ISOGEOMETRIC ANALYSIS FOR DYNAMIC MODEL SIMULATION

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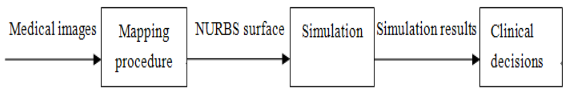
Dynamic model, isogeometric analysis, Non-Uniform Rational B-spline, simulation, control point, error estimation.

ABSTRACT

This paper proposes a method of constructing a dynamic model of a ventricle based on isogeometric simulation so as to diagnose cardiac disease more accurately. Isogeometric simulation is an accurate simulation technology based on NURBS, which has evolved into an essential tool for a semi-analytical representation of geometric entities. Especially, a new method of moving control points is used to achieve a dynamic model of the ventricle. This method promises the model to be very accurate, efficient, and successive, in comparison with traditional models. Furthermore, the paper also puts forward a new error estimation method, which adopts the vector norm to get an overall analysis of the error coefficient in each direction. The error estimation method avoids a complicated estimation for each knot. It can not only be used to evaluate the value of the error accurately, but also reduce the local error by adjusting the control points. Moreover, the proposed NURBS model can especially be useful to analyze the motion and dynamics of the heart, and it is important for doctors to find early cues of cardiac diseases.

INTRODUCTION

With the improvement of people's living standard, more and more people pay much attention to their health. Recently, cardiac disease has become one of the diseases that threaten human health and life safety. According to the report of WHO (World Health Organization), the rate of death lead by cardiovascular disease on average accounts for a third of the total death. There are more than seventeen million people died from cardiac diseases every year. Heart is an extremely complex integrated system. It is integrated with electrophysiology, blood fluid mechanics, dynamics, and biochemical properties. As the Left Ventricle (LV) is the pump of the blood circulation of the whole body, it plays an important role in the cardiac function. The LV is the focus in current researches of heart, and modeling and simulation are two major means to study complex biological problems. With the help of powerful image processing ability and computational ability of the computer, active mechanism of the heart can be carried out thoroughly, a cardiac model can be built too. Moreover, model can not only be used to simulate the heart, but also simulate real movement process of the heart. The simulation of the cardiac valve (Michel 2006), the mechanical properties, and the blood fluid mechanics properties provide information for clinical diagnosis of cardiac disease (Fig. 1).



Figures 1: The Process of Computer Aided Diagnosis

At present, imaging techniques, such as computed tomography (CT), magnetic resonance imaging (MRI), positron emission tomography, single photon emission computed tomography, ultrasound, and X-ray, provide noninvasive methods to study internal organs in vivo (Verhaeghe 2007 and Guttman 1997). Medical imaging technology aims to get a surface to represent the accurate geometry of the heart, and of the development of medicinal imaging techniques, much more useful cardiac information has been provided while clinical diagnosis and treatment of cardiac diseases become more complex. It is the first step to obtain many other functional parameters, especially for those related to myocardial kinetics. In the view of geometry, all kinds of cardiac models can be divided into three categories: surface model, solid model and deformable model.

In the early years, scholars and experts did their researches with a simple geometric shape (a bullet without of the top), which represents the LV (Dulce 1993). However, it was rather rough, and it could only offer a few diagnostic parameters. The refinement of the LV surface with a parametric equation method (Such as sine function) was more flexible than other methods. It described more details of the heart at the same time. Mcinerney and Terzopous (1995) had rebuilt the LV surface model by the particularity of the heart's internal material. Furthermore, Young et al. (1995) and Park et al. (2003) used finite-element methods to represent and analyze the cardiac model. Static, comprehensive end-diastolic cardiac surfaces including four cardiac chambers and connected vasculature are presented as a triangular mesh. Mitchell (2002) first proposed a solid model to simulate the dynamic ventricle. The development of a fully three-dimensional active

