Haptic Modeling in Rapid Product Development

Yonghua Chen[1], Zhengyi Yang[2] and Lili Lian[3]

[1] The University of Hong Kong, yhchen@hkucc.hku.hk
[2] The University of Hong Kong, yangzy@graduate.hku.hk
[3] The University of Hong Kong, lianlili@hkusua.hku.hk

ABSTRACT

This paper presents an integrated product development platform. Haptic modeling, due to its growing applications to different aspects of product development, is envisioned as the core technology for the proposed rapid product development platform. Since haptic modeling is developed based on physical laws, it is anticipated as the natural link between the virtual world and practical applications. In the proposed platform, haptic devices are used as the central mechanisms for reverse engineering, shape modeling, virtual prototyping, machining tool path planning and tolerance inspection path planning. The hardware system is constructed by attaching a digitizing probe to a haptic device Phantom®. This configuration enables the force guided digitization in reverse engineering. When a three dimensional computer model is constructed by either haptic shape modeling or reverse engineering, both tool path planning and coordinate measuring machine (CMM) tolerance inspection path planning can be carried out in a haptic environment. Physical models can be made by either computer numerical controlled machining or rapid prototyping machines.

Keywords: Haptic modeling; Product development; Reverse engineering; Tool path planning.

1. INTRODUCTION

In recent years, haptic modeling has been used in the fields of medicine, education, entertainment, computer arts, and engineering design and manufacturing. Using haptic modeling in a virtual design environment, designers are able to feel and deform virtual objects in a natural 3D setting, rather than being restricted to 2D projections for input and output. In haptic modeling, force feedback provides additional sensory cues, enabling designers to gain a richer understanding of the 3D environment.

A critical issue in virtual haptic design is the development of a mechanics model for different materials and shaping methods. Jansson and Vergeest proposed a discrete mechanics model for deformable bodies based on inter-atomic interaction, and recursive resolution reduction [1]. Dachille *et al*. reported a haptic B-spline deformation method where point, normal, and curvature constraints of B-spline surfaces are interactively specified and modified [2]. Since haptic devices are designed to simulate physical processes, haptic modeling technologies have become an integral part of virtual prototyping systems in which realistic process modeling is required [3]. Using haptic modeling, a user can not only view the objects designed in the CAD environment, but also touch, grasp and move them in the virtual space to detect possible collisions with other objects [4]. For more realistic manufacturing process planning, Chang *et al*. presented a multi-sensory virtual environment with visual, haptic, and aural feedbacks for five-axis CNC milling process simulation [5].

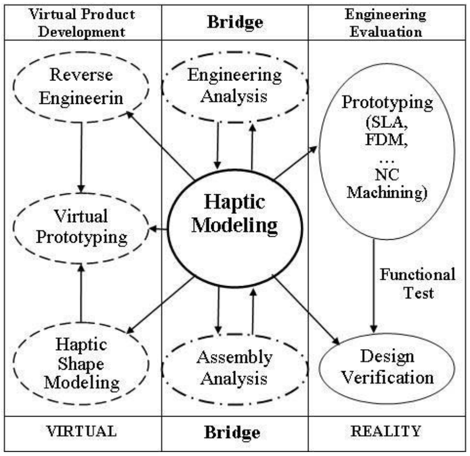
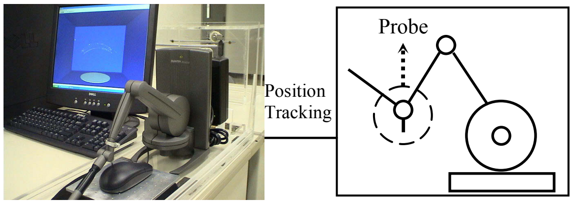


Fig.1. The proposed haptic based product development platform

Haptic modeling is also used in tele-operations. In tele-operation, the master-slave system is one of the most widely known approaches. A variant of the master-slave system is the bilateral system that allows for the feedback of the reaction force to the master manipulator (a haptic device) when the slave manipulator has contact with an object [6]. Mitshuishi *et al*. [7] developed a prototype tele-machining system using multi-axis force data and stereo sound information. In their system, the force information from the multi-axis force sensor is used not only to determine the machining and the operation state but is also reflected back to the operator through a three-degree-of-freedom joystick to give the operator the impression that he is directly manipulating the object.

