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Apêndice A

Neste apêndice estão as matrizes relacionadas à cinemática direta do manipulador TA-40, bem como as matrizes da Jacobiana de Identificação, para a formulação dos erros generalizados.

Considere os parâmetros D.H. q_1, q_2, q_3, q_4, q_5 e q_6 para o manipulador robótico TA-40, definido na Figura 40.

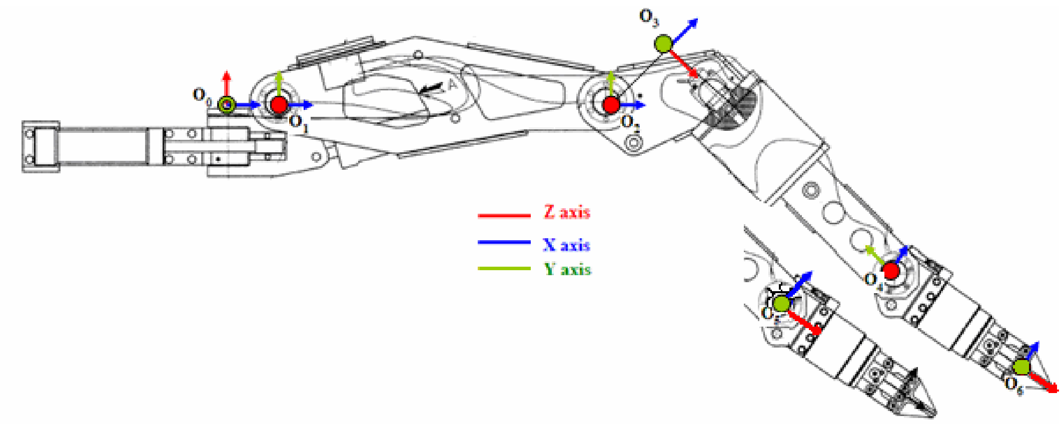

Figura 40: Sistema de coordenadas do TA-40.

8.1.
Posição da Extremidade

X=(((cos(q1)*cos(q2)*cos(q3)-cos(q1)*sin(q2)*sin(q3))*cos(q4)

+sin(q1)*sin(q4))*sin(q5)-(-cos(q1)*cos(q2)*sin(q3)

-cos(q1)*sin(q2)*cos(q3))*cos(q5))*d6

+(cos(q1)*cos(q2)*sin(q3)+cos(q1)*sin(q2)*cos(q3))*d4

+cos(q1)*cos(q2)*a3*cos(q3)-cos(q1)*sin(q2)*a3*sin(q3)

+cos(q1)*a2*cos(q2)+a1*cos(q1)

Y=(((sin(q1)*cos(q2)*cos(q3)-sin(q1)*sin(q2)*sin(q3))*cos(q4)
-cos(q1)*sin(q4))*sin(q5)-(-sin(q1)*cos(q2)*sin(q3)
-sin(q1)*sin(q2)*cos(q3))*cos(q5))*d6
+(sin(q1)*cos(q2)*sin(q3)+sin(q1)*sin(q2)*cos(q3))*d4
+sin(q1)*cos(q2)*a3*cos(q3)-sin(q1)*sin(q2)*a3*sin(q3)
+sin(q1)*a2*cos(q2)+a1*sin(q1)

Z=((sin(q2)*cos(q3)+cos(q2)*sin(q3))*cos(q4)*sin(q5)
-(-sin(q2)*sin(q3)+cos(q2)*cos(q3))*cos(q5))*d6
+(sin(q2)*sin(q3)-cos(q2)*cos(q3))*d4+sin(q2)*a3*cos(q3)
+cos(q2)*a3*sin(q3)+a2*sin(q2)

