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A Apêndice A

Este apêndice contém as equações relacionadas à cinemática e dinâmica do robô manipulador Schilling Titan IV, bem como as matrizes do jacobiano que relaciona as velocidades da ferramenta com respeito às juntas do robô.

A.1 Matriz Homogênea

Considere os parâmetros D-H da tabela 3.1 obtidos da modelagem do robô mostrada na figura 3.4, então podem-se obter as matrizes homogêneas de transformação

$$A_{1}^{0} = \begin{bmatrix} \cos \theta_{1} & 0 & \sin \theta_{1} & l_{2} \cos \theta_{1} \\ \sin \theta_{1} & 0 & -\cos \theta_{1} & l_{2} \sin \theta_{1} \\ 0 & 1 & 0 & l_{1} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$
(A-1)

$$A_{2}^{1} = \begin{bmatrix} \cos \theta_{2} & -\sin \theta_{2} & 0 & l_{3} \cos \theta_{2} \\ \sin \theta_{2} & \cos \theta_{2} & 0 & l_{3} \sin \theta_{2} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$
(A-2)

$$A_{3}^{2} = \begin{bmatrix} \cos \theta_{3} & -\sin \theta_{3} & 0 & l_{4} \cos \theta_{3} \\ \sin \theta_{3} & \cos \theta_{3} & 0 & l_{4} \sin \theta_{3} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$
(A-3)

$$A_{4}^{3} = \begin{bmatrix} \cos\theta_{4} & 0 & -\sin\theta_{4} & l_{5}\cos\theta_{4} \\ \sin\theta_{4} & 0 & \cos\theta_{4} & l_{5}\sin\theta_{4} \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$
(A-4)

$$A_5^4 = \begin{bmatrix} \sin\theta_5 & 0 & \cos\theta_5 & 0 \\ -\cos\theta_5 & 0 & \sin\theta_5 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$
(A-5)

$$A_6^5 = \begin{bmatrix} \cos\theta_6 & -\sin\theta_6 & 0 & 0\\ \sin\theta_6 & \cos\theta_6 & 0 & 0\\ 0 & 0 & 1 & l_6\\ 0 & 0 & 0 & 1 \end{bmatrix}$$
(A-6)

Com estas matrizes, obtém-se a matriz ${\bf T}$

4

$$\mathbf{T} = \mathbf{A}_{1}^{0} \mathbf{A}_{2}^{1} \mathbf{A}_{3}^{2} \mathbf{A}_{4}^{3} \mathbf{A}_{5}^{4} \mathbf{A}_{6}^{5} \tag{A-7}$$

Definindo

$$\mathbf{T} = \begin{bmatrix} \mathbf{n} & \mathbf{t} & \mathbf{b} & \mathbf{x} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Então obtemos a posição e orientação do efetuador terminal do robô.

$$\mathbf{n} = \begin{bmatrix} \cos\theta_6 \sin\theta_5 \cos\theta_1 \cos(\theta_2 + \theta_3 + \theta_4) + \cos\theta_6 \cos\theta_5 \sin\theta_1 + \sin\theta_6 \cos\theta_1 \sin(\theta_2 + \theta_3 + \theta_4) \\ \cos\theta_6 \sin\theta_5 \sin\theta_1 \cos(\theta_2 + \theta_3 + \theta_4) - \cos\theta_6 \cos\theta_5 \cos\theta_1 + \sin\theta_6 \sin\theta_1 \sin(\theta_2 + \theta_3 + \theta_4) \\ \cos\theta_6 \sin\theta_5 \sin(\theta_2 + \theta_3 + \theta_4) - \sin\theta_6 \cos(\theta_2 + \theta_3 + \theta_4) \end{bmatrix}$$