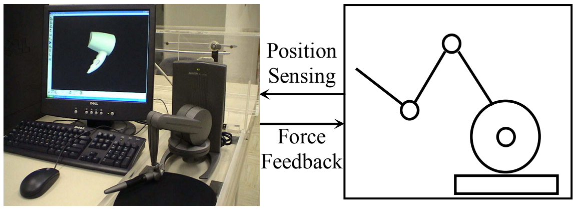
In this paper, the major inter-relationships between haptic modeling and product development are examined. A system incorporating haptic reverse engineering, haptic shape modeling, tool path planning, engineering analysis and haptic CMM inspection path planning capabilities are investigated.



Object Digitization

Haptic Device with Probe

Fig.2. The links between reverse engineering and haptic modeling



Haptic Shape Modeling

Haptic Devices

Fig.3. The links between shape modeling and haptic modeling

Product development is a systems engineering involving many aspects of work. Fig. 1 shows some of the major issues in a product development process. Due to the increasing power of computing technologies and virtual reality techniques, many works of the product development process are being done in a virtual environment, as shown in the left column of Fig. 1. Shape modeling and reverse engineering are the major means of product geometry input. With the availability of geometric models of all the parts of a product, virtual prototyping can lead to the realistic process modeling, such as simulating the effects of manufacturing processes, limit and fit analysis, dynamic simulation and maintenance analysis. Assembly sequence planning and engineering analysis can also be done in a haptic system. When a part design is available, it can be either prototyped by a rapid prototyping machine or machined by a CNC machine. When a part is to be machined, tool path planning and CMM inspection planning can also be done in a haptic system. In the proposed virtual product development environment, the haptic modeling hardware is expanded further to include reverse engineering as shown in Fig. 2 where a probe is attached to a commercial haptic device Phantom, where only the position of a tracking probe is recorded. Apart from digitization, haptic modeling can also be used for editing scattered point cloud from reverse engineering. In recent years, haptic modeling has been frequently used for freeform shape modeling. A commercially available haptic shape modeling system called FreeForm was marketed by SensAble Technologies since 1999 [8]. The links between shape modeling and haptic modeling is by means of both position sensing and force modeling as shown in Fig. 3.

2. HAPTIC SHAPE MODELING AND REVERSE ENGINEERING

In today's computer aided design systems, a computer model can be either created by a designer or scanned from an existing part. Using haptic modeling, creating a computer model resembles the very natural way that is practiced by designers. The following shows how different it is to create a computer model using a haptic system.

2.1. Haptic Shape Modeling

In contrast to traditional 2D mouse-keyboard interfaces used in most of the commercial modeling systems, a haptic shape modeling system is more intuitive and natural. The sense of touch broadens the human-computer bandwidth. FreeForm® is a commercialized shape modeling software released by SensAble® Technologies. As shown in Fig. 3, users can create digital models in a similar intuitive and direct manner as physical modeling with clay or wax while taking advantage of the flexibility and efficiency provided by a digital environment [8]. The force feed back of a haptic system also provides extra sensory cues that allow easy and intuitive operations that are unimaginable by using a mouse. For example, the sketch on a ring surface as in Fig.4 can be done in a haptic system without much difficult. A toy design as in Fig. 5 can be painted at will as if the designer is working on a physical model. However, at present state, FreeForm is suitable only for conceptual or industrial design, rather than engineering design. The reason is the system lacks a well-established and user-friendly parameter-driven mechanism.

