# Adaptive Control

# Adaptive Control

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# Preface

Adaptive control has been a remarkable field for industrial and academic research since 1950s. Since more and more adaptive algorithms are applied in various control applications, it is considered as important for practical implementation. As it can be confirmed from the increasing number of conferences and journals on adaptive control topics, it is certain that the adaptive control is a significant guidance for technology development.

Also adaptive control has been believed as a breakthrough for realization of intelligent control systems. Even with the parametric and model uncertainties, adaptive control enables the control system to monitor the time varying changes and manipulate the controller for desired performance. Therefore adaptive control has been considered to be essential for time varying multivariable systems. Moreover, now with the advent of high-speed microprocessors, it is possible to implement the innovative adaptive algorithms even in real time situation.

With the efforts of many control researchers, the adaptive control field is abundant in mathematical analysis, programming tools, and implementational algorithms. The authors of each chapter in this book are the professionals in their areas. The results in the book introduce their recent research results and provide new idea for improved performance in various control application problems.

The book is organized in the following way. There are 16 chapters discussing the issues of adaptive control application to model generation, adaptive estimation, output regulation and feedback, electrical drives, optical communication, neural estimator, simulation and implementation:

Chapter One: Automatic 3D Model Generation based on a Matching of Adaptive Control Points, by N. Lee, J. Lee, G. Kim, and H. Choi

Chapter Two: Adaptive Estimation and Control for Systems with Parametric and Nonparametric Uncertainties, by H. Ma and K. Lum

Chapter Three: Adaptive Output Regulation of Unknown Linear Systems with Unknown Exosystems, by I. Mizumoto and Z. Iwai

Chapter Four: Output Feedback Direct Adaptive Control for a Two-Link Flexible Robot Subject to Parameter Changes, by S. Ozcelik and E. Miranda

Chapter Five: Discrete Model Matching Adaptive Control for Potentially Inversely Non-Stable Continuous-Time Plants by Using Multirate Sampling, by S. Alonso-Quesada and M. De la Sen

Chapter Six: Hybrid Schemes for Adaptive Control Strategies, by R. Ribeiro and K. Queiroz

Chapter Seven: Adaptive Control for Systems with Randomly Missing Measurements in a Network Environment, by Y. Shi and H. Fang

Chapter Eight: Adaptive Control based on Neural Network, by S. Wei, Z. Lujin, Z. Jinhai, and M. Siyi

Chapter Nine: Adaptive Control of the Electrical Drives with the Elastic Coupling using Kalman Filter, by K. Szabat and T. Orlowska-Kowalska

Chapter Ten: Adaptive Control of Dynamic Systems with Sandwiched Hysteresis based on Neural Estimator, by Y. Tan, R. Dong, and X. Zhao

Chapter Eleven: High-Speed Adaptive Control Technique based on Steepest Descent Method for Adaptive Chromatic Dispersion Compensation in Optical Communications, by K. Tanizawa and A. Hirose

Chapter Twelve: Adaptive Control of Piezoelectric Actuators with Unknown Hysteresis, by W. Xie, J. Fu, H. Yao, and C. Su

Chapter Thirteen: On the Adaptive Tracking Control of 3-D Overhead Crane Systems

Chapter Fourteen: Adaptive Inverse Optimal Control of a Magnetic Levitation System, by Y. Satoh, H. Nakamura, H. Katayama, and H. Nishitani

Chapter Fifteen: Adaptive Precision Geolocation Algorithm with Multiple Model Uncertainties, by W. Sung and K. You

Chapter Sixteen: Adaptive Control for a Class of Non-affine Nonlinear Systems via Neural Networks, by Z. Tong

We expect that the readers have taken a basic course in automatic control, linear systems, and sampled data systems. This book is tried to be written in a self-contained way for better understanding. Since this book introduces the development and recent progress of the theory and application of adaptive control research, it is useful as a reference especially for industrial engineers, graduate students in advanced study, and the researchers who are related in adaptive control field such as electrical, aeronautical, and mechanical engineering.