8.2. Jacobiana de Identificação

A seguir está a Matriz Jacobiana de Identificação, composta por quatro linhas e quarenta e duas colunas. Com o objetivo de auxiliar a aplicação, a jacobiana será exposta na forma de algoritmo.

```
function Je = jacobiana_identificacao(q1,q2,q3,q4,q5,q6)
%matriz jacobiana de identificação
%entradas = seis ângulos das juntas do manipulador

%calcula-se os senos e cossenos antecipadamente para aumentar a velocidade
c1 = cos(q1);c2 = cos(q2);c3 = cos(q3);c4 = cos(q4);c5 = cos(q5);c6 = cos(q6);
s1 = sin(q1);s2 = sin(q2);s3 = sin(q3);s4 = sin(q4);s5 = sin(q5);s6 = sin(q6);
%parâmetros DH do manipulador TA-40 em milímetros
a1=0.115;a2=0.753;a3=0.188;d4=0.747;a6=0.360;
% J_X,0
Je(1,1) = 1;
Je(2,1) = 0;
Je(3,1) = 0;
```

%$J_{Y,0}$

Je(1,2) = 0;

Je(2,2) = 1;

Je(3,2) = 0;

% $J_{Z,0}$

Je(1,3) = 0;

Je(2,3) = 0;

Je(3,3) = 1;

%$J_{S,0}$

Je(1,4)=c3*a3*s2+s3*a3*c2-d4*c3*c2-a6*c5*c3*c2+a6*c5*s3*s2
+d4*s3*s2+a6*s5*c4*s3*c2+s2*a2+a6*s5*c4*c3*s2;

Je(2,4) = 0;

Je(3,4)=-c3*a3*c2*c1-c1*a1-a6*c5*s3*c2*c1-a6*c5*c3*s2*c1-a6*s5*s4*s1
+s3*a3*s2*c1-d4*s3*c2*c1-d4*c3*s2*c1-a6*s5*c4*c3*c2*c1-
c2*a2*c1+a6*s5*c4*s3*s2*c1;

%$J_{R,0}$

Je(1,5)=s3*a3*s2*s1-s1*a1-a6*c5*s3*c2*s1+a6*s5*c4*s3*s2*s1
-a6*s5*c4*c3*c2*s1-d4*c3*s2*s1-c3*a3*c2*s1
+a6*s5*s4*c1-d4*s3*c2*s1-a6*c5*c3*s2*s1-c2*a2*s1;

Je(2,5)=c3*a3*c2*c1+c1*a1+a6*c5*s3*c2*c1+a6*c5*c3*s2*c1+a6*s5*s4*s1
-s3*a3*s2*c1+d4*s3*c2*c1+d4*c3*s2*c1+a6*s5*c4*c3*c2*c1
+c2*a2*c1-a6*s5*c4*s3*s2*c1;

Je(3,5) =0;

%$J_{P,0}$

Je(1,6) = 0;

Je(2,6)=-c3*a3*s2-s3*a3*c2+d4*c3*c2+a6*c5*c3*c2-a6*c5*s3*s2-d4*s3*s2
-a6*s5*c4*s3*c2-s2*a2-a6*s5*c4*c3*s2;

Je(3,6)=-s3*a3*s2*s1+s1*a1+a6*c5*s3*c2*s1-a6*s5*c4*s3*s2*s1
+a6*s5*c4*c3*c2*s1+d4*c3*s2*s1+c3*a3*c2*s1
-a6*s5*s4*c1+d4*s3*c2*s1+a6*c5*c3*s2*s1+c2*a2*s1;

%$J_{X,1}$

Je(1,7) =c1;

Je(2,7) =s1;

Je(3,7) =0;

%$J_{Y,1}$

Je(1,8) =0;

Je(2,8) =0;

Je(3,8) =1;

%$J_{Z,1}$

Je(1,9) =s1;

Je(2,9) =-c1;

Je(3,9) = 0;

