LINEAR INTERPOLATION OF FOUR-DIMENSIONAL TABULATED DATA FOR COMPUTERS WITH SINGLE SUBSCRIPTED VARIABLE CAPABILITY

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Preliminary Design Office

November 19, 1971

NASA

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama
**Title and Subtitle**
Linear Interpolation of Four-Dimensional Tabulated Data For Computers with Single Subscripted Variable Capability

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**Abstract**
Using only a one-dimensional subscripted variable, a Fortran computer subprogram was developed to linearly interpolate tabulated data of functions of four or less variables, the primary motivation being faster computation.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>MATHEMATICAL MODEL</td>
<td>1</td>
</tr>
<tr>
<td>METHOD OF LINEAR INTERPOLATION FOR</td>
<td></td>
</tr>
<tr>
<td>FOUR DIMENSIONS</td>
<td>4</td>
</tr>
<tr>
<td>METHOD OF LINEAR INTERPOLATION IN FEWER THAN FOUR DIMENSIONS</td>
<td>5</td>
</tr>
<tr>
<td>COMPUTER SUBPROGRAM</td>
<td>7</td>
</tr>
<tr>
<td>APPENDIX A: FOUR-DIMENSIONAL LINEAR INTERPOLATION SUBPROGRAM FOR</td>
<td></td>
</tr>
<tr>
<td>COMPUTERS WITH SINGLE SUBSCRIPTED VARIABLE CAPABILITY</td>
<td>9</td>
</tr>
<tr>
<td>APPENDIX B: FOUR-DIMENSIONAL LINEAR INTERPOLATION SUBPROGRAM FOR</td>
<td></td>
</tr>
<tr>
<td>COMPUTERS WITH DOUBLE SUBSCRIPTED VARIABLE CAPABILITY</td>
<td>15</td>
</tr>
</tbody>
</table>

# LIST OF ILLUSTRATIONS

<table>
<thead>
<tr>
<th>Figure</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Four-dimensional (3 × 3 × 3 × 3) array mapped into a one-dimensional array</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>Schematic of four-dimensional interpolation</td>
<td>6</td>
</tr>
</tbody>
</table>
### DEFINITION OF SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>I, J, K, L</td>
<td>Number of elements in X, Y, Z, W arrays, respectively</td>
</tr>
<tr>
<td>II, JJ, KK, LL</td>
<td>Indices of X, Y, Z, W values just less than XS, YS, ZS, WS, respectively</td>
</tr>
<tr>
<td>I₁, I₂, I₃, I₄</td>
<td>Subscripts of Q for W dimension interpolation</td>
</tr>
<tr>
<td>I'₁, I'₂, I'₃, I'₄</td>
<td>Subscripts of Q for W dimension interpolation</td>
</tr>
<tr>
<td>N</td>
<td>Number of elements in one-dimensional Q array</td>
</tr>
<tr>
<td>Q</td>
<td>One-dimensional dependent variable array</td>
</tr>
<tr>
<td>T₁, T₂, S₁, S₂</td>
<td>Values for Z dimension interpolation</td>
</tr>
<tr>
<td>T'₁, T'₂, S'₁, S'₂</td>
<td>Values for Z dimension interpolation</td>
</tr>
<tr>
<td>U₁, U₂, U'₁, U'₂</td>
<td>Values for Y dimension interpolation</td>
</tr>
<tr>
<td>V₁, V₂</td>
<td>Values for X dimension interpolation</td>
</tr>
<tr>
<td>X, Y, Z, W</td>
<td>One-dimensional independent variable arrays</td>
</tr>
<tr>
<td>XS, YS, ZS, WS</td>
<td>Coordinates of point for which Q is to be evaluated</td>
</tr>
</tbody>
</table>
LINEAR INTERPOLATION OF FOUR-DIMENSIONAL
TABULATED DATA FOR COMPUTERS WITH SINGLE
SUBSCRIPTED VARIABLE CAPABILITY

INTRODUCTION

At present several numerical methods exist for interpolation of tabulated data of functions of several variables, notable of which are the Gregory-Newton, Gauss, and Lagrangian. These methods depend, however, upon the calculation of finite differences or coefficients to fitted polynomials. If the tabulated data are approximately linear, the above methods are very accurate but the computation time involved is excessive, especially for digital computer applications. Linear interpolation has approximately the same accuracy but with much less computation time.