**Kwanho You**

*Sungkyunkwan University, Korea*

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# 1

# Automatic 3D Model Generation based on a Matching of Adaptive Control Points

Na-Young Lee[1], Joong-Jae Lee[2], Gye-Young Kim[3] and Hyung-Il Choi[4]
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*[2]Center for Cognitive Robotics Research, Korea Institute of Sciene and Technology*
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## Abstract

The use of a 3D model helps to diagnosis and accurately locate a disease where it is neither available, nor can be exactly measured in a 2D image. Therefore, highly accurate software for a 3D model of vessel is required for an accurate diagnosis of patients. We have generated standard vessel because the shape of the arterial is different for each individual vessel, where the standard vessel can be adjusted to suit individual vessel. In this paper, we propose a new approach for an automatic 3D model generation based on a matching of adaptive control points. The proposed method is carried out in three steps. First, standard and individual vessels are acquired. The standard vessel is acquired by a 3D model projection, while the individual vessel of the first segmented vessel bifurcation is obtained. Second is matching the corresponding control points between the standard and individual vessels, where a set of control and corner points are automatically extracted using the Harris corner detector. If control points exist between corner points in an individual vessel, it is adaptively interpolated in the corresponding standard vessel which is proportional to the distance ratio. And then, the control points of corresponding individual vessel match with those control points of standard vessel. Finally, we apply warping on the standard vessel to suit the individual vessel using the TPS (Thin Plate Spline) interpolation function. For experiments, we used angiograms of various patients from a coronary angiography in Sanggye Paik Hospital.
Keywords: Coronary angiography, adaptive control point, standard vessel, individual vessel, vessel warping.

## 1. Introduction

X-ray angiography is the most frequently used imaging modality to diagnose coronary artery diseases and to assess their severity. Traditionally, this assessment is performed directly from the angiograms, and thus, can suffer from viewpoint orientation dependence and lack of precision of quantitative measures due to magnification factor uncertainty

(Messenger et al., 2000), (Lee et al., 2006) and (Lee et al., 2007). 3D model is provided to display the morphology of vessel malformations such as stenoses, arteriovenous malformations and aneurysms (Holger et al., 2005). Consequently, accurate software for a 3D model of a coronary tree is required for an accurate diagnosis of patients. It could lead to a fast diagnosis and make it more accurate in an ambiguous condition.
In this paper, we present an automatic 3D model generation based on a matching of adaptive control points. Fig. 1 shows the overall flow of the proposed method for the 3D modelling of the individual vessel. The proposed method is composed as the following three steps: image acquisition, matching of the adaptive control points and the vessel warping. In Section 2, the acquisitions of the input image in standard and individual vessels are described. Section 3 presents the matching of the corresponding control points between the standard and individual vessels. Section 4 describes the 3D modelling of the individual vessel which is performed through a vessel warping with the corresponding control points. Experimental results of the vessel transformation are given in Section 5. Finally, we present the conclusion in Section 6.