$$\mathbf{t} = \begin{bmatrix} -\sin\theta_6\sin\theta_5\cos\theta_1\cos(\theta_2+\theta_3+\theta_4) - \sin\theta_6\cos\theta_5\sin\theta_1 + \cos\theta_6\cos\theta_1\sin(\theta_2+\theta_3+\theta_4) \\ -\sin\theta_6\sin\theta_5\sin\theta_1\cos(\theta_2+\theta_3+\theta_4) + \sin\theta_6\sin\theta_5\cos\theta_1 + \cos\theta_6\sin\theta_1\sin(\theta_2+\theta_3+\theta_4) \\ -\sin\theta_6\sin\theta_5\sin(\theta_2+\theta_3+\theta_4) - \cos\theta_6\cos(\theta_2+\theta_3+\theta_4) \end{bmatrix}$$

$$\mathbf{b} = \begin{bmatrix} \cos\theta_1 \cos\theta_5 \cos(\theta_2 + \theta_3 + \theta_4) - \sin\theta_1 \sin\theta_5 \\ \sin\theta_1 \cos\theta_5 \cos(\theta_2 + \theta_3 + \theta_4) + \cos\theta_1 \sin\theta_5 \\ \cos\theta_5 \sin(\theta_2 + \theta_3 + \theta_4) \end{bmatrix}$$

$$\mathbf{x} = \begin{bmatrix} [l_2 + l_3 \cos \theta_2 + l_4 \cos(\theta_2 + \theta_3) + (l_5 + l_6 \cos \theta_5) \cos(\theta_2 + \theta_3 + \theta_4)] \cos \theta_1 - l_6 \sin \theta_1 \sin \theta_5 \\ [l_2 + l_3 \cos \theta_2 + l_4 \cos(\theta_2 + \theta_3) + (l_5 + l_6 \cos \theta_5) \cos(\theta_2 + \theta_3 + \theta_4)] \sin \theta_1 + l_6 \cos \theta_1 \sin \theta_5 \\ l_1 + l_3 \sin \theta_2 + l_4 \sin(\theta_2 + \theta_3) + (l_5 + l_6 \cos \theta_5) \sin(\theta_2 + \theta_3 + \theta_4) \end{bmatrix}$$

A.2 Matriz Jacobiana

A matriz Jacobiana é dado por

$$J = \begin{bmatrix} J_{L1} & J_{L2} & J_{L3} & J_{L4} & J_{L5} & J_{L6} \\ J_{A1} & J_{A2} & J_{A3} & J_{A4} & J_{A5} & J_{A6} \end{bmatrix}$$

onde

$$J_{L1} = \begin{bmatrix} -[l_2 + l_3 \cos \theta_2 + l_4 \cos(\theta_2 + \theta_3) + (l_5 + l_6 \cos \theta_5) \cos(\theta_2 + \theta_3 + \theta_4)] \sin \theta_1 - l_6 \cos \theta_1 \sin \theta_5 \\ [l_2 + l_3 \cos \theta_2 + l_4 \cos(\theta_2 + \theta_3) + (l_5 + l_6 \cos \theta_5) \cos(\theta_2 + \theta_3 + \theta_4)] \cos \theta_1 - l_6 \sin \theta_1 \sin \theta_5 \\ 0 \end{bmatrix}$$

$$J_{L2} = \begin{bmatrix} -[l_3 \sin \theta_2 + l_4 \sin(\theta_2 + \theta_3) + (l_5 + l_6 \cos \theta_5) \sin(\theta_2 + \theta_3 + \theta_4)] \cos \theta_1 \\ -[l_3 \sin \theta_2 + l_4 \sin(\theta_2 + \theta_3) + (l_5 + l_6 \cos \theta_5) \sin(\theta_2 + \theta_3 + \theta_4)] \sin \theta_1 \\ [l_3 \cos \theta_2 + l_4 \cos(\theta_2 + \theta_3) + (l_5 + l_6 \cos \theta_5) \cos(\theta_2 + \theta_3 + \theta_4)] \end{bmatrix}$$

$$J_{L3} = \begin{bmatrix} -[l_4 \sin(\theta_2 + \theta_3) + (l_5 + l_6 \cos \theta_5) \sin(\theta_2 + \theta_3 + \theta_4)] \cos \theta_1 \\ -[l_4 \sin(\theta_2 + \theta_3) + (l_5 + l_6 \cos \theta_5) \sin(\theta_2 + \theta_3 + \theta_4)] \sin \theta_1 \\ [l_4 \cos(\theta_2 + \theta_3) + (l_5 + l_6 \cos \theta_5) \cos(\theta_2 + \theta_3 + \theta_4)] \end{bmatrix}$$