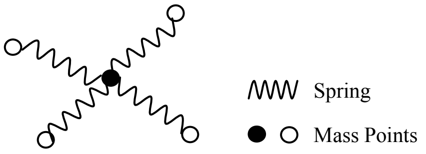
Fig. 4. Sketch on a ring surface

In the authors' research, shape modeling consists of two categories of operations: adding material and removing material. The former is emulated as adding tool swept volume to existing part. And the latter is simulated as a virtual material removal process similar to the milling process. When interactively removing material using a virtual tool such as a ball-end milling cutter, a user can feel the physically realistic presence of the material with force feedback throughout the process. The whole modeling procedure is decomposed into unit machining operation. The parameters of each unit machining operation are recorded and can be changed later. The model will be regenerated after parameters change. Thus a parameter-driven modeling mechanism can be implemented. This part of work is still under active research.

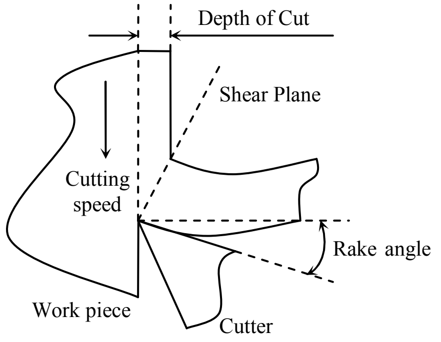
Fig. 5. Paint a toy monkey at will

2.2. Haptic Rendering

In order to create a touchable environment, many haptic rendering methodologies have been developed. Applications can be found in the fields of surgical or dental operation training, motor skill training, art sculpturing, and concept modeling [9-14]. Most of the haptic rendering methods used are based on tool contact simulation, surface tracing, or object cutting. The force models are based on elastic deformation. None of them considered actual material removing processes, in which the plastic deformation is dominant. As shown in Fig. 6 (a), the mass-spring model is widely used to represent the models with elastic characteristics. While in machining, the basic mechanism is material removing. A cutting force is applied to the material such that the local stress exceeds the yield stress of the material resulting in plastic deformation and shearing of the material along the shear plane angle (Fig. 6. (b)).



(a) Elastic Deformation



(b) Plastic Deformation

Fig. 6. Elastic deformation and Plastic deformation

To reflect the force in plastic deformation, a volume-based haptic rendering of milling process is developed for the proposed haptic virtual machining system. Both the object and the milling tool are represented by a volumetric data structure called Spatial Run-Length Encoding (S-RLE) developed by the authors [15]. The haptic response is implemented with the Phantom haptic arm from SensAble® Technologies.

The haptic rendering of the parts in milling process is divided into two parts: the haptic rendering of contact and the haptic rendering of material removing. The former is a static rendering and related to the collisions between tool shank and in-progress workpiece; and the latter is a dynamic rendering and related to the force generated by the movements of effective cutting part. The contact force modeling can employ the existing force models, while the material removing force is calculated based on energy consumption.

Many efforts have been taken on modeling the cutting force in various machining processes, such as turning, drilling, and milling. But not every force model is feasible to be used for haptic rendering that features a relatively high update rate.

The simplest model relates the cutting power P (m^2kg/s^3) to the material removal rate (MRR) (m^3/s) by the following equation [16]:

$$P = K \cdot (MRR) \tag{1}$$

where K ($kg/(ms^2)$) is the unit power consumption. The spindle motor power (P) is equal to the tangential cutting force times the tooth velocity. Therefore, the tangential cutting force is easily found by the following:

$$F_t = K \cdot (MRR) / v \tag{2}$$

where v (m/s) is the tooth velocity. The radial force is calculated by multiplying the tangential force by a constant K_r:

$$F_r = K_r \cdot F_t \tag{3}$$

The volumetric model is simple to implement and can be calculated efficiently to meet the need of high update rate in haptic rendering. The values of K and K_r depend on workpiece material, cutting tool geometry and cutting conditions. A series of experiments have been carried out previously by the authors to calcuate the coefficients K and K_r.

The estimation of MRR is also simple:

$$MRR = VR / HC \tag{4}$$

VR is the material removed in a period of haptic cycle. HC is the period of haptic cycle (generally, smaller than 1ms).