With the purpose of faster computation, a Fortran digital computer subprogram was developed to linearly interpolate tabulated data of four or fewer dimensions. As a test of the program's proficiency and accuracy, it was used to interpolate approximately linear aerodynamic data which were tabulated as a function of four variables. The results of the linear interpolations were compared with those of Lagrangian interpolations of the same data. The answers varied only in the fourth decimal place; however, the linear routine extracted approximately 1000 values in the time it took the Lagrangian routine to extract 400 values. The slight inaccuracy of the linear method was offset by its inherent speed.

MATHEMATICAL MODEL

The first step in establishing a mathematical model for the linear interpolation of a function Q of the four independent variables X, Y, Z, and W in tabulated form would be to express Q as a subscripted variable of the fourth dimension:

\[ Q = Q(X(I), Y(J), Z(K), W(L)) \]  

(1)

with a single subscripted variable for each of the independent variables, where I, J, K, and L are the number of elements in each array, respectively.
Linear interpolation could then be accomplished easily by finding the location of the desired point \(Q(XS, YS, ZS, WS)\) from the independent variable arrays. This method is fine for large computers, but it fails for many smaller machines which allow a maximum of only three subscripts. To permit utilization of the method on any computer with one-dimensional subscripted variable capability, the four-dimensional \(Q\) array may be mapped into a one-dimensional array \(Q^* (N)\) (the * notation will be dropped for brevity in the following discussion).

The mapping is as follows, selecting a \((3 \times 3 \times 3 \times 3)\) array as an example:

\[
\begin{align*}
Q(1) &= Q(1, 1, 1, 1) \\
Q(2) &= Q(1, 1, 1, 2) \\
Q(3) &= Q(1, 1, 1, 3) \\
Q(4) &= Q(1, 1, 2, 1) \\
Q(5) &= Q(1, 1, 2, 2) \\
Q(6) &= Q(1, 1, 2, 3) \\
Q(7) &= Q(1, 1, 3, 1) \\
Q(8) &= Q(1, 1, 3, 2) \\
Q(9) &= Q(1, 1, 3, 3) \\
Q(10) &= Q(1, 2, 1, 1) \\
Q(11) &= Q(1, 2, 1, 2) \\
&\quad \vdots \\
Q(N') &= Q(I', J', K', L')
\end{align*}
\]

\[
N' = (I' - 1) \cdot J \cdot K \cdot L + (J' - 1) \cdot K \cdot L + (K' - 1) \cdot L + L'.
\]
For the \((3 \times 3 \times 3 \times 3)\) example there will be \(I \cdot J \cdot K \cdot L\) or 81 elements in the Q(N) array. Figure 1 depicts the complete mapping for the \((3 \times 3 \times 3 \times 3)\) example. However, because of the form of certain mapping equations [see equations (5)], the number of elements in Q must be increased by \(L \cdot (K + 1) + 1\). These added terms are for working storage, and their values must be initially zero. Therefore, the number of elements in Q must be

\[
N = I \cdot J \cdot K \cdot L + L \cdot (K + 1) + 1.
\]  

(4)

Figure 1. Four-dimensional \((3 \times 3 \times 3 \times 3)\) array mapped into a one-dimensional array.
Associated with the one-dimensional Q array will still be a one-dimensional array for each of the independent variables X, Y, Z, and W. These arrays contain the data points along the respective independent variable ranges, e.g., X may vary from 10 to 100 in increments of 10, thus giving 10 values for the X array. The elements of these arrays must be in nondecreasing order.

**METHOD OF LINEAR INTERPOLATION FOR FOUR DIMENSIONS**

After the dependent and independent variable arrays have been established, the dependent variable Q may be determined for a given point with independent variables (XS, YS, ZS, WS) by linear interpolation.

Initially, the location of the point's independent variable coordinates within the respective independent variable arrays must be ascertained. For example, XS obviously lies between some X(II) and X(II + 1); also YS lies between some Y(JJ) and Y(JJ + 1), etc. The indices of prime interest are II, JJ, KK, and LL. If any of the point's coordinates happen to coincide with the last entry in the respective array, that corresponding index is equated to the array dimension, e.g., II = I. Also, if any of the point's coordinates lie outside the range of their respective arrays, these variables are assumed to be the endpoints.