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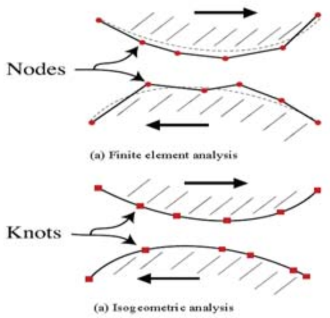
appearance model (3-D AAM) requires no additional interactively supplied information. The deformable models had wildly been used in computer vision and graphics, and were adopted by many scholars. This is not only because the deformable model can strongly adapt to the changing nature of the heart, but also because it has more advantages on medical image segmentation, matching, and cardiac motion tracking. Amini proposed a surface deformable model, while Johan Montagnat (2005) extended the deformable model framework to tackle the segmentation of 4D images by introducing temporal regularizing constraints in addition to spatial regularizing constraints.

Nowadays, the traditional finite element method can't make a consecutive mechanical analysis directly with a CAD model (such as B-spline, T-spline), and one mesh is no longer enough. Recent trends taking place in engineering analysis and high-performance computing are demanding greater precision and tighter integration of the overall modeling-analysis process. A finite element mesh is only an approximation of the CAD geometry, which we view as "exact". This approximation (see Fig. 2) can in many situations create errors in analytical results.



Figures 2: (a) Polynomial Finite Elements (b) Isogeometric Analysis based on NURBS.

It is apparent that the way to break down the barriers between engineering design and analysis is to reconstitute the entire process, but at the same time maintain compatibility with existing practices. A fundamental step is to focus on one, and only one, geometric model, which can be utilized directly as an analysis model, or from which geometrically precise analysis models can be automatically built. This will require a change from classical finite element analysis to an analysis procedure based on CAD representations. This concept is referred to as isogeometric analysis (IGA), and it was introduced in Hughes et al. (2005).

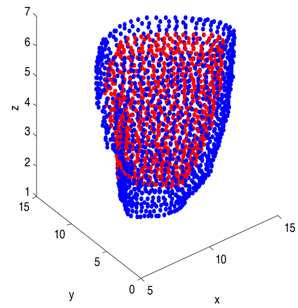
IGA is a new computational method that can provide a consecutive mechanical analysis to the traditional CAD models, and does not need to cater to the FEA with a grid partition. The basic idea of IGA is to analyze and calculate parameters based on the geometric descriptions of entities. Above all, it avoids a classical second modeling compared to the FEA. Later, a NURBS framework was proposed in order to instantiate the concept of IGA. Furthermore, there are two important issues that we have to discuss, but have not appeared in any literatures. One is which model adapts to the changing cardiac shape, where we require the model not only to be dynamic, but also flexible for shape deformation. The other is how to evaluate a model that is accurate for computation of functional parameters. For these emerging problems, this paper proposes the new method of moving the control points to achieve a dynamic model of the LV. From CT cardiac medical images, a manual segmentation is used to find the anatomical boundaries of the cardiac ventricles, and get the coordinates of the point cloud. Then, the coordinates of the control points can be computed, which manipulate the whole heart. Compared to the traditional models, this method has a better accuracy, topology and continuity. What's more, this paper also puts forward a new error estimation method, which avoids a complicated error estimate for each knot.

MODELING

Isogeometric simulation is recently a more accurate simulation technology based on NURBS or T-spline curves. Zhang and Bazilevs (2007) introduced a model for vessel, and it is also based on NURBS isogeometric simulation. Besides, NURBS curve and surface is the most popular approach for modeling. NURBS has the advantages and the convenience for modeling free surface, representing all kinds of conic surface precisely. Furthermore, there are many effective and stable algorithms to develop NURBS entities. Four steps could be concluded through the whole modeling.

