Six Degree-of-Freedom Haptic System
For Desktop Virtual Prototyping Applications

Elaine Chen
SensAble Technologies Inc.
215 First Street, Cambridge, MA 02142, USA.
tel : (617)621-0150
fax : (617)621-0135
e-mail : echen@sensable.com
http :://www.sensable.com

Contact in France:
Sim Team
11, Bd Brune, 75014 Paris, FRANCE
tél: +33.1.45.45.15.55
fax: +33.1.45.45.16.17
e-mail : simteam@simteam.com
http:://www.simteam.com

Abstract

The realism of virtual prototyping applications can be substantially improved by the inclusion of six degree-of-freedom force and torque feedback. This paper describes the design requirements for a haptic device for this application, presents a prototype 6DOF haptic feedback system developed within SensAble Technologies Inc., and discusses the benefits it provides within an example application involving maintenance analysis.

Résumé

Le réalisme des applications de prototypage virtuel peut être grandement amélioré par l'emploi d'un système à retour d'effort à six degrés de liberté. Ce papier expose les contraintes de conception d'un tel dispositif, décrit un prototype de produit à retour d'effort à six degrés de liberté développé par SensAble Technologies Inc., et présente les avantages de cette solution au travers d'une application d'analyse de maintenabilité.

1. Introduction

Desktop virtual prototyping refers to the process by which a new design can be evaluated on a computer without the need to create a physical prototype. The benefits are many and profound: reduced cycle time, reduced cost and increased flexibility facilitate a much more interactive, concurrent and efficient engineering process.

Desktop virtual prototyping spans a wide range of activities, from product visualization to fit analysis, dynamic simulation and maintenance analysis. Maintenance analysis is concerned with the investigation of whether or not a component can be inserted into and extracted from its target environment. This activity is particularly significant in aircraft engines and automobiles, where components must be accessible for speedy repair.

Doing this analysis in the real world is easy, because the operator can feel surface constraints and contact forces as he or she rotates and manipulates a part into place. Replicating the same task in an interactive virtual prototyping application is much more difficult. The software is required to perform collision detection and compute a response in a complicated environment, which is a very challenging problem to solve.

Assuming that the software issues can be addressed, the user is still limited by the human-computer interface. An ideal interface should provide an easy way to control the position and orientation of a virtual object in 3D space. It should also provide the user with useful object contact information. A traditional computer interface with a mouse as an input device falls far short of providing an intuitive 3D interface. First of all, the mouse is a two-dimensional input device while an object in free space has six degrees of freedom (x,y,z, roll, pitch,yaw). While there are some six degree-of-freedom (6DOF) input devices on the market, their ranges of motion are typically small and the user cannot map hand movements freely to object movement. Secondly, and more importantly, none of these devices provide a sense of touch. Trying to manipulate an object through a tortuous path in maintenance analysis using only visual feedback can be very difficult.

This sense of touch includes not only translational force feedback, but rotational or torque feedback. When two objects interact, 3DOF contact forces can occur anywhere on the objects. The distance between the center of gravity of each object and an outlying contact point constitutes a moment arm, resulting in a 3DOF reaction torque due to the contact force ($\vec{T} = \vec{r} \times \vec{F}$). This reaction torque combines with force and vision to help a user manipulate objects in the real world. The lack of this 6DOF force/torque feedback would make it difficult to control virtual objects in a simulation.

We believe that a useful device in a virtual maintenance analysis scenario must satisfy the following requirements: it must allow the user to move his or her hand freely in a reasonably unrestricted working volume in translation and in rotation on the desktop; it must provide a sense of touch; and it must do so in all six degrees of freedom.

In this paper, we will review the state of the art in virtual prototyping software and haptic feedback hardware. We will explore the design requirements for a force feedback device for maintenance analysis applications. We will then present a novel 6DOF prototype device based on the PHANTOM™ Premium 3.0 large workspace device, and describe its integration into an example application that includes a simulation of a maintenance analysis task, the Boeing VPS™ demonstration.

2. Prior art

Virtual prototyping is an active area of research with presence from both academic and commercial groups. We will provide a few illustrative examples of prior art in software and hardware, but this is by no means an exhaustive list.