Again, referring to the (3 x 3 x 3 x 3) array in Figure 1, the linear interpolation method may be illustrated with sample values for (II, JJ, KK, LL) of (1, 2, 1, 2). These known indices facilitate the determination of the appropriate values of Q, which must be interpolated in each of the four dimensions. As noted in Figure 1, these particular elements of the Q array are subscripted I₁, I₂, I₃, I₄, I₁', I₂', I₃', I₄', and are obtained from the following mapping equations:

\[
I_1 = (II - 1) \cdot J \cdot K \cdot L + (JJ - 1) \cdot K \cdot L + (KK - 1) \cdot L + LL
\]

\[
I_2 = I_1 + L
\]

\[
I_3 = I_1 + K \cdot L
\]

\[
I_4 = I_3 + L
\]

(5)
The primed subscripts are obtained by adding $J \cdot K \cdot L$ to the preceding unprimed subscripts, respectively. The equation for $I_4$ forces the $Q$ storage requirement increase referred to above.

A schematic of the necessary linear interpolations in each of the four dimensions is shown in Figure 2. Interpolation of the aforementioned subscripted elements of $Q$ in the $W$ dimension yields the values $T_1, T'_2, S_1, T'_1, T'_2, S'_1, S'_2$. These values are then interpolated in the $Z$ dimension to produce $U_1, U_2, U'_1, U'_2$, which are interpolated to obtain $V_1$ and $V_2$ in the $Y$ dimension. $Q(XS, YS, ZS, WS)$ is then obtained from the $X$ dimension interpolation of $V_1$ and $V_2$. The linear interpolations are of the form

$$Q = V_1 + \frac{XS - X(I I)}{X(I I + 1) - X(I I)} \cdot V_2 \tag{6}$$

The required value of $Q$ is thus easily obtained once the appropriate $Q$ subscripts are known.

**METHOD OF LINEAR INTERPOLATION IN FEWER THAN FOUR DIMENSIONS**

The previous equations pertaining to linear interpolation of four-dimensional tabulated data may also be used with 1, 2, or 3 dimensions. The only necessary requirements for three dimensions are that $L$ and $LL$ be equated to one, $W(1)$ be equated to zero, and $W(2)$ be equated to a positive real number.

In two dimensions the three-dimensional requirements must be met in addition to similar requirements on the $Z$ dimension parameters: $K = 1, KK = 1, Z(1) = 0$, and $Z(2) > 0$, with additional simplifications:

$$I_3 = I_1 \tag{7}$$

$$I_4 = I_2$$

For one dimension the two-dimensional requirements must be met plus similar requirements on the $Y$ parameters: $J = 1, JJ = 1, Y(1) = 0, Y(2) > 0$. There is no need now for the primed indices on $Q$ since the interpolation equations need hold for only the unprimed indices.
Figure 2. Schematic of four-dimensional interpolation.
COMPUTER SUBPROGRAM

Two Fortran computer subprograms were written for linear interpolation of tabulated data of four or fewer dimensions. Listings of these routines are given in Appendix A and B. The routine referred to in Appendix A requires no more than single-subscript capability, whereas that in Appendix B requires double-subscript capability. The computer word storage allocations for the respective routines are Routine A, 727, and Routine B, 718. Routine B is preferred because of its smaller storage allocation and slightly faster computation time. However, it is somewhat more complicated in the expression of its arguments.

The included comment cards at the beginning of each routine should be sufficient to enable easy use of the methods based on the mathematical model presented herein.
APPENDIX A

FOUR-DIMENSIONAL LINEAR INTERPOLATION
SUBPROGRAM FOR COMPUTERS WITH SINGLE
SUBSCRIPTED VARIABLE CAPABILITY
FUNCTION TLU4D (N,J,K,L,X,Y,Z,W,0,XS,YS,ZS,\*)
DIMENSION XU), Y(L), ZC1), W<1), 0(1), V<2)

FOUR-DIMENSIONAL TABLE LOOK-UP ROUTINE

0 IS A FUNCTION OF THE FOUR VARIABLES X,Y,Z, AND W. IN THE
TABLE, A ONE DIMENSIONAL ARRAY IS ENTERED FOR EACH VARIABLE AND
Q. THE DIMENSIONS OF THE ARRAYS ARE SPECIFIED AS...

N NUMBER OF ELEMENTS IN X ARRAY
J NUMBER OF ELEMENTS IN Y ARRAY
K NUMBER OF ELEMENTS IN Z ARRAY
L NUMBER OF ELEMENTS IN W ARRAY

THE VALUES OF 0 IN THE TABLE ENTRY ARRAY ARE EXPRESSED AS IN
THIS EXAMPLE OF A 3,3,3,3 ARRAY...