It can be observed from the above equations that the magnitude of the cutting force is determined by the volume of removed material and cutting parameters; and the direction of cutting force is determined by the geometry of removed material and cutting parameters.

2.3 Reverse Engineering

Unlike the traditional manufacturing philosophy of designs being transposed into products, reverse engineering measures, analyses, modifies, and produces the products based on existing artifacts [17]. Using 3-D data collected by a tactile probe that is mounted on a machine tool or a co-ordinate measuring machine (CMM), a CAD model can be created and employed in many subsequent manufacturing processes. An in-depth review of reverse engineering is discussed in a paper by Varady *et al.* [18].

In the proposed system, by attaching a probe, the haptic device is expanded to incorporate the function of a digitizing device, as shown in Fig. 7. The probe is made of stainless steel and the probe fixture is made of light aluminum. A plate with a matrix of holes is used for part fixture and probe calibration. When the system enters Reverse Engineering mode, the position of the probe tip is tracked.

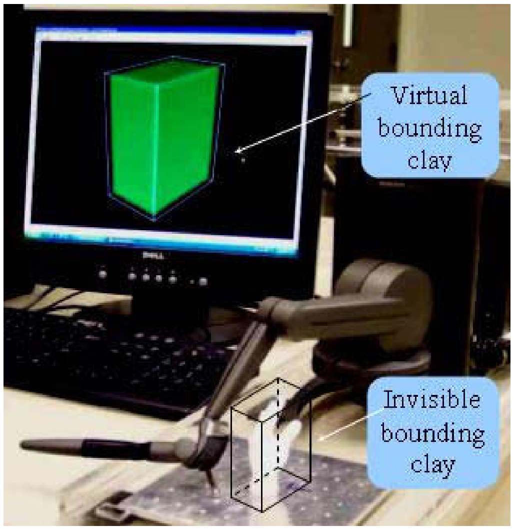


Fig. 7. Defining the virtual clay

Fig. 8. Sculpting to rediscover the hand model

This device can be used in a traditional articulated digitization environment where the probe is held by hand. When a switch is turned on, the spatial coordinates of the probe tip is recorded. The result of digitization is a point cloud. Since there is no constraint on the moving path of the probe, redundant and chaotic points are resulted. In the proposed haptic based digitization environment, a piece of virtual clay enclosing the actual part is first defined. The virtual clay is visible on the monitor while invisible but touchable around the part as shown in Fig. 7. When digitizing the object, the probe is swept around the virtual clay to rediscover the object. Fig. 8 shows the emerging model while removing the virtual clay. It can be seen that the resulting model from digitization is a volume model instead of point cloud. The volume model is unambiguous compared to point clouds from existing digitization methods. At present, due to the demanding computational power of haptic systems, the resolution of the proposed digitization method is only applicable to concept design where accuracy is not a dominant requirement.

Fig. 9. A tooth brush and its computer model

3. HAPTIC BASED STRESS AND STRAIN ANALYSIS

In the early product design stage, it is desirable to evaluate some of the functional performances even before a product is made. Take the design of a tooth brush in Fig.9 as an example. A hard toothbrush may hurt the denture especially when used by children; while a too soft toothbrush may bend too much to be controlled. In order to have different stiffness of the brush neck, either the brush "neck" geometry, or the material of the "neck" can be changed. After a change, designers can feel the different stiffness and deformation while applying a force at the head of the toothbrush as in Fig. 10. At this preliminary stage of our research, the applied force is constrained in a constant direction. Desired "neck" stiffness can be found by changing the soft-material pattern or volume and doing the haptic force-deformation simulation. Through this kind of trial-and-error, a typical process in product design, designers can get the right stiffness with their desired geometry or material composition. In order to be more intuitive, an indicator showing the applied load and corresponding bending stress is added as shown in Fig. 11.