The data acquision of LV's CT Images

The data in this paper comes from the patients' CT images. First of all, Anatomical boundaries of the LV can be marked with a manual notation segmentation method (Ru 2012), and many asf files of the data can be created by the MATLAB program. Secondly, the points with the same layer and same number could be obtained by surface fitting method. Resampling helps to solve the problems of integrating the different size at different m-



Figures 3: Point Cloud by Manual Notation Method

oments and different layers. Then, the data can be read into MATLAB, which could display the points in the form of 3-D point cloud (see Fig. 3).

NURBS curve and surface

This section gives a brief overview of isogeometric analysis based on NURBS. A more detailed description of the isogeometric approach can be described by T.J.R. Hughes (2005). For an introductory text on NURBS, see Rogers (2001), while a more detailed treatment is given in the book of Piegl and Tiller (1997). Mathematical theory of isogeometric analysis for h-refined meshes may be found in the recent work of Bazilevs et al. (2006).

NURBS is referred to Non-Uniform Rational B-spline curve, which is defined as follows:

$$P(K) = \frac{\sum_{i=0}^{n} N_{i,m}(K)\omega_i P_i}{\sum_{i=0}^{n} N_{i,m}(K)\omega_i} \quad (1)$$

where ***P(K)*** is a position vector of the curve, $N_{i,m}(K)$ is the m-spline basis function. P_i is a control point, ω_i is a weight factor, and ***K*** is a knot vector. The B-spline basis functions are defined recursively starting with piecewise constants:

$$\begin{cases} N_{i,0}(K) = \begin{cases} 1 & (K_i \le K \le K_{i+1}) \\ 0 & (other) \end{cases} \\ N_{i,m}(K) = \dfrac{(K-K_i)N_{i,m-1}(K)}{K_{i+m}-K_i} + \dfrac{(K_{i+m+1}-K)N_{i+1,m-1}(K)}{K_{i+m+1}-K_{i+1}} \quad (m \ge 1) \end{cases} \quad (2)$$

The value and space of the knot vector could be unrestricted. So, we can get different mixed-function shape at different intervals, and it provides more freedom for control curve. Any point on the curve impacting the curve has more than a control point (Except of the endpoints of the Bezier), the knot likes a border, when the control point lose influence at this border, another control point will replace it.

Given a control net $\{P_{i,j}\}$, i=1, 2, …, n, j=1, 2, …, m, polynomial order p and q, and knot vectors ***U***=[u_0, u_1, …, u_{m+p}], and ***V***=[v_0, v_1, …, v_{n+p}], a tensor product NURBS surface is defined by:

$$P(u,v) = \frac{\sum_{i=0}^{m}\sum_{j=0}^{n} \omega_{ij} P_{ij} N_{i,p}(u) N_{j,q}(v)}{\sum_{i=0}^{m}\sum_{j=0}^{n} \omega_{ij} N_{i,p}(u) N_{j,q}(v)}, u, v \in [0,1]$$

where $N_{i,p}(u)$ and $N_{j,p}(v)$ are univariate B-spline basis functions of order p and q, corresponding to knot vector ***U*** and ***V***, respectively.

A calculation of control points and weight factor

A tensor product NURBS surface is defined by:

$$P(u,v) = \frac{\sum_{i=0}^{m}\sum_{j=0}^{n} \omega_{ij} P_{ij} N_{i,p}(u) N_{j,q}(v)}{\sum_{i=0}^{m}\sum_{j=0}^{n} \omega_{ij} N_{i,p}(u) N_{j,q}(v)}$$

Assuming constant weights, the matrix equation of each component of the N sampling points (N>m*n) is:

$$P_r^{x,y,z} = \frac{N(i,:) P_w^{x,y,z} N^T(:,j)}{N(i,:) w N^T(:,j)} \quad (3)$$

where m is the number of control points along the u direction, while n is the number of control points along the v direction, i=1, …, m, j=1, …, n, r=i+(j-1) *m. ***N*(*i*, :)** is the i-th row of the matrix:

$$N = \begin{bmatrix} N_{11} & \dots & N_{1m} \\ \dots & \dots & \dots \\ N_{i1} & \dots & N_{im} \\ \dots & \dots & \dots \\ N_{n1} & \dots & N_{nm} \end{bmatrix}$$

