Experimental Approach for the Estimation of Cardiac Output of Left Ventricular Assist Device Using Multi-dimensional Interpolation Technique

*K. S. Om, *W. W. Choi, J. M. An†, S. K. Park†, Y. H. Jo†, *J. S. Choi,
*J. J. Lee, H. C. Kim†, B. G. Min†

*Dept. of Biomedical Engineering, College of Engineering, Seoul National University
†Dept. of Biomedical Engineering, College of medicine, Seoul National University

ABSTRACT

Cadiac output estimation scheme of LVAD using multi-dimensional interpolation technique was introduced in this paper. This paper also show appropriate input-output data for estimation. Experimental results show our approach is a good one for the estimation of nonlinear hemodynamics.

Introduction

Automatic Cardiac Output (*CO*) control scheme is one of important goal in·the study of artificial heart [1]. The first step is to find the nonlinear function of *CO* ($x1$, $x2$, $\cdots$ xn). There have been much researches to find the nonlinear hemodynamics, but the results are not so satisfactory when they were employed in real situations [2][3].

So, many researchers seek to find the nonlinear hemodynamics from other scheme such as Neural Network (NN) and so on. When we use NN, it is necessary to get input-output data sufficiently from real situations, and there remain problems to find appropriate NN. In this paper, we developed multi-dimensional interpolation technique to estimate cardiac output and appropriate input-output data table (Look-Up Table, LUT) [4]. We tested our method at Left Ventricular Assist Device (LVAD) which was developed at Seoul National University. Test results show our approach is practically good method.

LVAD

Usually, the output of LVAD is said to be 'Assist Output (*AO*)' rather than cardiac output. From now, we use the Assist Output (*AO*) as a terminology.

In the LVAD which was developed at Seoul National University, the *AO* depends on 5 variables as Eq. (1).

$$AO = f(SV, DV, SL, LAP, AoP) \qquad (1)$$

where SV : Stroke Velocity
DV : Diastolic Velocity
SL : Stroke Length
LAP : Left Atrium Pressure
AoP : Aortic Pressure

The LVAD is being enhanced by modifying valve, sac volume, housing, and using magnet, and so on. So development of model each time is time-exhausting one and it does not produce satisfactory estimate at real situations as stated before.

Multi-dimensional Interpolation Technique

There are two aspect to enhance the estimate of interpolation scheme. One is to get small interval of LUT, and the other is to use complex interpolation algorithm. In this paper, we consider the simplest LUT - each variable consists of large, middle, and small, and 5-dimensional linear interpolation.

If the input variables are $x1[]$, $x2[]$, $x3[]$, $x4[]$, and $x5[]$, the output function $y(x1, x2, x3, x4, x5)$ is

$$
\begin{aligned}
&y_a[i][j][m][n][r] \\
&= y(x_{1a}[i], x_{2a}[j], x_{3a}[m], x_{4a}[n], x_{5a}[r])
\end{aligned}
\tag{2}
$$

The goal is to estimate, by interpolation, the function y at some untabulated point $(x1, x2, x3, x4, x5)$.

If

$$
\begin{cases}
x_{1a}[\,i\,] \le x_1 \le x_{1a}[\,i+1\,] \\
x_{2a}[\,j\,] \le x_2 \le x_{2a}[\,j+1\,] \\
x_{3a}[\,m\,] \le x_3 \le x_{3a}[\,m+1\,] \\
x_{4a}[\,n\,] \le x_4 \le x_{4a}[\,n+1\,] \\
x_{5a}[\,r\,] \le x_5 \le x_{5a}[\,r+1\,]
\end{cases}
\tag{3}
$$