On the software side, many academic and commercial groups concentrate on fundamental research on basic algorithms. The General Electric Corporate R&D web site [9] describes “Product Vision”, a software tool for off-line automatic path planning. It does not facilitate real time collision detection. An excellent survey of real-time collision detection algorithms can be found in [17]. Well-known examples include I-COLLIDE [7] and V-COLLIDE [13]. These algorithms typically do not cover collision response. Baraff [2] provides a good discussion on physically based simulations with collision response but does not address integration with haptics in an industrial scale virtual environment with arbitrary geometry. Gregory [10] presents H-COLLIDE, a fast point-polymesh haptic exploration module. Johnson [15] has published results on point exploration of a NURBS surface. Both deal with point exploration and do not address 6DOF haptic rendering issues. There is also much activity in applied virtual assembly research. Jayaram [14] describes an immersive virtual assembly environment for assembling solid model parts. Popescu [23] describes a system in which a haptic glove controls the hand of a virtual human agent, whose global motions are controlled by voice. Neither system presents realistic haptic cues for object contact in a complex virtual environment. There are a number of representative vendors on the commercial side, such as Engineering Automation Inc. (URL: www.eai.com) , Division (URL: www.division.com) and Mechanical Dynamics (URL: www.adams.com). Their products provide visualization, tolerance analysis, dynamics simulation and other functions but do not supply a sense of touch.

On the hardware side, illustrative examples of haptic devices include the Rutgers dextrous hand master [6], the Immersion Feelit Mouse [11], and the PHANTOM [18] [24]. Force feedback joysticks and steering wheels abound in the home PC market, such as the SideWinder Force Feedback Pro Joystick [20]. Specialized haptic devices have been built for the medical market, such as the AccuTouch Tactile Feedback Device for catheter insertion simulation [12]. These devices do not provide 6DOF force feedback. The devices that do provide 6DOF force feedback are not optimized for desktop use. The Argonne Arm [3], arguably the first haptic display to be developed, is a human scale robot arm. The “Salisbury/JPL Arm” [4] is another example. The SpacePen [8] has 20 cubic meters of viable workspace. These devices are not appropriate for desktop use. Agronin [1] describes a 6DOF joystick actuated by strings. Lawrence [16] has a device that can provide up to 6DOF force feedback. Berkelman [5] describes a floor mounted magnetic levitation haptic device with a small range of motion. Salcudean [22] describes a similar interface with an even smaller range of motion. The Freedom 6 [21] has low peak force and a small range of motion in two of the three rotational freedoms. While these devices can deliver excellent force feedback, they all suffer from workspace limitations, especially in rotation, which reduce their usability in a maintenance analysis environment.

3. Design requirements

As we mentioned earlier, there are three key requirements for a haptic device for maintenance analysis applications:

- Allowing the user to move his or her hand freely on the desktop
- Providing a sense of touch
- Possessing six active degrees of freedom

We consulted a number of potential customers in the aerospace and automotive industries to understand their needs in maintenance planning and analysis. We also did some qualitative human perception experiments and informal surveys and questionnaires in an effort to quantify some of the design parameters. Based on the input from our customers we have compiled a list of rough design requirements. These requirements are summarized in Table 1.

The translational ROM (range of motion) is based on informal discussions with maintenance engineers for jet engines. Since the parts and assemblies are large, a larger workspace would be more realistic. The rotational ROM is based on anecdotal experience with small workspace devices, which required excessive clutching motions that reduced the usability of the device. The rest of the requirements were based on simple haptic experiments and common rules of thumb for designing haptic devices. Another consideration is that the peak force and torque should be high enough for "crisp" feedback but not so high that it causes repetitive hand injuries.

Table 1: Haptic Device Design Requirements

Description	**Requirement**
ROM - Translational	At least 1mx 1m x 1m
ROM - Rotational	Allows free wrist rotation
Active DOFs	6
Footprint	Fits on a desktop
Peak force	4 lbf
Peak torque	95 oz-in
Stiffness	Maximize
Backdrive friction	Minimize
Moving inertia	Minimize
Backlash	Minimize
End effector	Stylus or handle
Function button	Required

4. Prototype system

Based on these qualitative design requirements, we set out to quickly develop a prototype of a 6DOF haptic device that can used in maintenance analysis applications.

4.1 Device description

The PHANTOM Premium 6DOF Prototype is a desk mounted force feedback system that provides six degree-of-freedom force and torque feedback. The system consists of the device itself, accompanying power electronics, a remote/safety switch, and a PCI interface card. The device is leveraged from haptic technology developed and implemented in standard PHANTOM 3DOF force feedback devices [Figure 1].

