision between the 3D models. When the virtual guides collide, a haptic force is generated that guides the user to align and insert the pin in the hole.

Dynamic decomposition of degrees of freedom (DIOD)

While both Seth et al. and Tching et al. focused on enforcing geometric constraints as the transition between the free movement phase and the constrained movement phase, Veit et al. [16] chose a different approach based on detecting changes in velocity of the moving object.

The DIOD (Decomposition and Integration Of Degrees of Freedom) approach [16] builds upon the work of Frees and Kessler [29]. In that previous work, the authors evaluated a manipulation task where changes in the velocity of the moving object triggered the switch from free movement to fine positioning movement. In their research, when the velocity of movement was fast, the object moved at a 1:1 ratio of real (tracked) velocity to virtual object velocity. When the user's movement slowed, the ratio of real velocity to virtual velocity changed such that large movements in real space produced smaller movements in virtual space. The result is that during the second phase of interaction, the user's motion is scaled such that he/she can move farther (while moving slowly) and produce smaller virtual movements, thus facilitating precise positioning. The ratio of the real velocity to the virtual velocity is described as the *C:D* ratio (control: display).

Veit et al. [16] divide the assembly task into a ballistic phase and a control phase. In the ballistic phase users have the ability to freely move and manipulate an object in space at a 1:1 *C:D* ratio. During the fine positioning phase, instead of scaling the resultant velocity, the total velocity is decomposed along three orthogonal directions and the *C:D* scaling is applied only to the component of the velocity that is below a given threshold. If the velocity in the x-direction, for example, reaches the threshold level indicating a transition from free movement to fine positioning movement, then the *C:D* ratio is adjusted only for movement in the x-direction. A minimum threshold for any of the orthogonal velocity components is specified to stop movement if the velocity is very small. The effect of this single axis scaling is to mitigate small errors in position tracking and human movement in free space; therefore, supporting fine positioning.

RESULTS

Even though these three methods were developed based on the same philosophy, the methods show significant differences in what they desire to achieve. The AGC and the VCG methods are both designed to handle the challenges of CAD model manipulation. Both rely on collision detection as part of the scenario and both seek to minimize the amount of pre-processing of CAD models prior to import into the virtual scene. The DIOD method and AGC do not involve the use of a haptic interface; however, the VCG is designed to accommodate a 6 DOF haptic device.

An evaluation of the VCG method was performed by Tching et al. [21]. Using a 6 DOF haptic device, participants were asked to insert a peg into one of four holes in a grid. Each trial implemented the VCG in a slightly different manner. They were interested in determining 1) how the method compared to using no constraints (no haptics) and 2) whether visual display of the virtual constraint on the moving object or on the fixed object affected performance. They measured performance by recording task time for each insertion. Participants completed a post task survey, recording their impressions of the experience.

The results clearly showed that the VCG method reduced task time compared to performing the task without constraints. The best performance occurred when using the VCG method with visual display of virtual constraints on the moving object and on the fixed object.

Veit et al. [16] compared the DIOD method to the PRISM method proposed by Frees and Kessler [29]. They asked participants to position a sphere within a cubic volume, making sure none of the sphere extended beyond the bounds of the cube. Four trials presented the participants with an increasingly smaller sized cube. In this way, the task difficulty varied from easy to very hard in four discrete steps. The sphere size remained constant throughout the study. The performance metric was how many correct positionings can be accomplished in one minute. The results showed a significant difference, based on ANOVA, between performance in the Hard and Very Hard trials, with the DIOD method outperforming the PRISM method.

The results from these two studies indicate that using the Two Phase Model approach holds great promise for improving our ability to assembly CAD models. Both studies concluded that the use of one method for free motion and another method for fine positioning, with a plan for transitioning from one phase to the next, is an improvement over current methods of virtual object manipulation.

CONCLUSIONS

In conclusion, using the Two Phase Model as the conceptual framework upon which to explore solutions to the virtual object manipulation task provides the research community with a basis from which to explore multiple different implementations. Three different research groups, from three different countries, have published their work independently in separate conferences and journals. Presenting them as different implementations based on the same conceptual framework provides the research community with a unifying approach from which to move forward.

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