%$J_{S,1}$

```
Je(1,10)=s3*a3*s2*s1-a6*c5*s3*c2*s1+a6*s5*c4*s3*s2*s1-a6*s5*c4*c3*c2*s1
         -d4*c3*s2*s1-c3*a3*c2*s1+a6*s5*s4*c1-d4*s3*c2*s1-a6*c5*c3*s2*s1
         -c2*a2*s1;
Je(2,10)=c3*a3*c2*c1+a6*c5*s3*c2*c1+a6*c5*c3*s2*c1+a6*s5*s4*s1
         -s3*a3*s2*c1+d4*s3*c2*c1+d4*c3*s2*c1+a6*s5*c4*c3*c2*c1
         +c2*a2*c1-a6*s5*c4*s3*s2*c1;
Je(3,10) =0;
```

%$J_{R,1}$

```
Je(1,11)=-c3*a3*s2*c1-d4*s3*s2*c1+d4*c3*c2*c1-s2*a2*c1-s3*a3*c2*c1
         -a6*s5*c4*c3*s2*c1-a6*s5*c4*s3*c2*c1-a6*c5*s3*s2*c1
         +a6*c5*c3*c2*c1;
Je(2,11)=-d4*s3*s2*s1-a6*s5*c4*s3*c2*s1+d4*c3*c2*s1-a6*s5*c4*c3*s2*s1
         -s3*a3*c2*s1-c3*a3*s2*s1-s2*a2*s1+a6*c5*c3*c2*s1-a6*c5*s3*s2*s1;
Je(3,11)=c3*a3*c2+d4*c3*s2+d4*s3*c2-s3*a3*s2+a6*s5*c4*c3*c2
         +c2*a2+a6*c5*c3*s2+a6*c5*s3*c2-a6*s5*c4*s3*s2;
```

%$J_{P,1}$

Je(1,12)=d4*s3*s2*s1+a6*s5*c4*s3*c2*s1-d4*c3*c2*s1+a6*s5*c4*c3*s2*s1
+s3*a3*c2*s1+c3*a3*s2*s1+s2*a2*s1-a6*c5*c3*c2*s1
+a6*c5*s3*s2*s1;

Je(2,12)=-c3*a3*s2*c1-d4*s3*s2*c1+d4*c3*c2*c1-s2*a2*c1-s3*a3*c2*c1
-a6*s5*c4*c3*s2*c1-a6*s5*c4*s3*c2*c1-a6*c5*s3*s2*c1
+a6*c5*c3*c2*c1;

Je(3,12)=-a6*s5*s4;

%$J_{X,2}$

Je(1,13) =c2*c1;

Je(2,13) =c2*s1;

Je(3,13) =s2;

%$J_{Y,2}$

Je(1,14) =-s2*c1;

Je(2,14) =-s2*s1;

Je(3,14) =c2;

%$J_{Z,2}$

Je(1,15) = s1;

Je(2,15) =-c1;

Je(3,15) =0;

%$J_{S,2}$

Je(1,16) = -a6*s5*c4*c3*s1-a6*c5*s3*s1-c3*a3*s1-d4*s3*s1+a6*s5*s4*c2*c1;

Je(2,16)= a6*c5*s3*c1+a6*s5*c4*c3*c1+a6*s5*s4*c2*s1+d4*s3*c1+c3*a3*c1;

Je(3,16) = a6*s5*s4*s2;

%$J_{R,2}$

Je(1,17)=-c3*a3*s2*c1-d4*s3*s2*c1+d4*c3*c2*c1-s3*a3*c2*c1
-a6*s5*c4*c3*s2*c1-a6*s5*c4*s3*c2*c1
-a6*c5*s3*s2*c1+a6*c5*c3*c2*c1;

Je(2,17)=-d4*s3*s2*s1-a6*s5*c4*s3*c2*s1+d4*c3*c2*s1-a6*s5*c4*c3*s2*s1
-s3*a3*c2*s1-c3*a3*s2*s1+a6*c5*c3*c2*s1-a6*c5*s3*s2*s1;
Je(3,17)=c3*a3*c2+d4*c3*s2+d4*s3*c2-s3*a3*s2+a6*s5*c4*c3*c2
+a6*c5*c3*s2+a6*c5*s3*c2-a6*s5*c4*s3*s2;