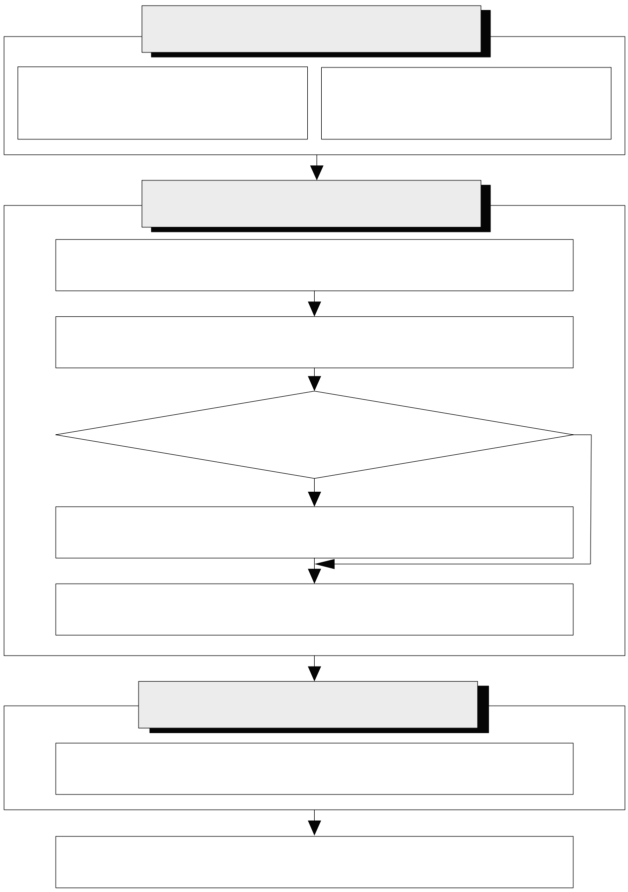


Fig. 1. Overall flow of the system configuration

## 2. Image Acquisition

We have generated a standard vessel because the shape of the arterial is different for each individual vessel, where the standard vessel can be adjusted to suit the individual vessel (Chalopin et al., 2001), (Lee et al., 2006) and (Lee et al., 2007). The proposed approach is based on a 3D model of standard vessel which is built from a database that implemented a Korean vascular system (Lee et al., 2006).
We have limited the scope of the main arteries for the 3D model of the standard vessel as depicted in Fig. 2.

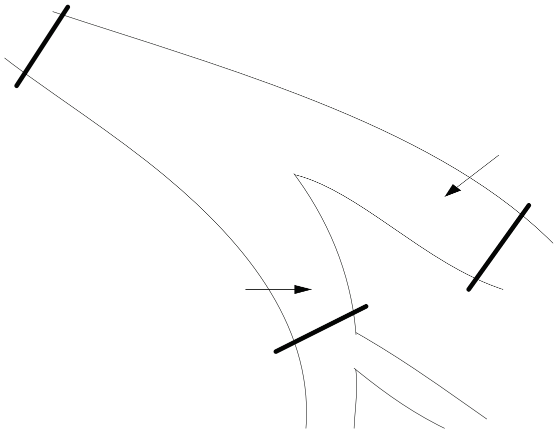


Fig. 2. Vessel scope of the database for the 3D model of the standard vessel

Table 1 shows the database of the coronary artery of Lt. main (Left Main Coronary Artery), LAD (Left Anterior Descending) and LCX (Left Circumflex artery) information. This database consists of 40 people with mixed gender information.

| | age | Lt. main | | | LAD | | | LCX | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Os | distal | length | Os | distal | length | Os | distal | length |
| below 60 years of old (male) | 48.4±5.9 | 4.3±0.4 | 4.1±0.5 | 9.9±4.2 | 3.8±0.4 | 3.6±0.4 | 17.0±5.2 | 3.5±0.4 | 3.3±0.3 | 19.2±6.1 |
| above 60 years of old (male) | 67.5±5.4 | 4.5±0.5 | 4.4±0.4 | 8.4±3.8 | 3.9±0.3 | 3.6±0.3 | 17.2±5.8 | 3.6±0.4 | 3.4±0.4 | 24.6±8.9 |
| below 60 years of old (female) | 44.9±19.9 | 3.7±1.8 | 3.4±1.6 | 10.6±6.2 | 3.3±1.5 | 3.1±1.4 | 14.1±5.5 | 2.9±1.3 | 2.8±1.2 | 21.3±9.2 |
| above 60 years of old (female) | 70.7± 4.4 | 4.3±0.7 | 4.1±0.6 | 12.5±7.9 | 3.5±0.6 | 3.4±0.5 | 22.3±7.3 | 3.3±0.4 | 3.1±0.3 | 27.5±3.7 |

Left Main
Coronary Arter

Table 1. Database of the coronary artery

To quantify the 3D model of the coronary artery, the angles of the vessel bifurcation are measured with references to LCX, Lt. main and LAD, as in Table 2. Ten individuals regardless of their gender and age were selected randomly for measuring the angles of the vessel bifurcation from six angiograms. The measurement results, and the average and standard deviations of each individual measurement are shown in Table 2.