$$J_{L4} = \begin{bmatrix} -(l_5 + l_6 \cos \theta_5) \sin(\theta_2 + \theta_3 + \theta_4) \cos \theta_1 \\ -(l_5 + l_6 \cos \theta_5) \sin(\theta_2 + \theta_3 + \theta_4) \sin \theta_1 \\ (l_5 + l_6 \cos \theta_5) \cos(\theta_2 + \theta_3 + \theta_4) \end{bmatrix}$$

$$J_{L5} = \begin{bmatrix} -l_6 \sin \theta_5 \cos(\theta_2 + \theta_3 + \theta_4) \cos \theta_1 - l_6 \sin \theta_1 \cos \theta_5 \\ -l_6 \sin \theta_5 \cos(\theta_2 + \theta_3 + \theta_4) \sin \theta_1 + l_6 \cos \theta_1 \cos \theta_5 \\ l_6 \sin \theta_5 \sin(\theta_2 + \theta_3 + \theta_4) \end{bmatrix}$$

$$J_{L6} = \begin{bmatrix} 0\\0\\0 \end{bmatrix}$$

$$J_{A1} = \begin{bmatrix} 0\\0\\1 \end{bmatrix}$$
$$J_{A2} = \begin{bmatrix} \sin \theta_1\\-\cos \theta_1\\0 \end{bmatrix}$$
$$J_{A3} = \begin{bmatrix} \sin \theta_1\\-\cos \theta_1 \end{bmatrix}$$

$$J_{A4} = \begin{bmatrix} \sin \theta_1 \\ -\cos \theta_1 \\ 0 \end{bmatrix}$$

0

$$J_{A5} = \begin{bmatrix} -\cos\theta_1\sin(\theta_2 + \theta_3 + \theta_4) \\ -\sin\theta_1\sin(\theta_2 + \theta_3 + \theta_4) \\ \cos(\theta_2 + \theta_3 + \theta_4) \end{bmatrix}$$

$$J_{A6} = \begin{bmatrix} \cos\theta_1\cos(\theta_2 + \theta_3 + \theta_4)\cos\theta_5 - \sin\theta_1\sin\theta_5 \\ \sin\theta_1\cos(\theta_2 + \theta_3 + \theta_4)\cos\theta_5 + \cos\theta_1\sin\theta_5 \\ \cos\theta_5\sin(\theta_2 + \theta_3 + \theta_4) \end{bmatrix}$$

A.3 Algoritmo Walker-Orin

Em seções anteriores se definiu a equação geral assumida para o robô manipulador em estudo. Vamos simular a sua dinâmica direta assim,

$$\boldsymbol{\tau} = \mathbf{H}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{G}(\mathbf{q})$$
 (A-8)

Seja uma função $SUB(\mathbf{q}, \dot{\mathbf{q}}, \ddot{\mathbf{q}}; \boldsymbol{\tau})$ que calcula $\boldsymbol{\tau}$, utilizando a equação da dinâmica inversa do robô manipulador de n graus de liberdade. Seus

argumentos são os vetores de deslocamento, velocidade e aceleração das juntas. Agora vamos explicar os métodos 1 e 3 do algoritmo de Walker e Orin.

A.3.1 Método 1

Da equação (A-8), nota-se que os torques nas juntas são uma função linear das acelerações das juntas. Portanto, seja **b** definido como um vetor "bias", igual ao torque produzido só pelas acelerações gravitacionais, centrífugos e coriolis, assim

$$\mathbf{b} = \mathbf{H}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{G}(\mathbf{q})$$
(A-9)

Então, as acelerações nas juntas podem ser obtidas computando a equação linear

$$\mathbf{H}(\mathbf{q})\ddot{\mathbf{q}} = (\boldsymbol{\tau} - \mathbf{b}) \tag{A-10}$$

O vetor bias **b** pode ser facilmente calculado, definindo $\mathbf{q}, \dot{\mathbf{q}}$ do seu estado atual, fazendo $\ddot{\mathbf{q}} = 0$, é usando a função do programa $SUB(\mathbf{q}, \dot{\mathbf{q}}, 0; \mathbf{b})$. O torque computado pela função SUB com esses valores de entrada é igual ao vetor bias **b**.