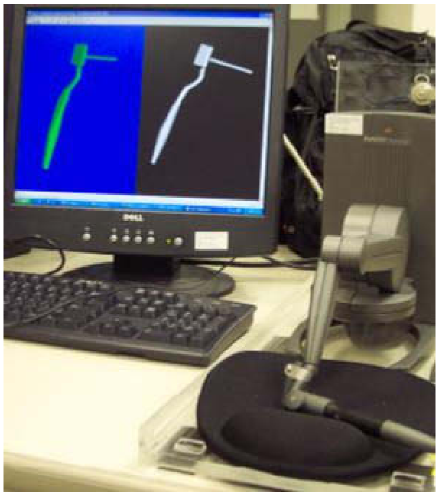


Fig. 10. Toothbrush design modeling

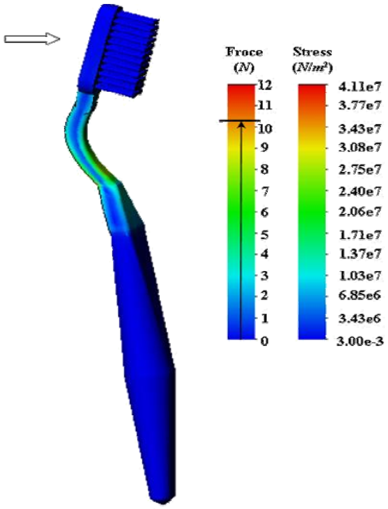


Fig. 11. The force indicator

The haptic simulation is based on finite element method (FEM). Element topology selection is the first step of

FEM. Volumetric finite element is used in our method. 3D elements array are constructed to represent the object. In order to simplify the computation, only the linear terms in the displacement components are used and the higher order terms neglected. To achieve high update rate as required by haptic modeling, force and displacement relationship are pre-computed based on the following [19].

The relationships between the components of the strain and the displacement components **u**, **v**, and **w** at a point are,

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{zx} \end{Bmatrix} = \begin{bmatrix} \frac{\partial}{\partial x} & 0 & 0 \\ 0 & \frac{\partial}{\partial y} & 0 \\ 0 & 0 & \frac{\partial}{\partial z} \\ \frac{\partial}{\partial y} & \frac{\partial}{\partial x} & 0 \\ 0 & \frac{\partial}{\partial z} & \frac{\partial}{\partial y} \\ \frac{\partial}{\partial z} & 0 & \frac{\partial}{\partial x} \end{bmatrix} \begin{Bmatrix} \mathbf{u} \\ \mathbf{v} \\ \mathbf{w} \end{Bmatrix}$$

or

$$\{\mathbf{E}\} = [B]\{\mathbf{u}\} \qquad (5)$$

where $\{\mathbf{E}\}$ and $\{\mathbf{u}\}$ are the strain and displacement vectors, respectively. For linear, isotropic, and elastic materials, the relations between the components of stress and strain can be represented by using only two independent elastic constants: Young's modulus E and Poisson's ratio υ. According to the generalized Hooke's law, we have this:

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{xy} \\ \tau_{yz} \\ \tau_{zx} \end{Bmatrix} = [D] \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{zx} \end{Bmatrix}, \text{ or } \{\mathbf{G}\} = [D]\{\mathbf{E}\} \qquad (6)$$

where $\{\mathbf{G}\}$ and $\{\mathbf{E}\}$ are the stress and strain vectors, respectively; and $[D]$ is given by

$$\frac{E}{(1+v)(1-2v)} \times \begin{bmatrix} 1-v & v & v & & & \\ v & 1-v & v & & & \\ v & v & 1-v & & & \\ & & & \frac{1-2v}{2} & & \\ & & & & \frac{1-2v}{2} & \\ & & & & & \frac{1-2v}{2} \end{bmatrix} \qquad (7)$$

Based on the above equations, a finite element system to compute displacements from force inputs is established as

$$[K]\{\boldsymbol{Q}\} = \{\boldsymbol{F}\} \qquad (8)$$

where [K] is the global stiffness matrix, this matrix in general being symmetrical and banded, $\{\boldsymbol{Q}\}$ the global displacement vector, and $\{\boldsymbol{F}\}$ the global force vector. The resulting Eq. (8) is then solved subject to constraints.