| | RAO30° CAUD30° | RAO30° CRA30° | AP0° CRA30° | LAO60° CRA30° | LAO60° CAUD30° | AP0° CAUD30° |
|---|---|---|---|---|---|---|
| 1 | 69.17 | 123.31 | 38.64 | 61.32 | 84.01 | 50.98 |
| 2 | 53.58 | 72.02 | 23.80 | 51.75 | 99.73 | 73.92 |
| 3 | 77.28 | 97.70 | 21.20 | 57.72 | 100.71 | 71.33 |
| 4 | 94.12 | 24.67 | 22.38 | 81.99 | 75.6 | 69.57 |
| 5 | 64.12 | 33.25 | 31.24 | 40.97 | 135.00 | 61.87 |
| 6 | 55.34 | 51.27 | 41.8 | 80.89 | 119.84 | 57.14 |
| 7 | 71.93 | 79.32 | 50.92 | 87.72 | 114.71 | 58.22 |
| 8 | 67.70 | 59.14 | 31.84 | 58.93 | 92.36 | 70.16 |
| 9 | 85.98 | 60.85 | 35.77 | 54.45 | 118.80 | 78.93 |
| 10 | 47.39 | 60.26 | 34.50 | 47.39 | 67.52 | 34.79 |
| Average | 68.67 | 66.18 | 33.21 | 62.31 | 100.83 | 62.69 |
| Standard deviation | 14.56 | 29.07 | 9.32 | 15.86 | 21.46 | 13.06 |

Table 2. Measured angles of the vessel bifurcation from six angiographies

Fig. 3 illustrates the results of the 3D model generation of the standard vessel from six angiographies: RAO (Right Anterior Oblique)30° CAUD (Caudal)30°, RAO30° CRA (Cranial Anterior)30°, AP (Anterior Posterior)0° CRA (Cranial Anterior)30°, LAO (Left Anterior Oblique)60° CRA30°, LAO60° CAUD30°, AP0° CAUD30°.

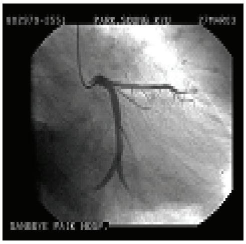
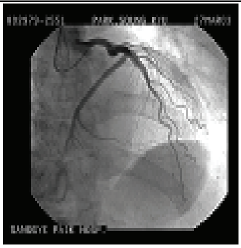
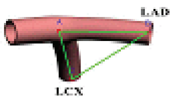
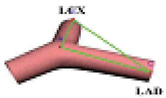
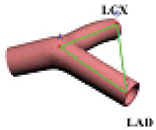
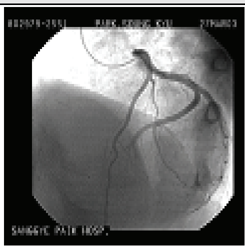
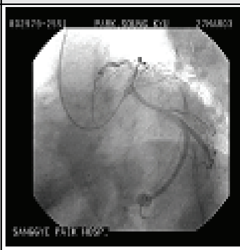
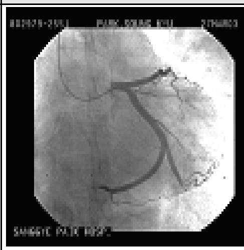
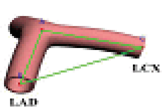
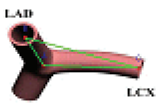
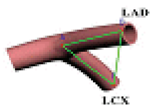
<table>
<tr><td>View</td><td>RAO30°<br>CAUD30°</td><td>RAO30°<br>CRA30°</td><td>AP0°<br>CRA30°</td></tr>
<tr><td>Angiogram</td><td></td><td></td><td></td></tr>
<tr><td>3D Model</td><td></td><td></td><td></td></tr>
<tr><td>View</td><td>LAO60°<br>CRA30°</td><td>LAO60°<br>CAUD30°</td><td>AP0°<br>CAUD30°</td></tr>
<tr><td>Angiogram</td><td></td><td></td><td></td></tr>
<tr><td>3D Model</td><td></td><td></td><td></td></tr>
</table>

Fig. 3. 3D model generation of the standard vessel from six angiographies

Evaluating the angles of the vessel bifurcation from six angiographies can reduce the possible measurement error which occurs when the angle from a single view is measured.