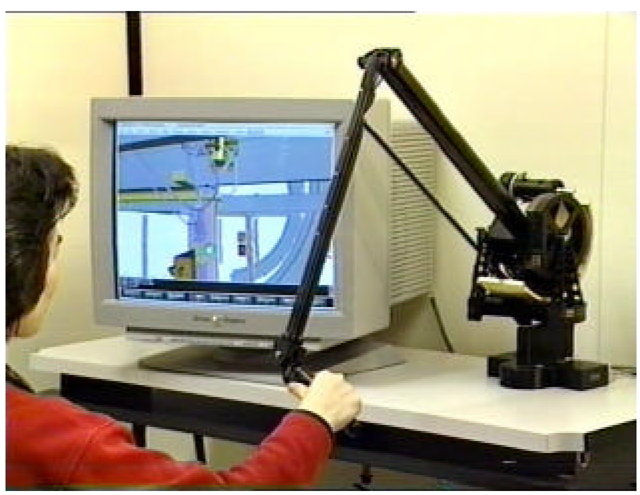

Figure 1. PHANTOM Premium 6DOF Prototype
(Photograph courtesy of The Boeing Company, M&CT)

To provide force feedback, the base of a standard PHANTOM Premium 3.0 force feedback device is used. The 3.0 is a large haptic device that accommodates free arm and hand motions about the shoulder as the center of rotation. The 3.0 base uses cable-capstan drive trains. Its motors are equipped with co-located position sensors. The base motor (primarily responsible for left-right motions, or x motions) is grounded. A cable transmission converts motor rotations to the rotation of a large disk which carries the rest of the mechanism. The second and third motors (primarily responsible for up-down and in-out motions, or y and z motions) ride on a ring mounted on the large disk, using a cable-capstan drive. The second and third motors control the position of two linkages in a four-bar parallel linkage design. The sensor-motor packages measure the endpoint position and provide force feedback in three translational degrees of freedom.

To provide torque feedback, a proprietary instrumented gimbal is attached to the last link of the PHANTOM (the link we typically call the shin). This instrumented gimbal encapsulates three additional sensors and actuators in a compact package. The gimbal provides torque feedback in three orthogonal rotational degrees of freedom. It allows largely unencumbered movements of the hand with the wrist as a center of rotation.

The end effector takes the shape of a handle and measures less than an inch in diameter. It is roughly the size and shape of a large permanent felt tip marker. It sports one switch which can be programmed to produce visual and/or haptic effects.

The 6DOF device is driven by a 6-axis power amplifier box and interfaces to a Pentium based Windows NT computer via a PCI controller card. Low level communications between the PC and the PCI card are handled by the PHANTOM Device drivers (PDD). The PDD maintains a 1 kHz servo update rate to ensure stable closed loop control of the device. The device kinematics and other robotic calculations are handled within the PDD. High level force and position calculations are provided by the the GHOST® Software Developer's Kit (SDK). The SDK provides a high level C++ programming interface for generating haptic effects. Haptic effects handled by the SDK can be based on geometry (such as point haptic exploration), or on force-time profiles (such as sinusoidal vibrations and jolts). or the user can define their own custom force fields [24]. Currently the SDK only supports 3DOF forces based on point haptic exploration. Using new extensions we have developed for the 6DOF system, custom torques can be superimposed onto these 3DOF forces. These extensions allow a 6DOF application to read a 4x4 homogeneous transform describing the global position and orientation of the end effector, calculate 6DOF forces and torques in the application, and command these 6DOF global forces and torques to the device.

4.2 Device performance

Preliminary specifications of the device are outlined in Table 2. The peak force of the device is 4.9 lbf and the nominal positioning resolution is 0.001 inch at the end effector. Typical backdrive friction is approximately 0.75 oz. The translational range of motion is about 16”x23”x33”, approximating the range of motion of the human arm. The peak torque is 95.3 oz-in and the nominal resolution is 0.013 degrees in each axis. Typical backdrive friction in rotation is about 2oz-in in the yaw and pitch directions and about 1 oz-in the roll direction. The rotational range of motion is 330 degrees in the yaw and roll directions and 220 degrees in the pitch direction.

The qualitative feedback we collected from this device has been positive. Potential users are pleased with its large workspace both in translation and in rotation. Indeed the translational workspace may be a little too large for true desktop operation. The feedback also indicates that the device's friction and inertia characteristics are well within the acceptable range for a compelling application in this area.