And matrix $\boldsymbol{P^x_w}$ is:

$$P^x_\omega = \begin{bmatrix} P^x_{11}\omega_{11} & \dots & P^x_{1m}\,\omega_{1n} \\ \dots & \dots & \dots \\ \dots & \dots & \dots \\ P^x_{m1}\omega_{m1} & \dots & P^x_{mn}\omega_{mn} \end{bmatrix}$$

Matrix ***w*** is:

$$w = \begin{bmatrix} \omega_{11} & \dots & \omega_{1n} \\ \dots & \dots & \dots \\ \dots & \dots & \dots \\ \omega_{m1} & \dots & \omega_{mn} \end{bmatrix}$$

Taking advantage of:

$$N(i,:) P_\omega N^T(:,j) = [N(i,:) \otimes N^T(:,j)] : P_\omega = C(r,:) P_{cv} \quad (4)$$

where $\boldsymbol{P_{cv}}$ is the column vector containing the control points (obtained proceeding row-wise) and ***C*(*r*, :)** is the row vector containing the elements of $\boldsymbol{N(i, :) \otimes N^T(:, j)}$. We can write the system:

$$P_r^{x,y,z} = C \cdot P_{cv}^{x,y,z} \quad (5)$$

where ***C*** is the matrix whose rows are ***C*(*r*, :)**. Finally, solving the rectangular system for ***B*** in the least square sense we obtain the components of the control points.

Dynamic isogeometric models

A framework of IGA (Bazilevs 2006) consists of five items and features. NURBS is very suitable for representing cardiac shapes because of its advantages of several characteristics. First of all, smooth and continuous; Secondly, flexible to represent both simple and complex shapes by some control points; Last but not the least, easy to be modified locally without changing the shape in a global way. Usually, there are three methods to modify the shape of NURBS: 1) Move control points; 2) Adjust weight factor; 3) Change the knot vector. In the case of the invariable of LV's knot vector, this paper adopts the first method of moving control points to modify the model, and presents a new dynamic model. The NURBS curve has the homogeneous coordinate representation (Au 1995):

$$C^h(u) = \sum_{i=0}^{n} N_{i,k}(u)\omega_i \begin{bmatrix} C(u) \\ 1 \end{bmatrix}$$

A change in the position of control point P_1 to $P_1{}'$, moves the curve point $\boldsymbol{C(u)}$ to $\boldsymbol{C'(u)}$, with:

$$C^h(u) = \sum_{i=0}^{n} N_{i,k}(u)\omega_i \begin{bmatrix} P_1 \\ 1 \end{bmatrix}$$

$$C'^h(u) = \sum_{i=0, i\neq j}^{n} N_{i,k}(u)\omega_i \begin{bmatrix} P_1 \\ 1 \end{bmatrix} + N_{j,k}(u)\omega_j \begin{bmatrix} P_1+\Delta P \\ 1 \end{bmatrix}.$$

Let $\triangle \boldsymbol{C^h(u)} = \boldsymbol{C'^h(u)} - \boldsymbol{C^h(u)}$, it follows that:

$$\Delta C^h(u) = N_{i,k}(u)\omega_i \begin{bmatrix} \Delta P \\ 0 \end{bmatrix}$$

So the NURBS curve definition gives:

$$\Delta C^h(u) = \sum_{i=0}^{n} N_{i,k}(u)\omega_i \begin{bmatrix} C'(u)-C(u) \\ 0 \end{bmatrix} \qquad (6)$$

Combining these together, the effect of changing a control point can be written as $\triangle \boldsymbol{C^h(u)}$. Similarly, we can conclude that the effect of changing a control point on a NURBS surface is

$$\Delta S(u,v) = \frac{\sum_{i=0}^{m}\sum_{j=0}^{n}\omega_{ij}P_{ij}N_{i,p}(u)N_{j,q}(v)}{\sum_{i=0}^{m}\sum_{j=0}^{n}\omega_{ij}N_{i,p}(u)N_{j,q}(v)} \begin{bmatrix} S'(u,v)-S(u,v) \\ 0 \end{bmatrix} \qquad (7)$$