4. HAPTIC BASED TOOL PATH GENERATION

In CNC machining, a lot of effort has been spent on tool path planning [20]. Recently, a tool path generation method based on haptic interfaces is reported in [21]. Haptic device is used by users to "teach" a milling machine to machine a virtual part so that collision free tool path can be generated and accessibility is assured in cases where computational methods are not efficient and reliable as shown in Fig. 12. However, the method is focused on finish milling because the geometry of raw material stock is not considered. Since only the part is haptic rendered, it is difficult to generate tool path in rough machining, in which the raw material stock properties and machining allowance must be taken into account. In the authors' research, haptic virtual machining starts from a raw material stock. The virtual machining is separated into two stages in line with the real machining process: rough machining and finish machining.

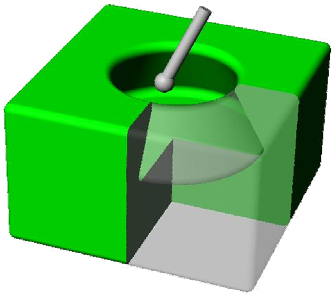


Fig. 12. Accessibility in tool path planning

At rough machining stage, the design surfaces of the part are offset a distance for machining allowance. And the offset surfaces are haptic rendered as static rigid surfaces. Thus, the virtual tool cannot penetrate the offset surfaces. The tool paths are un-constrained like a free-hand sculpturing.

At finishing stage, the design surfaces of the part are modeled as impenetrable and tool path is constrained by a structured set of machining parameters. These constraints could be geometrical or physical. For example, when the virtual tool moved manually is approaching a rigid surface, a perceptible force is sent to Phantom arm, the user then can move the tool away to avoid collision. Similarly by applying a cluster of force constraint planes, we can confine the virtual tool within a structured space. Z-constant tool path can be generated with the force guidance as shown in Fig. 13 where the tool can only move on the defined plane.

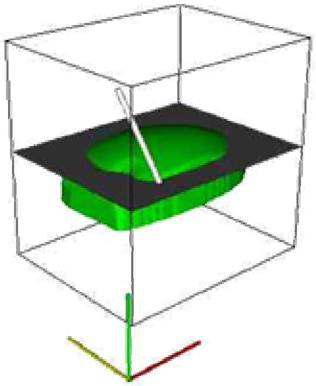


Fig. 13. A force plane constraining the tool movement

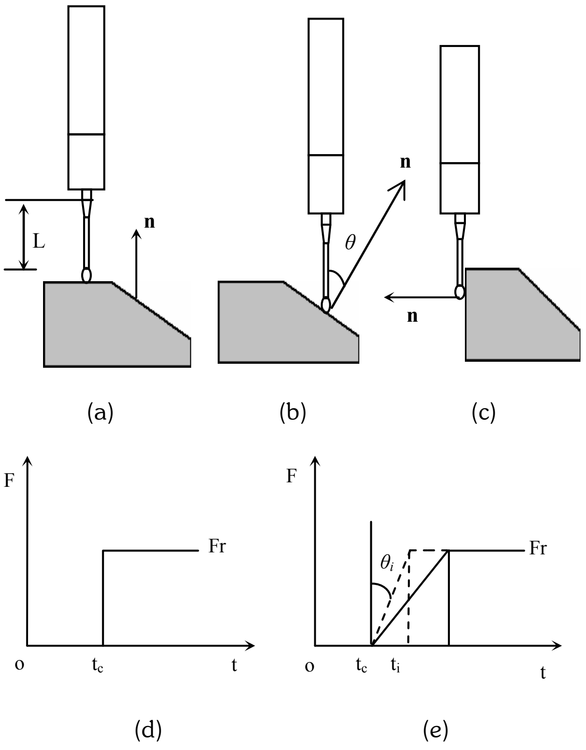
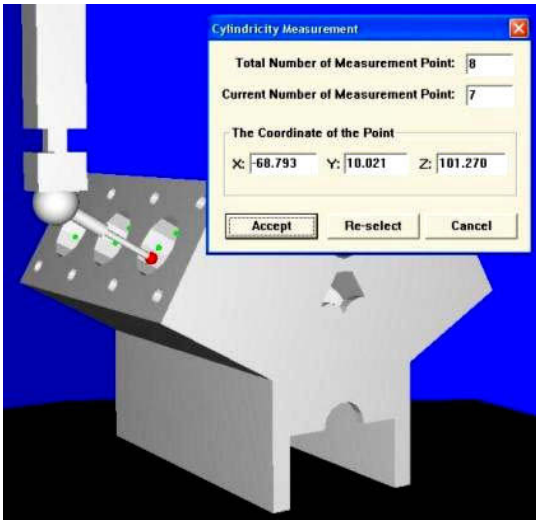