Table 2. Preliminary specifications for the PHANTOM Premium 6DOF Prototype

Nominal resolution	*Translational*		0.001	inch	0.02	mm
	Rotational		0.013	degrees	0.0002	radians
Backlash, no load	*Translational*		N/A		N/A	
	Rotational	less than	1.300	degrees	0.023	radians
Maximum force and torque	*Translational*		4.9	lbf	22	N
	Rotational		95.275	oz-in	670.947	mNm
Continuous force and torque	*Translational*		0.7	lbf	3	N
	Rotational		14.796	oz-in	104.199	mNm
Mechanical bandwidth	*Translational*					
	Rotational	roughly	30.000	Hz		
Backdrive friction	*Translational*		0.75	oz	0.2	N
	Rotational	less than	9.5	oz-in	67.2	mNm
Nominal stiffness	*Translational*		5.7	lbf/in	1	N/mm
	Rotational,yaw+pitch	greater than	32.000	oz-in/deg	12911.7	mNm/rad
	Rotational, roll	greater than	32.000	oz-in/deg	12911.7	mNm/rad
Max angular error at peak torque	*Rotational,yaw+pitch*	less than	2.578	degrees	0.045	radians
	Rotational, roll	less than	0.462	degrees	0.008	radians
Footprint			8"x8"		20x20cm	
Workspace	*Translational*		16"x23"x33"		42x59x 82cm	
	Rotational, yaw	roughly	330	degrees	5.760	radians
	Rotational, pitch	roughly	220	degrees	3.840	radians
	Rotational, roll	roughly	330	degrees	5.760	radians

The maximum force and torque on the device seemed appropriate for desktop applications, although it was noticed that the sensitivity of torque perception was consistently greater in the roll freedom compared to the pitch and yaw freedom. This is a very interesting observation. Our hypothesis is that the roll freedom excites different tactile sensors in the hand compared to the other two freedoms. In the roll freedom, tactile sensors in the fingertips are involved as well as kinesthetic sensors in the joints, whereas kinesthestic perception dominates in the other two freedom. We postulate that the presence of tactile feedback reinforces the torque perception in the roll freedom. The non-homogeneous feel of torque in the hand is an interesting area of future research that is perhaps best explored by conducting designed haptic perception experiments to understand the difference between the axes in a controlled and systematic manner.

5. Validation of functionality: Boeing VPS™ integration

While the device performed adequately in simple demonstrations, we were interested in investigating whether it was usable in a real-world environment. We teamed up with the Mathematics and Computing Technologies Division (M&CT) of the Boeing Company. We provided them with a PHANTOM Premium 6DOF prototype, and they integrated it with their collision detection and contact response software called VPS™ [19]. In a short period of time, the inventors of VPS at M&CT produced a demonstration program which allows the user to control the position and orientation of a test object in a moderately complex, industrial scale rigid virtual environment using the 6DOF device [Figure 1]. The forces and torques acting on the test object are calculated by the VPS software. The VPS software uses voxel-based representations for the objects in the environment and a surface "point shell" representation for the test object. This method can efficiently detect approximate surface contact between the test object and the environment. The calculations can be done at the haptic update rate of 1000Hz, despite a virtual environment complexity of several hundred thousand polygons. Force calculations are based on applying a simple repelling force at any point that is 1 voxel away from contact with objects in the environment. The simulation and real time motion control modules run on a Windows NT computer while the graphics module runs on a separate SGI Octane.

In one version of this demonstration, the 6DOF prototype controls a teapot in a simulated aircraft landing gear environment [Figure 2]. There is an area where a vertical channel is defined by a U-bracket in the back and two vertical pipes with fittings in front (see arrow in [Figure 2]). When the teapot is dropped into this channel, it can only move up and down or rotate. As the features on this teapot collide with the pipe fittings, the user feels corresponding contact forces and torques.

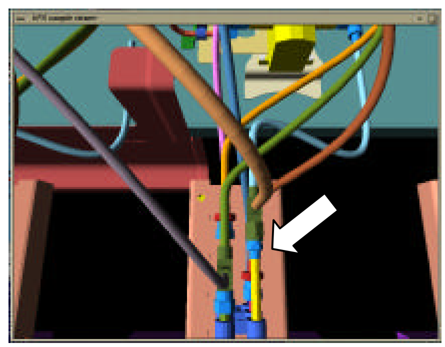

Figure 2. Simulated landing gear

There is a confined space at the bottom of this vertical channel. The teapot can fit in that confined space only in one orientation. The types of activities involved in sliding the teapot into the vertical space, sidestepping spatial obstructions, and rotating it to fit in the bottom space are similar to those performed by an engineer in a maintenance analysis task.