ERROR ESTIMATION

In order to evaluate the LV model developed above, this paper puts forward a new error estimation method. The method will be more precise, it can optimize the model by adjusting the control points. Moreover, it is particularly applicable to estimate a dynamic model because of the characteristic of vector norm. If the model based on isogeometric simulation is called NURBS solid, the equation of the error can be drawn as:

Error=|NURBS solid-Target solid| (8)

The error from the above formula is just some 3-D coordinate points. However, only through these points can't we find the error intuitively. So, we adopt the vector norm to get an overall analysis of the error coefficient:

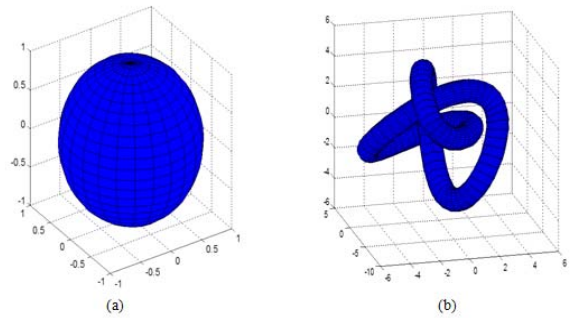
$$\varepsilon_x = \frac{\|X'-X\|_2}{\|X\|_2} \quad \varepsilon_y = \frac{\|Y'-Y\|_2}{\|Y\|_2} \quad \varepsilon_z = \frac{\|Z'-Z\|_2}{\|Z\|_2} \qquad (9)$$

in each direction. Where (***X'***, ***Y'***, ***Z'***) are the components of the NURBS solid and (***X***, ***Y***, ***Z***) are the components of the target solid. When $\varepsilon_x=\varepsilon_y=\varepsilon_z=0$, the error is zero along all three directions (ideal model), while ε_x, ε_y, $\varepsilon_z>0$, the error is proportional to the coefficient, i.s. a bigger coefficient makes a greater error.

DISCUSSION

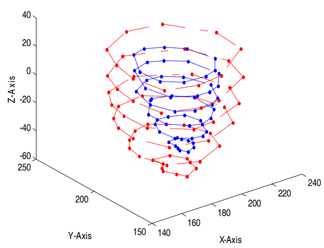
Experiments and results

Some models based on the method presented above could be built. The method could be not only used to simulate a static object, but also a dynamic one (Fig. 4).

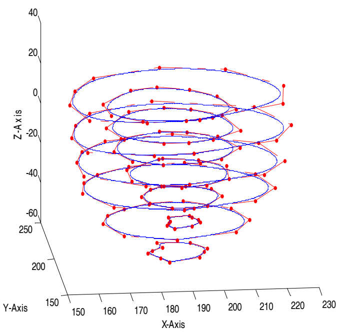


Figures 4: (a) A Static Model-balloon, (b) A Dynamic Model-Deformable Pipeline

So, it is convenient to build a dynamic LV model too. To begin with, the point cloud data can be obtained by manual segmentation. And then, according to the formula (5), we can calculate every 6×10 control points of the internal and external surface of the LV. At last, a three-dimensional control points figure is shown by MATLAB (Fig. 5).