It is difficult to transform the standard vessel into individual vessel in a 3D space (Lee et al., 2006) and (Lee et al., 2007). Therefore, we projected the 3D model of the standard vessel into 2D projection. Fig. 4 shows the projected images of the standard vessel on a 2D plane through the projection. The projection result can be view as vertices or polygons based.

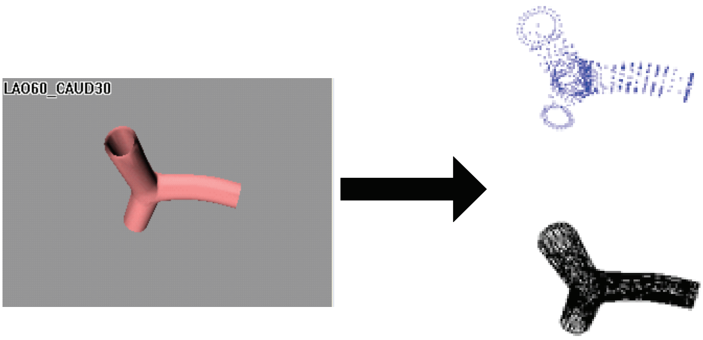



Fig. 4. Projection result for 2D image of standard vessel

### 3. Matching of the Adaptive Control Points

To transform a standard vessel into an individual vessel, it is important to match corresponding control points (Lee et al., 2006) and (Lee et al., 2007). In this paper, we extracted feature points of the vessel automatically and defined as control points (Lee et al., 2006) and (Lee et al., 2007). Feature points mean is referred to the corner points of an object or points with higher variance brightness compared to the surrounding pixels in an image, which are differentiated from other points in an image. Such feature points can be defined in many different ways in (Parker, 1996) and (Pitas, 2000). They are sometimes defined as points that have a high gradient in different directions, or as points that have properties that do not change in spite of specific transformations. Generally feature points can be divided into three categories (Cizek et al., 2004). The first one uses a non-linear filter, such as the SUSAN corner detector proposed by Smith (Woods et al., 1993) which relates each pixel to an area centered by a pixel. In this area, it is called the SUSAN area; all the pixels have similar intensities as the center pixel. If the center pixel is a feature point (some times a feature point is also referred to as a "corner"), SUSAN area is the smallest one among the pixels around it. A SUSAN corner detector can suppress a noise effectively without derivating an image. The second one is based on a curvature, such as the Kitchen and Rosenfeld's method (Maes et al., 1997). This kind of method needs to extract edges in advance, and then elucidate the feature points using the information on the curvature of the edges. The disadvantage of this method is required more needs a complicated computation, e.g. curve on fitting, thus its processing speed is relatively slow. The third method is exploits a change of the pixel intensity. A typical one is the Harris and Stephens' method (Pluim et al., 2003). It produces a corner response through an eigenvalues analysis. Since it does not need to use a slide window explicitly, its processing speed is very fast. Accordingly, this paper used the Harris corner detector to find the control points of standard and individual vessels (Lee et al., 2006) and (Lee, 2007).

### 3.1 Extraction of the Control Points

The Harris corner detector is a popular interest point detector due to its strong invariance such as rotation, scale, illumination variation and image noise (Schmid et al., 2000) and (Derpanis, 2004). It is based on the local auto-correlation function of a signal. The local auto-correlation function measures the local changes of the signal with patches shifted by a small amount in different directions (Derpanis, 2004). However, the Harris corner detector has a problem where it can mistake those non-corner points.
Fig. 5 shows extracted 9 control points in individual vessel by using the Harris corner detector. We noticed that some of the extracted control points are non-corner points. To solve this problem of the Harris corner detector, we extracted more control points of individual vessel than standard vessel. Fig. 6 shows the extraction of control points from individual and standard vessels.