We have found that the presence of force and torque feedback helps tremendously in making this task at all achievable. It is almost impossible to find the right orientation of the teapot to fit in the bottom space without haptic feedback, however good the visual feedback can become. It is possible to find the orientation with 3DOF haptic feedback and some trial and error. The task becomes much easier with 6DOF haptic feedback. This demonstration illustrates the power of a 6DOF haptic device used in conjunction with 6DOF haptic rendering software. Together, they provide the ability to realistically simulate maintenance conditions in a complex environment, paving the way to a useful tool that can be used to dramatically increase productivity in maintenance analysis.

6. Discussion

Building and testing the PHANTOM 6DOF Prototype was a very educational experience. While we knew approximately what we wished to achieve, we were able to gather valuable feedback by having the real prototype in our hands and feeling the impact of torque and force feedback. We were also fortunate in being able to work with our M&CT partners at the Boeing Company. M&CT already had a software engine for computing object-object interaction and 6DOF haptic rendering, but they were not able to validate their system as a whole before our prototype was presented to them. Once all the pieces were in place, they were able to quickly create a compelling demo. The same demo was lacking in realism if operated with a standard 3DOF PHANTOM. This again confirms that 6DOF force feedback is very valuable in this type of application.

While the feedback from the 6DOF prototype was positive, there were also some interesting observations. One such observation concerns the workspace size. While many of our early customers wanted a large workspace, it became clear that a large workspace directly translates into large arm movements, which can become tiring after a short time. It seems that there are two distinct markets that require different workspace sizes: a training and ergonomic analysis market, where a big workspace is required, and a design analysis market, where a desktop based workspace is more appropriate. We have taken this feedback and developed a 6DOF breadboard on the PHANTOM Premium 1.5 platform, which adheres more to the desktop metaphor. Preliminary results are promising and we believe that the desktop based workspace could have a great impact when used as a design aid in conjunction with a virtual prototyping application.

Another interesting observation is that torques in the roll direction are more readily felt than torques in the pitch and yaw directions. As mentioned in Section 4, this is probably because of excitation of tactile as well as kinesthetic sensors in the hand in the roll direction as opposed to kinesthetic sensors in the other directions. This may have implications in "tuning" an application in an empirical and subjective manner: perhaps torques along the direction of the handle should be artificially attenuated to match the subjective feel of the other two axes. The outcome would not be physically accurate, but it would "feel" right to our (highly imprecise) haptic perception system.

A third observation regards the shape of the end effector and how it is held in the hand. Holding the current end effector like a pen results in reduced control, since the amount of pinch force that the fingers can apply is reduced, making it possible for the handle to spin out of the hand. Holding it like a handle provides much better control, but it could awkward for fine manipulation. It may be desirable to change the shape of the end effector and the peak torque to match the unique needs of each application.

We designed the 6DOF prototype with virtual prototyping as the first potential area of application. We targeted maintenance analysis applications in particular. Companies which are most likely to benefit from this technology are those in the aerospace and automotive industries, where the parts are many and large, maintainability is a major concern, and it is prohibitively expensive to produce physical prototypes. In the long run, however, all product design can stand to profit from such a desktop design aid. In the design of any product, it is always important to ensure that it can be assembled and disassembled speedily and without problems. If this technology were packaged into major CAD systems, it would speed up the product development cycle and allow better products to be designed and prototyped in less time and cost. The device can also improve the realism in other virtual simulations that can benefit from 6DOF force feedback, including medical simulations, molecular modeling and teleoperation.

7. Summary and Conclusions

The quality and usability of virtual prototyping applications can be substantially improved by the integration of a 6DOF haptic device. This device must have a large translational and rotational workspace and present forces and torques in full 6 degrees of motion. We have realized these and other design specifications in the PHANTOM Premium 6DOF Prototype, a large workspace device with acceptable performance for desktop virtual prototyping applications. This device has been integrated into the Boeing VPS software, which simulates maintenance analysis in a large scale industrial environment. We think that the 6DOF technology in this work and in continuing research will provide much value to virtual prototyping applications on the desktop.

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