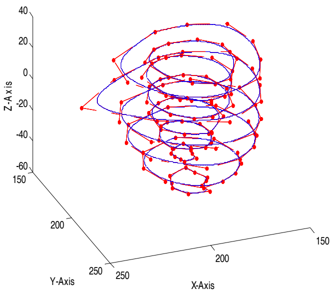


Figures 5: 6×10 Control Points of The Inner And Outer Surface of The LV



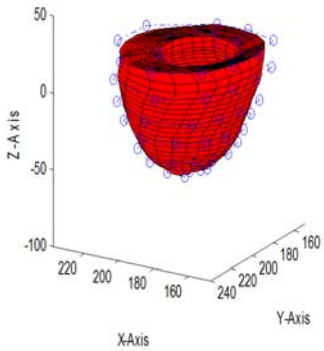
Figures 6: NURBS Curves of The LV

Some curves can be drawn by three order NURBS fitting according to the above control points. These NURBS curves can be used to simulate out the internal and external surface of the LV (see Fig. 6). Fig. 7 is a change of moving one control point, which manipulates the NURBS curve.



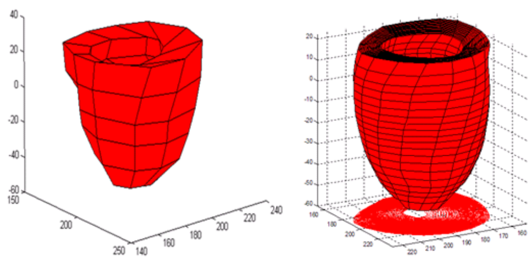
Figures 7: The Change by Moving A Control Point

In summary, a dynamic solid model of the LV based on isogeometric simulation is simulated by NURBS surface fitting (see Fig. 8).



Figures 8: A Solid Model of The LV With Control Points

Traditional finite element model (Jiang 2011), see Fig. 9 (a). The curvature of (a) and (b) (Fig. 10), Compared (a) with (b), (b) line of curvature is smoother than (a) line of curvatu-

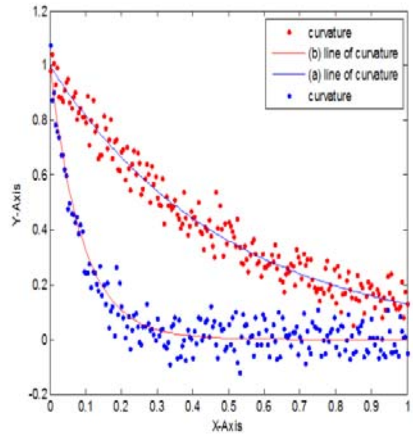


(a) (b)

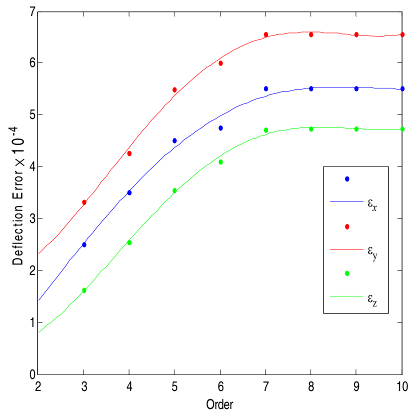
Figures 9: (a) A Traditional Hexahedral Solid Model of The LV Based on The FEA, (b) A Solid Model of The LV Based on The IGA

re expect of the interval [0, 0.1], in which the curvatures are outliers.

The error of the external surface of the LV can be calculated by formula (9), see Fig. 11. From Fig. 11, we can see that when we use the vector norm to test and analyze error, it is easy to decompose the error along



Figures 10: Curvature And Lines of Curvature



Figures 11: Error Curves of Deflection Error

each direction so that to make a reduction of the error by adjusting the control points conveniently. Moreover, the error will converge to a fixed value, which meets the characteristics of NURBS completely. From the view of fitting, this proves a feasibility of the error estimation.

Efficiency and accuracy

The proposed method is based on a NURBS-based isogeometric model, this methodology, encompassing a very general class of applications, is applied to problems of cardiac left Ventricle modeling and simulation. In addition, a set of procedures enabling the construction of analysis-suitable NURBS geometries directly from patient-specific imaging data is outlined.

The approach is compared with representative benchmark problems, yielding very good results. Here, we further test the efficiency and accuracy of this model. The efficiency is analyzed by both computation complexity and experimental results. However, practical experiments coincide well with the estimations.