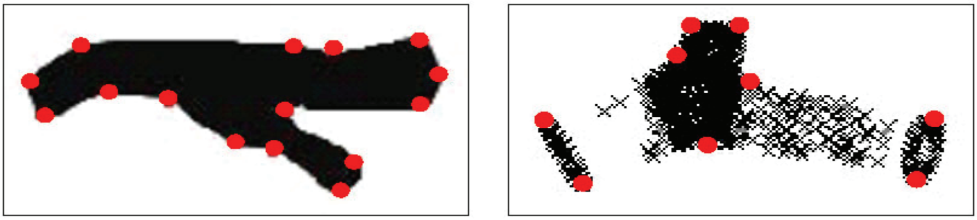
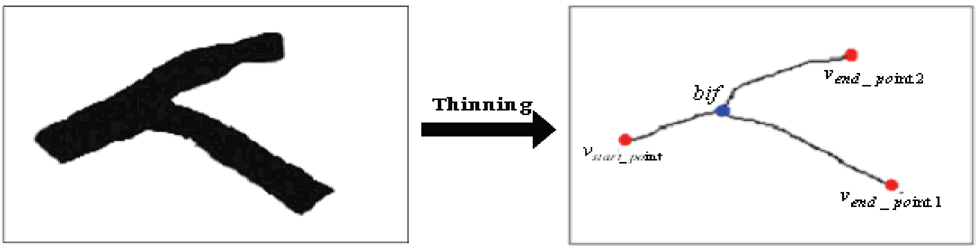


Fig. 5. Extracted 9 control points in individual vessel

### 3.2 Extraction of Corner Points

We performed thinning by using the structural characteristics of vessel to find the corner points among the control points of individual vessel which is extracted with the Harris corner detector (Lee, 2007). Fig. 7 shows the thinning process for detection of corner points in individual vessel.




(a) Segmented vessel (b) Thinned vessel

Fig. 6. Thinning process for detection of corner points in individual vessel

A vascular tree can be divided into a set of elementary components, or primitives, which are the vascular segments, and bifurcation (Wahle et al., 1994). Using this intuitive

representation, it is natural to describe the coronary tree by a graph structure (Chalopin et al., 2001) and (Lee, 2007).
A vascular tree of thinned vessel consists of three vertices ( $v_{point}$ ) and one bifurcation ( $bif$ ) as the following equation (1). Here, vertices ( $v_{point}$ ) are comprised a start point ( $v_{start\_point}$ ) and two end points ( $v_{end\_point1}, v_{end\_point2}$ ).

$$I_{thin} = \{ v_{point}, bif \}$$
$$v_{point} = \{ v_{start\_point}, v_{end\_point1}, v_{end\_point2} \} \tag{1}$$

If the reference point is a vertex, the closest two control points to the vertex are defined as the corner points. If the reference point is a bifurcation, the three control points that are closest to it after comparing the distances between the bifurcation and all control points are defined as the corner points. As shown in Fig. 7, if the reference point is the vertex ( $v_{start\_point}$ ), $v_1$ and $v_2$ become the corner points; if the reference point is the bifurcation ( $bif$ ), $v_6, v_{11}$ and $v_{15}$ become the corner points (Lee, 2007).