Q(1) = 0(1,1,1,1)
Q(2) = 0(1,1,1,2)
Q(3) = 0(1,1,1,3)
Q(4) = 0(1,1,2,1)
Q(5) = 0(1,1,2,2)
Q(6) = 0(1,1,2,3)
Q(7) = 0(1,1,3,1)
Q(8) = 0(1,1,3,2)
Q(9) = 0(1,1,3,3)
Q(10) = 0(1,2,1,1)
AND SO LN.

THE DIMENSION OF 0 MUST BE N*K*L*E+L*(K+1)+1 WHERE THE
L*(K+1)+1 TERM IS FOR WORKING STORAGE, THE ELEMENTS OF THE
WORKING STORAGE AREA OF THE ARRAY MUST BE INITIALLY ZEROED OUT.

GIVEN VALUES FOR THE FOUR VARIABLES (XS,YS,ZS,WS) THE ROUTINE
LINEARLY INTERPOLATES FOR THE VALUE OF 0(XS,YS,ZS,WS), THE
IF ANY OF THE FOUR VARIABLES XS,YS,ZS,WS LIE OUTSIDE THE
RANGE OF THEIR RESPECTIVE ARRAYS, THESE VARIABLES ARE ASSUMED
TO BE THE ENDPOINTS.
THE ROUTINE IS WRITTEN FOR FOUR DIMENSIONAL USAGE, BUT MAY BE
USED FOR 1,2, AND 3 DIMENSIONS. FOR A THREE-DIMENSIONAL TABLE
L MUST BE SET EQUAL TO 1 AND A DUMMY VARIABLE W(K) MUST BE SET
FOR THE W ARRAY AS 0(1)=0.0 AND W(2)=ANY POSITIVE VALUE
GREATER THAN 0. FOR A TWO-DIMENSIONAL TABLE K AND L MUST BE
EQUAL TO 1 WHILE THE DUMMY ARRAY REPLACES BOTH THE W AND Z
ARRAYS. FOR A ONE-DIMENSIONAL TABLE J,K,L MUST ALL BE SET
EQUAL TO 1 AND THE DUMMY ARRAY REPLACES THE Y,Z, AND W ARRAYS.
10 IF (X(I)-XS) 20,20,50
20 IF (I-N) 30,40,40
30 I=I+1
   GO TO 10
40 I=N
   GO TO 60
50 !I=I-1
60 IF (J-1) 70,70,80
70 JJ=1
   LL=1
   GO TO 300
80
90 IF (Y(I)-YS) 100,100,130
100 IF (I-J) 110,120,120
110 I=I+1
   GO TO 90
120 JJ=J
   GO TO 140
130 JJ=J-1
140 IF (K-1) 150,150,160
150 KK=1
   LL=1
   GO TO 300
160 I=I+1
170 IF (Z(I)-ZS) 180,190,210
180 IF (I-K) 190,200,200
190 I=I+1
   GO TO 170
200 KK=K
   GO TO 220
210 KK=K-1
220 IF (L-1) 230,230,240
230 LL=1
   GO TO 300
240 I=I+1
250 IF (W(I)-WS) 260,260,290
260 IF (I-L) 270,280,280
270 I=I+1
   GO TO 250
280 LL=L
   GO TO 300
290 LL=I-1
300 IN=J*KK*L
   IF (II) 320,310,320
310 I=I+1
320 IF (JJ) 340,330,340
330 JJ=1
340 IF (KK) 360,350,360
350 KK=1

12
360 IF (LL) 380,370,380
370 L1=1
380 I1=(I1-1)*NN*(JJ-1)*K*L+(K-1)*L+LL
I2=I1+L
IF (K-1) 390,390,400
390 I3=I1
I4=I2
GO TO 410
400 I3=I1+K*L
I4=I3+L
C
410 NO 440 I3=1,2,1
W1=(WS-W(LL))/(W(LL+1)-W(LL))
T1=Q(I1)+W1*(Q(I1+1)-Q(I1))
T2=Q(I2)+W1*(Q(I2+1)-Q(I2))
S1=q(I3)+W1*(q(I3+1)-q(I3))
S2=q(I4)+W1*(q(I4+1)-q(I4))
U1=T1*(Z5-Z(KK))*(T2-T1)/(Z(KK+1)-Z(KK))
U2=S2*(Z5-Z(KK))*(S2-S1)/(Z(KK+1)-Z(KK))
V(I)=U1*(YS-Y(JJ))*(U2-U1)/(Y(JJ+1)-Y(JJ))
IF (J-1) 420,420,430
420 V(2)=U2
GO TO 450
430 I3=1+NN
I2=I2+NN
I3=I3+NN
I4=I4+NN
440 CONTINUE
450 TLU4=V(I)*(XS-X(I1))*(V(2)-V(1))/(X(I1+1)-X(I1))
RETURN
END
APPENDIX B