For comparison with a few other results, Liu et al. (2000) established a three-dimensional finite element mechanical model of left ventricle. Curvature refers to any of a number of loosely related concepts in different areas of geometry. So, curvature is completely suitable for representing the smoothness of the curve. Compared (a) with (b) (Fig. 10), (a) line of curvature is smoother than (b) line of curvature. The linear change rate of (b) is lower than (a), it indicates that the model of the LV based on the IGA has a better robustness, smoothness, continuity, etc. The new approach is evaluated on two benchmark problems and applied to the cardiac left Ventricle. Very good results are obtained for the benchmark computations and the results for our patient-specific model in qualitative have a higher precision for a patient-specific model. This is because a NURBS curve can exactly represent most of common quadric surfaces or conic curves (Fig. 2). In fact, the error of this model comes from the Data Acquisition of LV's CT Images and the integration of formula (3). To estimate the precision in detail, some previous works on segmentation can be referred to Carneiro G. et al. (2012). From a lot of experiments, we may conclude that higher orders NURBS surfaces do not significantly increase the precision of results, but the computation complexity will increase with the higher order. Therefore, the 7×7 orders are suggested to be enough for practical implementation, it is in qualitative agreement with the results of the error estimation, in which 7×7 orders meet the convergence exactly.

CONCLUSION

Making a mechanical analysis to the traditional CAD models is a dream for the FEA scholars. After the IGA was introduced by Hughes et al., an idea was presented and implemented for generating a dynamic model of the LV based on isogeometric simulation, which was a preliminary work for a mechanical analysis to CAD models. Moving control points was a good method to trims the model in the case of the invariable of LV's weight factor. Owing to the inner advantages of NURBS in modeling, this model has a better accuracy, topology and continuity. Furthermore, a greater precision and efficient error estimation method was put forward in this paper. It adopted vector norm to get an overall analysis of the error coefficient in each direction, and avoided a complicated estimation for each knot. It could be not only used to evaluate the value of the error accurately, but also reduce the local error by adjusting the control points. Moreover, T-spline may be applied to further improve the accuracy of the model. A scheme to use T-spline for modeling will be described later.

REFERENCES

A. Young et al. 1995. "Tracking and finite element analysis of stripe deformation in magnetic resonance tagging." *IEEE Trans. Med. Imaging*, Vol. 14, No. 3, (Sep), 413–421.

C. K. Au and M. F. Yuen. 1995. "Yuen, Unified approach to NURBS curve shape modification, computer-aided design." Vol. 27, No. 2, 85-93.

Chao Jiang. 2011. "Reconstruction of Cardiac Dynamic Model and Stress Strain Analysis." Master, Zhejiang University of Technology.

Carneiro G. et al. 2012. "The Segmentation of the Left Ventricle of the Heart From Ultrasound Data Using Deep Learning Architectures and Derivative-Based Search Methods." *IEEE Transactions on Image Processing*, Volume: 21, Issue: 3, (March), 968 – 982.

Dulce M. C. et al. 1993. "Quantification of the left ventricular volumes and function with cine MR imaging: Comparison of geometric models with three-dimensional data." *Radiology*, 188(2): 371-376.

D. F. Rogers. 2001. "An Introduction to NURBS With Historical Perspective." *Academic Press*, *San Diego*, *CA*.

De Xin Li. et al. 2004. "Research on NURBS Curved Surface Weighted Factor and Its Application." *Journal of Xi'an University of Technolog*y, Vol. 20, No. 2.

Frangi A F. et a1. 2001. "Three dimensional modeling for functional analysis of cardiac Images: A review." *IEEE Transactions Medical Imaging*, 20 (1), 2-25.

Feng Liu. et a1. 2000. "The use of isoparametric transformation in three dimensional finite element mechanical model of human left ventricle." *BIOPHYSICA SINICA*, Vol.16, No.1 (Mar).