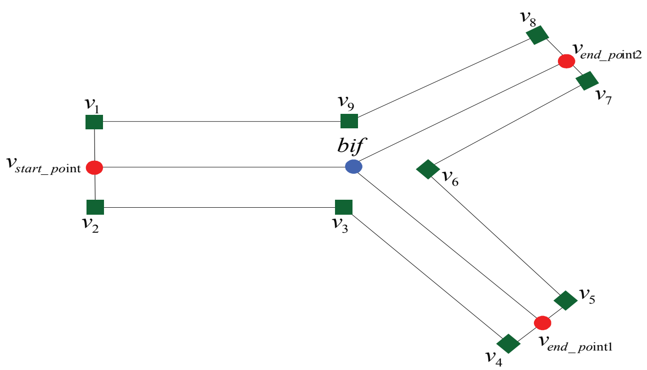
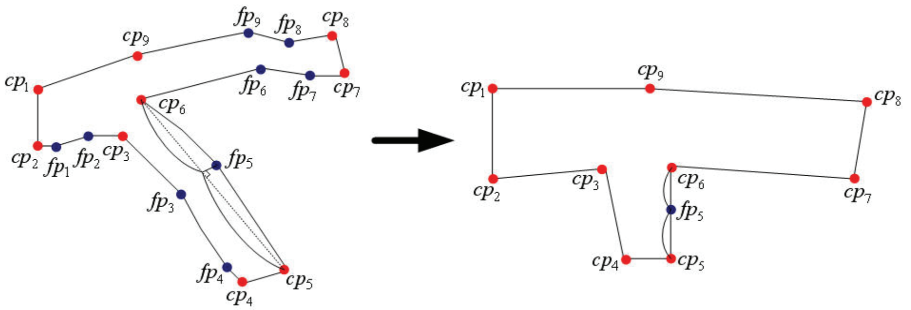



Fig. 7. Primitives of a vascular net

### 3.3 Adaptive Interpolation of the Control Points between Corner Points

Once the control points and corner points are extracted from an individual vessel, an interpolation for a standard vessel is applied. For an accurate matching, the control points are adaptively interpolated into the corresponding standard vessel in proportion to the distance ratio if there are control points between the corner points in an individual vessel (Lee, 2007).
Fig. 8 shows the process of an interpolation of the control points. Control points of a standard vessel are adaptively interpolated by the distance rate between control point ( $v_3$ ) and two corner points ( $v_2, v_4$ ) of an individual vessel. Fig. 8 (a) shows the extracted control

points from an individual vessel, and (b) shows an example of control point interpolated between a standard vessel and the corresponding corner points from (a) image.




(a) Individual vessel (b) Standard vessel

Fig. 8. Interpolation of the control points for a standard vessel

Fig. 9 shows the result of extracting the control points by using the Harris corner detector to the segmented vessel in the individual vessel and an adaptive interpolation of the corresponding the control points in the standard vessel.

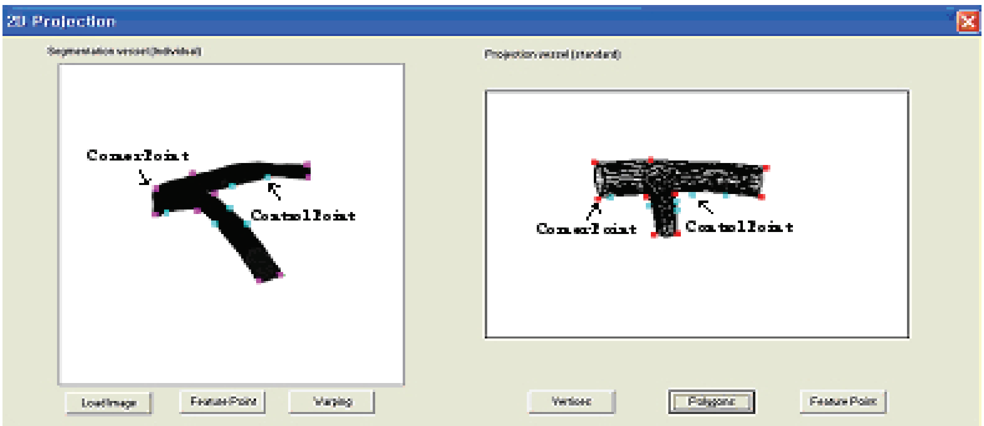



Fig. 9. Result of an adaptive interpolation of the corresponding control points

## 4. Vessel Warping

We have warped the standard vessel with respect to the individual vessel. Given the two sets of corresponding control points, $S = \{s_1, s_2, \ldots s_m\}$ and $I = \{i_1, i_2, \ldots i_m\}$, the warping is applied the standard vessel to suit the individual vessel. Here, $S$ is a set of control points in the standard vessel and $I$ is a set of one in the individual vessel (Lee et al., 2006) and (Lee et al., 2007).