the grid points are

$$
\begin{aligned}
y_1 &= y_a[i][j][m][n][r] \\
y_2 &= y_a[i][j][m][n][r+1] \\
y_3 &= y_a[i][j][m][n+1][r] \\
y_4 &= y_a[i][j][m][n+1][r+1] \\
y_5 &= y_a[i][j][m+1][n][r] \\
y_6 &= y_a[i][j][m+1][n][r+1] \\
y_7 &= y_a[i][j][m+1][n+1][r] \\
y_8 &= y_a[i][j][m+1][n+1][r+1] \\[1ex]
y_9 &= y_a[i][j+1][m][n][r] \\
y_{10} &= y_a[i][j+1][m][n][r+1] \\
y_{11} &= y_a[i][j+1][m][n+1][r] \\
y_{12} &= y_a[i][j+1][m][n+1][r+1] \\
y_{13} &= y_a[i][j+1][m+1][n][r] \\
y_{14} &= y_a[i][j+1][m+1][n][r+1] \\
y_{15} &= y_a[i][j+1][m+1][n+1][r] \\
y_{16} &= y_a[i][j+1][m+1][n+1][r+1] \\[1ex]
y_{17} &= y_a[i+1][j][m][n][r] \\
y_{18} &= y_a[i+1][j][m][n][r+1] \\
y_{19} &= y_a[i+1][j][m][n+1][r] \\
y_{20} &= y_a[i+1][j][m][n+1][r+1] \\
y_{21} &= y_a[i+1][j][m+1][n][r] \\
y_{22} &= y_a[i+1][j][m+1][n][r+1] \\
y_{23} &= y_a[i+1][j][m+1][n+1][r] \\
y_{24} &= y_a[i+1][j][m+1][n+1][r+1] \\[1ex]
y_{25} &= y_a[i+1][j+1][m][n][r] \\
y_{26} &= y_a[i+1][j+1][m][n][r+1] \\
y_{27} &= y_a[i+1][j+1][m][n+1][r] \\
y_{28} &= y_a[i+1][j+1][m][n+1][r+1] \\
y_{29} &= y_a[i+1][j+1][m+1][n][r] \\
y_{30} &= y_a[i+1][j+1][m+1][n][r+1] \\
y_{31} &= y_a[i+1][j+1][m+1][n+1][r] \\
y_{32} &= y_a[i+1][j+1][m+1][n+1][r+1]
\end{aligned}
\tag{4}
$$

The simplest linear interpolations are

$$
\begin{aligned}
f &= \frac{x_1 - x_{1a}[i]}{x_{1a}[i+1] - x_{1a}[i]} \\
g &= \frac{x_2 - x_{2a}[j]}{x_{2a}[j+1] - x_{2a}[j]} \\
u &= \frac{x_3 - x_{3a}[m]}{x_{3a}[m+1] - x_{3a}[m]} \\
v &= \frac{x_4 - x_{4a}[n]}{x_{4a}[n+1] - x_{4a}[n]} \\
w &= \frac{x_5 - x_{5a}[r]}{x_{5a}[r+1] - x_{5a}[r]}
\end{aligned}
\tag{5}
$$

(f, g, u, v, and w each lie between 0 and 1)

then the estimated value is

$$
\begin{aligned}
y(x_1, x_2, x_3, x_4, x_5) = {}& \\
&(1-f)(1-g)(1-u)(1-v)(1-w)y_1 \\
+&(1-f)(1-g)(1-u)(1-v)(w)y_2 \\
+&(1-f)(1-g)(1-u)(v)(1-w)y_3 \\
+&(1-f)(1-g)(1-u)(v)(w)y_4 \\
+&(1-f)(1-g)(u)(1-v)(1-w)y_5 \\
+&(1-f)(1-g)(u)(1-v)(w)y_6 \\
+&(1-f)(1-g)(u)(v)(1-w)y_7 \\
+&(1-f)(1-g)(u)(v)(w)y_8 \\
+&(1-f)(g)(1-u)(1-v)(1-w)y_9 \\
+&(1-f)(g)(1-u)(1-v)(w)y_{10} \\
+&(1-f)(g)(1-u)(v)(1-w)y_{11} \\
+&(1-f)(g)(1-u)(v)(w)y_{12} \\
+&(1-f)(g)(u)(1-v)(1-w)y_{13} \\
+&(1-f)(g)(u)(1-v)(w)y_{14} \\
+&(1-f)(g)(u)(v)(1-w)y_{15} \\
+&(1-f)(g)(u)(v)(w)y_{16} \\[1ex]
+&(f)(1-g)(1-u)(1-v)(1-w)y_{17} \\
+&(f)(1-g)(1-u)(1-v)(w)y_{18} \\
+&(f)(1-g)(1-u)(v)(1-w)y_{19} \\
+&(f)(1-g)(1-u)(v)(w)y_{20} \\
+&(f)(1-g)(u)(1-v)(1-w)y_{21} \\
+&(f)(1-g)(u)(1-v)(w)y_{22} \\
+&(f)(1-g)(u)(v)(1-w)y_{23} \\
+&(f)(1-g)(u)(v)(w)y_{24} \\
+&(f)(g)(1-u)(1-v)(1-w)y_{25} \\
+&(f)(g)(1-u)(1-v)(w)y_{26} \\
+&(f)(g)(1-u)(v)(1-w)y_{27} \\
+&(f)(g)(1-u)(v)(w)y_{28} \\
+&(f)(g)(u)(1-v)(1-w)y_{29} \\
+&(f)(g)(u)(1-v)(w)y_{30} \\
+&(f)(g)(u)(v)(1-w)y_{31} \\
+&(f)(g)(u)(v)(w)y_{32}
\end{aligned}
\tag{6}
$$