%$J_{P,2}$
Je(1,18) = s3*a3*s1-d4*c3*s1+a6*s5*c4*s3*s1-a6*c5*c3*s1+a6*s5*s4*s2*c1;
Je(2,18) = a6*s5*s4*s2*s1+a6*c5*c3*c1-s3*a3*c1-a6*s5*c4*s3*c1+d4*c3*c1;
Je(3,18) = -a6*s5*s4*c2;

%$J_{X,3}$
Je(1,19) = -s3*s2*c1+c3*c2*c1;
Je(2,19) = -s3*s2*s1+c3*c2*s1;
Je(3,19) =c3*s2+s3*c2;

%$J_{Y,3}$
Je(1,20) = s1;
Je(2,20) = -c1;
Je(3,20) = 0;

%$J_{Z,3}$
Je(1,21) = s3*c2*c1+c3*s2*c1;
Je(2,21) =s3*c2*s1+c3*s2*s1;
Je(3,21) =-c3*c2+s3*s2;

%$J_{S,3}$
Je(1,22)=-d4*s3*s2*c1+d4*c3*c2*c1-a6*s5*c4*c3*s2*c1-a6*s5*c4*s3*c2*c1
-a6*c5*s3*s2*c1+a6*c5*c3*c2*c1;
Je(2,22)=-d4*s3*s2*s1-a6*s5*c4*s3*c2*s1+d4*c3*c2*s1
-a6*s5*c4*c3*s2*s1+a6*c5*c3*c2*s1-a6*c5*s3*s2*s1;
Je(3,22)=d4*c3*s2+d4*s3*c2+a6*s5*c4*c3*c2+a6*c5*c3*s2+a6*c5*s3*c2
-a6*s5*c4*s3*s2;

$\%J_{R,3}$

Je(1,23) =   a6*s5*c4*s1+a6*s5*s4*s3*s2*c1-a6*s5*s4*c3*c2*c1;

Je(2,23) =-a6*s5*c4*c1+a6*s5*s4*s3*s2*s1-a6*s5*s4*c3*c2*s1;

Je(3,23) =-a6*s5*s4*s3*c2-a6*s5*s4*c3*s2;

$\%J_{P,3}$

Je(1,24) =-d4*s1+a6*s5*s4*c3*s2*c1-a6*c5*s1+a6*s5*s4*s3*c2*c1;

Je(2,24) = a6*c5*c1+a6*s5*s4*c3*s2*s1+a6*s5*s4*s3*c2*s1+d4*c1;

Je(3,24) = -a6*s5*s4*c3*c2+a6*s5*s4*s3*s2;

$\%J_{X,4}$

Je(1,25) =c4*c3*c2*c1+s4*s1-c4*s3*s2*c1;

Je(2,25) = c4*c3*c2*s1-s4*c1-c4*s3*s2*s1;

Je(3,25) =c4*s3*c2+c4*c3*s2;

$\%J_{Y,4}$

Je(1,26) =-s3*c2*c1-c3*s2*c1;

Je(2,26) = -s3*c2*s1-c3*s2*s1;

Je(3,26) =c3*c2-s3*s2;

$\%J_{Z,4}$

Je(1,27) = s4*s3*s2*c1-s4*c3*c2*c1+c4*s1;

Je(2,27) = -c4*c1-s4*c3*c2*s1+s4*s3*s2*s1;

Je(3,27) =-s4*s3*c2-s4*c3*s2;

$\%J_{S,4}$

Je(1,28) = -a6*s5*c4*s1-a6*s5*s4*s3*s2*c1+a6*s5*s4*c3*c2*c1;

Je(2,28) = a6*s5*c4*c1-a6*s5*s4*s3*s2*s1+a6*s5*s4*c3*c2*s1;

Je(3,28) =a6*s5*s4*s3*c2+a6*s5*s4*c3*s2;

$\%J_{R,4}$

Je(1,29) = -a6*s5*s3*c2*c1+a6*c5*s4*s1-a6*s5*c3*s2*c1+a6*c5*c4*c3*c2*c1
              -a6*c5*c4*s3*s2*c1;