Fig. 14. Contact between the probe tip and an object: (a) surface normal **n** inline with probe; (b) surface normal **n** at an angle with probe; (c) surface normal **n** perpendicular to probe; (d) rigid force feedback; (e) soft force feedback.

The movements of the virtual tool are recorded as the original cutter location data of tool path. Redundant data removing and tool path optimization are then performed to generate the final tool path.

5. HAPTIC CMM PATH PLANNING

When a part design is finalized, production planning must be conducted. As part of the integrated production process, product inspection must be planned before actual production takes place. Based on the CAD model of a part, off-line CMM inspection path planning can be done [22]. Unlike previous CMM path planning packages, the proposed haptic off-line CMM inspection path planning system allows user to operate on a virtual system as if he is working on a real CMM without worrying about damage the expensive probe. The realistic force feedback model is based on the probe contact orientation as shown in Fig.14. When any other parts of a CMM except the probe tip come into contact with an object, an instant rigid force and a warning signal are fed back to the user as in Fig. 14. (d). No coordinate reading is given. When a valid contact is reached as shown in Fig. 14 (a) to (c), a force feedback is given based on the model as in Fig. 14. (*e*).



Cylindricity Measurement

Total Number of Measurement Point: 8

Current Number of Measurement Point: 7

The Coordinate of the Point

X: -68.793 Y: 10.021 Z: 101.270

Fig. 15. Measurement of a V6 engine block

Figure 15 shows the measurement of inclined bores of a simplified V6 engine block using a bent probe. To select a measurement point, the user operates the haptic device just like operating a CMM control panel except the haptic system is even more realistic because the operator can feel the force when the probe tip comes into contact with an object. When a point is selected, it is highlighted and its coordinates saved. These points are guaranteed to be accessible in real measurement. If a measurement point is not desirable, another point can be easily defined. More work is needed to optimize the inspection path when all measuring points are defined.

6. ACKNOWLEDGMENTS

This research is supported by a grant from Hong Kong Research Grants Council under the code HKU 7073/02E.

7. REFERENCES

[1] Jansson, J. and Vergeest, J.S.M., A discrete mechanics model for deformable bodies, *Computer-Aided Design*, vol. 34, 2002, pp 913-928.

[2] Dachille IX, F., Qin, H. and Kaufman, A., A novel haptics-based interface and sculpting system for physics-based geometric design, *Computer-Aided Design*, vol. 33, 2001, pp 403-320.

[3] Chen, E., Six Degree-of-Freedom Haptic System for Desktop Virtual Prototyping Applications, in *Proceedings of the First International Workshop on Virtual Reality and Prototyping*, Laval, France, 1999, pp 97-106.

[4] Gutierrez, T., Barabero, J.I., Aizpitarte, M., Cariilo, A.R. and Eguidazu, A., Assembly simulation through haptic virtual prototypes, in *Proceedings of 3rd Phantom Users Group Workshop*, Dedham, MA, USA, 1998.