Guttman M A. et a1. 1997. "Analysis and visualization of cardiac function from MR images." *IEEE Computer Graphics and Application*, 17 (1), 30-38.

J.Verhaeghe. et a1. 2007. "Reconstruction for gated dynamic cardiac PET imaging using a tensor product spline basis." *IEEE Trans*. *Nucl. Sci*., Vol. 54, No. 1, (Feb), 80–91.

Johan Montagnat and Herve Delingette. 2005. "4D deformable models with temporal constraints: application to 4D cardiac image segmentation [J]." *Medical Image Analysis* , 9(1): 87-100.

J.A. Cottrell. et a1. 2005. "Isogeometric analysis of structural vibrations." *Computer Methods in Applied Mechanics and Engineering*, In press, Available as ICES Report 05-27, UT Austin.

K. Park. et a1. 2003. "A finite element model for functional analysis of 4D cardiac-tagged MR images." *Lect. Notes Comput*. *Sci*., vol. 2878, 491–498.

L. Piegl and W. Tiller. 1997. "The NURBS Book (Monographs in Visual Communication)." *2nd ed. Springer-Verlag*, New York.

Michel R. Labrosse. et a1. 2006. "Geometric modeling of functional trileaflet aortic valves: Development and clinical applications." *Journal of Biomechanics*, 2665–2672.

McInerney T. and Terzopoulos D. 1995. "A Dynamic finite element surface model for segmentation and tracking in multidimensional medical images with application to 4D image analysis [J]." *Computerized Medical Imaging and Graphics*, Jan, 19(1): 69–83.

Mitchell S.C. et al. 2009. "3-D active appearance models: segmentation of cardiac MR and Ultrasound images [J]." *IEEE transactions on medical imaging*, 21(9): 1167-1178.

Miao Miao Ru. 2012. "LV Modeling and Statistical Analysis of Parameters based on CT images." Master, Zhejiang University of Technology.

S. Y. Chen and Q. Guan. 2010. "Parametric Shape Representation by a Deformable NURBS Model for Cardiac Functional Measurements [J]." *IEEE Transactions on Biomedical Engineering*, X(Y):1-8.

T.J.R. Hughes. et al. 2005. "Isogeometric analysis Toward Integration of CAD and FEA."

T.J.R. Hughes. et al. 2005. "Isogeometric analysis: CAD, finite elements, NURBS, exact geometry, and mesh refinement." *Computer. Methods Appl. Mech. Engrg*, 194, 4135–4195.

T. J. R. Hughes. 2000. "The Finite Element Method: Linear Static and Dynamic Finite Element Analysis." *Dover Publications, Mineola*, NY.

Xiang Deng and Thomas S. Denney. 2004. "Three-dimensional myocardial strain reconstruction from tagged MRI using a cylindrical b-spline model [J]." *IEEE Transaction on Medical Imaging*, (July), 23(7): 861-867.

Y. Zheng. et al. 2008. "Four-chamber heart modeling and automatic segmentation for 3-D cardiac CT volumes using marginal space learning and steerable features." *IEEE Trans. Med. Imaging*, Vol. 27, No. 11, (Nov), 1668–1681.

Yong Jie Zhang. et al. 2007. "Patient-specific vascular NURBS modeling for isogeometric analysis of blood flow." *Computer methods in applied mechanics and engineering*, 196, 2943-2959.

Y. Bazilevs. et a1. 2006. "Isogeometric analysis: Approximation, stability and error estimates for h-refined meshes." *Mathematical Models and Methods in Applied Sciences*.

Y. Bazilevs. et a1. 2006. "Isogeometric fluid-structure interaction analysis with applications to arterial blood flow." *Mathematical Models and Methods in Applied Sciences*.

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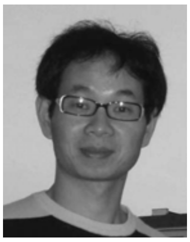

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