FOUR-DIMENSIONAL LINEAR INTERPOLATION
SUBPROGRAM FOR COMPUTERS WITH DOUBLE
SUBSCRIPTED VARIABLE CAPABILITY
FUNCTION TLU4D (M,X,Q,XS)
DIMENSION Q(1), V(2), P(5), X(1), M(1), L(4), X(1,1)

FOUR-DIMENSIONAL TABLE LOOK-UP ROUTINE

Q is a function of the four variables X, Y, Z, W and M is a one-dimensional array with four elements which are the number of elements in the independent variable arrays...

N = M(1) = number of elements in X array
J = M(2) = number of elements in Y array
K = M(3) = number of elements in Z array
L = M(4) = number of elements in W array

WHERE ...
X(1,N) corresponds to the X array
X(2,N) corresponds to the Y array
X(3,N) corresponds to the Z array
X(4,N) corresponds to the W array

AND ALSO ...
XS(1) corresponds to the point coordinate XS
XS(2) corresponds to the point coordinate YS
XS(3) corresponds to the point coordinate ZS
XS(4) corresponds to the point coordinate WS

The dimension of Q must be N*J*K*L + L*(K+1) + 1 where the L*(K+1) + 1 term is for working storage. The elements of the working storage area of the array must be initially zeroed out.

Given values for the four variables (XS, YS, ZS, WS) the routine linearly interpolates for the value of Q(XS, YS, ZS, WS), the answer being expressed as TLU4D.

If any of the four variables XS, YS, ZS, WS lie outside the range of their respective arrays, these variables are assumed to be the endpoints.

The routine is written for four-dimensional usage, but may be used for 1, 2, and 3 dimensions. For a three-dimensional table L must be set equal to 1 and a dummy variable D(K) must be set for the W array as D(1) = 0, 0 and D(2) = any positive value greater than 1. For a two-dimensional table K and L must be equal to 1 while the dummy array replaces both the W and Z arrays. For a one-dimensional table J, K, L must all be set equal to 1 and the dummy array replaces the Y, Z, and W arrays.
DO 100 J=1,4,1
I=M(J)
DO IN K=1,1
10 P(K)*X(J,K)
PS=XS(J)
IF (M(J)-1) 80,80,20
20 I=1
30 IF (P(I)-PS) 40,40,70
40 IF (I-M(J)) 50,60,60
50 I=I+1
GO TO 30
60 L(J)=M(J)
GO TO 100
70 L(J)=I-1
GO TO 100
80 DO 90 K=J,4,1
90 L(K)=1
GO TO 100
100 CONTINUE
DO 120 K=1,4,1
IF (L(K)) 120,110,120
110 L(K)=1
120 CONTINUE
N=M(2)+M(3)+M(4)
I1=(L(1)+1)*N*(L(2)+1)*M(3)+M(4)+(L(3)+1)*M(4)+L(4)
I2=I1+M(4)
IF (M(3)-1) 140,140,150
140 I3=I1
I4=I2
GO TO 160
150 I3=I3+M(3)+M(4)
I4=I4+M(4)
160 DO 190 K=1,2,1
I1=L(1)
J1=L(2)
K1=L(3)
LL=L(4)
W1=(XS(4)-X(4,KK))/X(4,LL+1)-X(4,LL))
T1=Q(11)*W1*(Q(11+1)=Q(11))
T2=Q(12)*W1*(Q(12+1)=Q(12))
S1=U(13)*W1*(Q(13+1)=Q(13))
S2=Q(14)*W1*(Q(14+1)=Q(14))
U1=T1+(XS(3)-X(3,KK))/(T2-T1)/(X(3,KK+1)-X(3,KK))
U2=2*S1/(X(3,KK+1)-X(3,KK))
V(K)=U1+(XS(2)-X(2,JK))/(U2-U1)/(X(2,JK+1)-X(2,JK))
IF (M(2)-1) 170,170,180
170 V(2)=U2
GO TO 200
180 I1=I1+N
I2=I2+N
I3=I3+N
I4=I4+N
190 CONTINUE
200 TLV0=V(1)+(XS(1)-X(1,1))*V(2)-V(1))/(X(1,11+1)-X(1,1))
RETURN
END
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By William R. Farr

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