[5] Chang, C.F., Varshney, A. and Ge, Q.J., Haptic and aural rendering of a virtual milling process, in *Proceedings of ASME 2001 Design Engineering Technical Conferences and Computers and Information in Engineering Conferences*, Pittsburgh, Pennsylvania, USA, 2001.

[6] Mitsuishi, M., Warisawa, S., Higashi, T., Kobayashi, O., Hatamura, Y., Nagao, T. and Kramer, B., A tele-maschining system using multi-axis force data and stereo sound information, in *Proceedings of IEEE International Workshop on Robot and Human Comminication*, Tokyo, Japan, 1992, pp 227-234.

[7] Mitsuishi, M., Hori, T., Hikita, T., Teratani, M., Watanabe, T., Nakanish, H. and Kramer, B., Experiments in tele-handling and tele-machining at the marco and micro scales, using the internet for operational environment transmission, in *Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems*, Pittsburgh, Pennsylvania, USA, 1995, pp 13-20.

[8] http://www.sensable.com

[9] Mahvash, M., Hayward, V. and Lloyd, J., Haptic rendering of tool contact, in *Proceedings of Eurohaptics*, August 2002, Edinburgh, Scotland, pp 110-115.

[10] Bielser, D. and Gross, M.H., Interactive simulation of surgical cuts, in *Proceedings of Pacific Graphics 2000*, IEEE Computer Society Press, 2000, pp 116-125.

[11] Tanaka, A., Hirota, K. and Kaneko, T., Virtual cutting with force feedback, in *Proceeding of VRAIS'98*, 1998.

[12] Kanai, S. and Takahashi, H., “Modeling and NC programming for free-form surfaces by haptic interfaces, in *Proceedings of DETC/Design for Manufacturing*, ASME, Irvine, California, USA, 1996, pp 509-518.

[13] Foskey, M., Otaduy, M.A. and Lin, M.C., ArtNova: Touch-enabled 3D model design, in *Proceedings of the IEEE Virtual Reality*, 2002.

[14] Gibson, S., 3D ChainMail: a fast algorithm for deforming volumetric objects, in *Proceedings of Symposium on Interactive 3D &Graphics*, Providence RI LISA, 1997, pp 149-154.

[15] Chen, Y.H. and Yang, Z.Y., Haptic Rendering Based on Spatial Run-length Encoding, *Robotics and Computer-Integrated Manufacturing*, Vol. 20, 2004, pp 237-246.

[16] Choi, B.K. and Jerard, R.B., *Sculptured Surface Machining Theory and Applications*, Kluwer Academic Publishers, 1998.

[17] Peng, Q.J. and Loftus, M., A new approach to reverse engineering based on vision information, *International Journal of Machine Tools & manufacture*, Vol. 38, 1998, pp 881-899.

[18] Varady, T., Martin, R.R., and Cox, J., Reverse engineering of geometric models - an introduction, *Computer-Aided Design*, Vol. 29, No. 4, 1997, pp 255-268.

[19] Kang, H. and Kak, A., Deforming Virtual Objects Interactively in Accordance with a Elastic Model, *Computer-Aided Design*, Vol. 28, No. 4, 1996, pp 251-262.

[20] Dragomatz, D. and Mann, S.A., Classified Bibliography of Literature on NC Milling Path Generation, *Computer-Aided Design*, Vol. 29, No. 3, 1997, pp 239-247.

[21] Balasubramaniam, M., Ho, S., Sarma, S. and Adachi, Y., Generation of collision-free 5-axis tool paths using a haptic surface, *Computer-Aided Design*, Vol. 34, No. 4, 2002, pp 267-279.

[22] Pahk, H.J., Burdekin, M. and Peggs, G.N., Development of Virtual Coordinate Measuring Machine Incorporating Probe Errors, in *Proceedings of The Institution of Engineers, Part B: Journal of Engineering Manufacture*, Vol. 212, No. B7, 1998, pp 533-548.