Je(2,29)=-a6*c5*s4*c1-a6*s5*s3*c2*s1-a6*s5*c3*s2*s1
-a6*c5*c4*s3*s2*s1+a6*c5*c4*c3*c2*s1;
Je(3,29) =a6*c5*c4*c3*s2-a6*s5*s3*s2+a6*c5*c4*s3*c2+a6*s5*c3*c2;

%$J_{P,4}$
Je(1,30) = a6*c5*s4*c3*c2*c1-a6*c5*c4*s1-a6*c5*s4*s3*s2*c1;
Je(2,30) = a6*c5*c4*c1+a6*c5*s4*c3*c2*s1-a6*c5*s4*s3*s2*s1;
Je(3,30) = a6*c5*s4*s3*c2+a6*c5*s4*c3*s2;

%$J_{X,5}$
Je(1,31)=c5*c4*c3*c2*c1+c5*s4*s1-s5*c3*s2*c1-s5*s3*c2*c1-c5*c4*s3*s2*c1;
Je(2,31)=-c5*s4*c1-c5*c4*s3*s2*s1+c5*c4*c3*c2*s1-s5*c3*s2*s1
-s5*s3*c2*s1;
Je(3,31)=s5*c3*c2-s5*s3*s2+c5*c4*s3*c2+c5*c4*c3*s2;

%$J_{Y,5}$
Je(1,32) = s4*s3*s2*c1-s4*c3*c2*c1+c4*s1;
Je(2,32) = -c4*c1-s4*c3*c2*s1+s4*s3*s2*s1;
Je(3,32) = -s4*s3*c2-s4*c3*s2;

%$J_{Z,5}$
Je(1,33)=c5*s3*c2*c1+c5*c3*s2*c1+s5*c4*c3*c2*c1
-s5*c4*s3*s2*c1+s5*s4*s1;
Je(2,33)=-s5*c4*s3*s2*s1+c5*c3*s2*s1+c5*s3*c2*s1
-s5*s4*c1+s5*c4*c3*c2*s1;
Je(3,33) = c5*s3*s2-c5*c3*c2+s5*c4*s3*c2+s5*c4*c3*s2;
%$J_{S,5}$
Je(1,34)=-a6*s5*s3*c2*c1+a6*c5*s4*s1-a6*s5*c3*s2*c1+a6*c5*c4*c3*c2*c1
-a6*c5*c4*s3*s2*c1;
Je(2,34)=-a6*c5*s4*c1-a6*s5*s3*c2*s1-a6*s5*c3*s2*s1
-a6*c5*c4*s3*s2*s1+a6*c5*c4*c3*c2*s1;
Je(3,34) =a6*c5*c4*c3*s2-a6*s5*s3*s2+a6*c5*c4*s3*c2+a6*s5*c3*c2;

%$J_{R,5}$

Je(1,35) = 0

Je(2,35) = 0

Je(3,35) = 0

%$J_{P,5}$

Je(1,36) = -a6*c4*s1-a6*s4*s3*s2*c1+a6*s4*c3*c2*c1;

Je(2,36) = a6*c4*c1-a6*s4*s3*s2*s1+a6*s4*c3*c2*s1;

Je(3,36) =a6*s4*c3*s2+a6*s4*s3*c2;

%$J_{X,6}$

Je(1,37)=s6*s4*s3*s2*c1-s6*s4*c3*c2*c1-c6*s5*s3*c2*c1
-c6*s5*c3*s2*c1+s6*c4*s1-c6*c5*c4*s3*s2*c1
+c6*c5*s4*s1+c6*c5*c4*c3*c2*c1;

Je(2,37)=-c6*c5*c4*s3*s2*s1-c6*c5*s4*c1-s6*s4*c3*c2*s1
-s6*c4*c1+s6*s4*s3*s2*s1-c6*s5*c3*s2*s1
+c6*c5*c4*c3*c2*s1-c6*s5*s3*c2*s1;