Experiments

We matched $x1$, $x2$, $x3$, $x4$, $x5$ to SV, DV, SL, LAP, AoP. And each has 3 or 2 cell values as follows.

SV : 10, 20, 30,
DV : 10, 20, 30,
SL : 4000, 5000, 6000,
LAP: 3, 10,
AoP: 50, 100, 150 [mmHg].

Here, as high LAP (ex : 20 [mmHg]) does not influence at AO, we considered only small (3) and middle (10) LAP. Then the possible case number is 3 × 3 × 3 × 3 × 2 = 162.

The performance of our approach can be verified by comparing the experimental value and estimated value which has the high probabilities of estimation error. These points lie between the cell value, and have 2 × 2 × 2 × 2 × 1 = 16 cases.

The results are in table 1. If we get the AO data from flow meter, the value change ± 0.1 ~ 0.2 [l / min]. So, we can say that this results have high precision.

Table 1. Test results [l / min]

SV	DV	SL	AoP	LAP	AO (Assist Output)	
					experiment	estimation
17	17	5000	80	6	2.70	2.58
17	23	〃	〃	〃	2.80	2.37
23	17	〃	〃	〃	2.90	2.94
23	23	〃	〃	〃	2.65	2.44
17	17	5600	〃	〃	2.80	2.75
17	23	〃	〃	〃	2.85	2.85
23	17	〃	〃	〃	3.45	3.40
23	23	〃	〃	〃	3.35	3.42
17	17	5000	120	〃	2.20	2.20
17	23	〃	〃	〃	1.95	2.01
23	17	〃	〃	〃	2.30	2.53
23	23	〃	〃	〃	1.70	2.14
17	17	5600	〃	〃	2.40	2.46
17	23	〃	〃	〃	2.50	2.51
23	17	〃	〃	〃	3.15	3.15
23	23	〃	〃	〃	3.10	3.16

Conclusions

In this paper, we developed AO estimation scheme of LVAD. We considered simple LUT and multi-dimensional linear interpolation technique, and verified high performance by experiment. As LUT consists of small cells, it does not require high memory. Considering this point, we think this approach is better than NN, because NN requires much input-output data and there remained other problem of selecting appropriate NN. Our research results can be extended to other problem of nonlinear hemodynamics estimation, optimal path finding problem using dynamic programming technique or generic algorithm, fuzzy control using large, middle, and small LUT data as a membership function of fuzzy inference and defuzzification [5].

REFERENCES

[1] Y. H. Jo, et all, "A Study of Interventricular Volume Pressure in a Totally Implantable Electromechanical Artificial Heart," *KOSOMBE Fall Conference*, pp. 222-226. 1995.

[2] J. F. Gardner, et all, "Aortic Pressure Estimation with Electro-Mechanical Circulatory Assist Devices," *J. of Electromechanical Engineering*. vol. 115. pp. 187-194, 1993.

[3] U. Tasch, J. W. Koontz, M. A. Ignatoski, D. B. Geselowitz, "An Adaptive Aortic Pressure Observer for the Penn State Electric Ventricular Assist Device," *IEEE Trans. Biomedical Engineering*, vol. 37, pp. 374-383, April. 1990.

[4] W. H. Press, *Numerical Recipes in C*, Cambridge university press, 1992.

[5] J. S. Choi, et all, "Development of an Algorithm for Regulation of Inlet Blood Flow in Electrohydraulic Left Ventricular Assist Device," *KOSOMBE Fall Conference*, pp. 211-215. 1995.