Je(3,37)=c6*c5*c4*c3*s2-s6*s4*s3*c2-c6*s5*s3*s2
+c6*c5*c4*s3*c2+c6*s5*c3*c2-s6*s4*c3*s2;

%$J_{Y,6}$

Je(1,38)=c6*s4*s3*s2*c1+c6*c4*s1+s6*s5*c3*s2*c1-c6*s4*c3*c2*c1
-s6*c5*s4*s1+s6*s5*s3*c2*c1-s6*c5*c4*c3*c2*c1+s6*c5*c4*s3*s2*c1;

Je(2,38)=s6*c5*c4*s3*s2*s1-c6*c4*c1+s6*c5*s4*c1-s6*c5*c4*c3*c2*s1
+s6*s5*s3*c2*s1+c6*s4*s3*s2*s1+s6*s5*c3*s2*s1-c6*s4*c3*c2*s1;

Je(3,38)=s6*s5*s3*s2-c6*s4*c3*s2-s6*c5*c4*c3*s2-s6*s5*c3*c2-c6*s4*s3*c2
-s6*c5*c4*s3*c2;

%$J_{Z,6}$

Je(1,39)=c5*s3*c2*c1+c5*c3*s2*c1+s5*c4*c3*c2*c1-s5*c4*s3*s2*c1
+s5*s4*s1;

Je(2,39)=-s5*c4*s3*s2*s1+c5*c3*s2*s1+c5*s3*c2*s1-s5*s4*c1
+s5*c4*c3*c2*s1;

Je(3,39)=c5*s3*s2-c5*c3*c2+s5*c4*s3*c2+s5*c4*c3*s2;

%$J_{S,6}$

Je(1,40) = 0;

Je(2,40) = 0;

Je(3,40) = 0;

%$J_{R,6}$

Je(1,41) = 0;

Je(2,41) = 0;

Je(3,41) = 0;

%$J_{P,6}$

Je(1,42) = 0;

Je(2,42) = 0;

Je(3,42) = 0;

A jacobiana de identificação, conforme calculada acima com 42 colunas, possui colunas linearmente dependentes e portanto não pode ser invertida. Para tanto, deletam-se as colunas: 3 5 9 11 15 17 21 23 27 29 32 33 34 35 40 41 42. A matriz reduzida possui 25 colunas linearmente independentes.

9
Apêndice B

Neste apêndice estão as matrizes relacionadas a calibragem de ambas as câmeras que foram utilizadas nas simulações de visão computacional. Para a calibração, as câmeras foram posicionadas a uma distância fixa entre si, e foram obtidas imagens de uma plataforma de calibração com as duas câmeras posicionadas em posições e angulações diversas em relação a própria plataforma.

A Figura 41 mostra a imagens da plataforma, obtidas na câmera esquerda e direita. A Figura 42 mostra uma imagem com os cantos do tabuleiro de chadrez obtidos para identificação. A Figura 43 mostra as posições de onde foram posicionadas as câmeras.

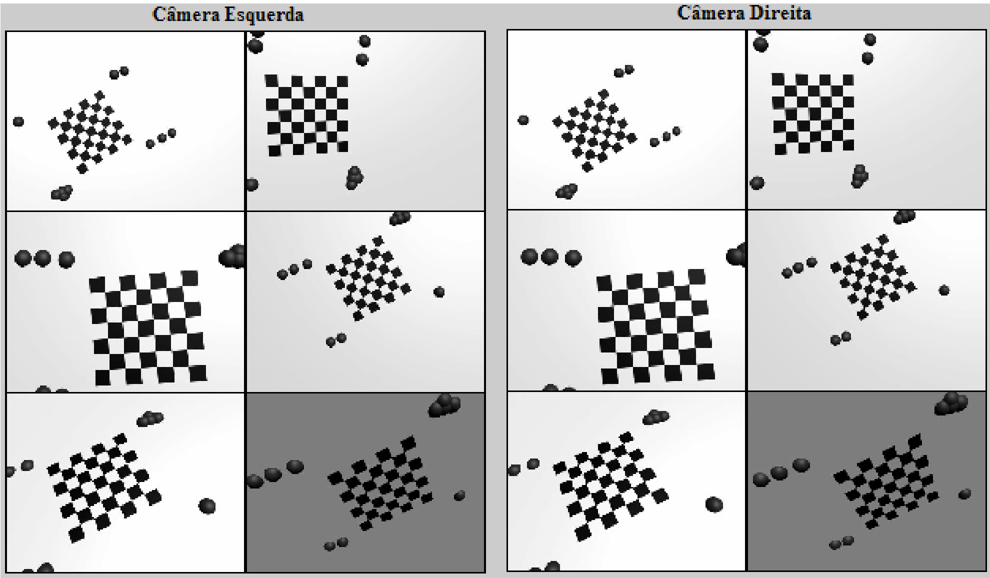

Figura 41: Imagens de Calibração tiradas da câmera esquerda e direita

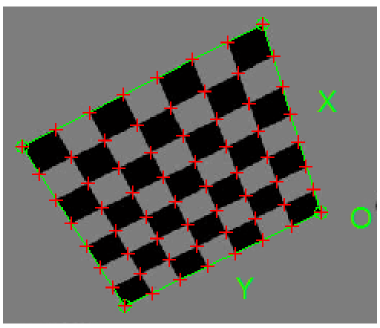

Figura 42: Pontos obtidos nas bordas da imagem

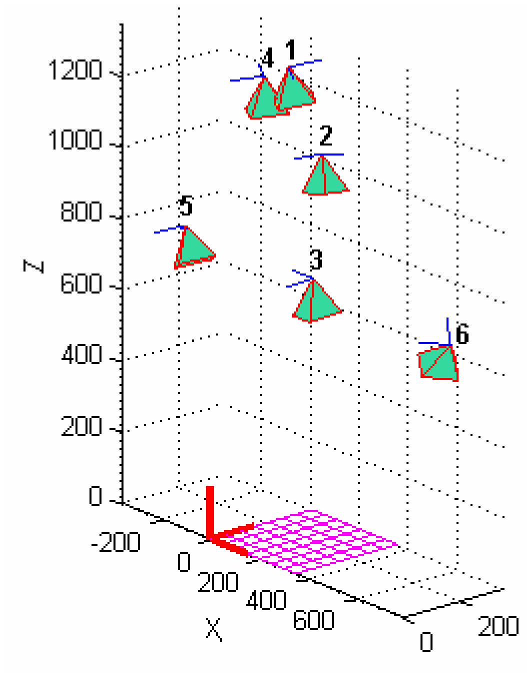

Figura 43: Posição das câmeras em relação ao tabuleiro.

Com base nestas imagens, foi utilizado o algoritmo de calibração, resultando nos seguintes parâmetros:

Câmera Esquerda:

Distância Focal: [622.722223 622.734845]

Ponto Principal: [319.645527 240.020607]

Rotação:: [0.995639 0.000059 -0.093285

0.000144 -1.000000 0.000901

-0.093285 -0.000910 -0.995639]

Translação: [-181.450138 95.014091 772.891183]

Câmera Direita:

Distância focal: [622.003404 621.914437]

Ponto Principal: [319.848589 239.641100]

Rotação: [0.995651 -0.000019 -0.093157

0.000049 -1.000000 0.000734

-0.093157 -0.000735 -0.995651]

Translação: [-181.689910 115.513783 771.803544]

Os parâmetros extrínsecos (posição e orientação das câmeras) estão expressos em relação ao sistema de coordenadas do mundo, conforme explicado na seção 3.3. Pode-se a partir de uma transformação homogênea transferir o sistema de coordenadas do mundo para a posição da câmera esquerda, resultando nos seguinte parâmetros extrínsecos:

Câmera Esquerda:
Rotação:: [1 0 0
0 1 0
0 0 1]
Translação: [0 0 0]

Câmera Direita:
Rotação: [1 0 0
0 1 0
0 0 1]
Translação: [50 0 0]