A dificuldade está em calcular a equação(A-10), para encontrar os valores da matriz **H**. Neste primeiro método, isto é conseguido através da definição de \mathbf{q} em seu estado atual, fazendo $\ddot{\mathbf{q}} = \mathbf{e}_j$, e chamando a função $SUB(\mathbf{q}, 0, \mathbf{e}_j; \mathbf{h}_j)$, onde \mathbf{e}_j é um vetor $n \times 1$ com *j*-ésimo elemento igual a 1 e os demais iguais a 0, e \mathbf{h}_j é a *j*-ésima coluna de **H**. Assim, \mathbf{h}_j é o torque nas juntas quando as velocidades são zero, sem efeitos gravitacionais, e as acelerações nas juntas $\ddot{\mathbf{q}}$ é iguais a \mathbf{e}_j .

Uma vez que todos os elementos da matriz \mathbf{H} são determinados, então as acelerações da junta são obtidas solucionando a equação (A-10)

A.3.2 Método 3

Neste método tem-se um procedimento diferente para calcular a matriz de inércia **H**. Somente a diagonal superior precisa ser calculada (devido à simetria) na seguinte ordem: $H_{n,n}, H_{n-1,n}, H_{n-2,n}, ..., H_{1,n}; H_{n-1,n-1}, H_{n-2,n-1}, ..., H_{1,n-1};$ etc. Para fazer isto, nota-se que quando computamos para a *j*-ésima coluna da matriz de inércia no método 1, $\ddot{\mathbf{q}}_i = 0$ para i > j. Ou seja, todos os seguintes n - j + 1 elos aparecem como um único corpo rígido. Deste sistema composto de elos com a sua massa total, a localização de seu centro de massa e seu momento de inércia seria,

$$\mathbf{F}_{j} = \mathbf{M}_{j} \mathbf{v}_{j} = \mathbf{M}_{j} (\mathbf{z}_{j} \times \mathbf{c}_{j}) = \mathbf{z}_{j-1} \times (\mathbf{M}_{j} \mathbf{c}_{j})$$

$$\mathbf{N}_{j} = \mathbf{E}_{j} \mathbf{z}_{j-1}$$

$$\mathbf{D}_{j} = \mathbf{E}_{j} \mathbf{z}_{j-1}$$

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onde os símbolos anteriormente não definidos são:

 \mathbf{M}_j = massa total do elo j até o elo n.

- $\dot{\mathbf{v}}_j$ = aceleração linear do centro de massa do sistema composto desde o elo *j* até o elo *n*.
- \mathbf{c}_j = localização do centro de massa do sistema composto do elo j até o elo n com respeito à origem de coordenadas do elo j - 1.

 $\mathbf{E}_{j} = \text{matriz}$ do momento de inércia do sistema composto do elo j até elo n.

Com essas acelerações, $\mathbf{F}_i \in \mathbf{N}_i$ são todos zeros para i < j. Utilizando isto,

$$\mathbf{f}_i = \mathbf{f}_{i+1} \tag{A-13}$$

$$\mathbf{n}_{i} = \mathbf{n}_{i+1} + \mathbf{p}_{i}^{*} \times \mathbf{f}_{i+1}$$
 para $i = 1, ..., j - 1$ (A-14)

е

$$\mathbf{f}_j = \mathbf{f}_j \tag{A-15}$$

$$\mathbf{n}_j = \mathbf{N}_j + \mathbf{c}_j + \mathbf{F}_j$$
 para $i = 1, \dots, j - 1$ (A-16)

Assim, inicializando com i = j, equação ?? até ??, pode ser usado para obter todos os valores de n_i e f_i , para $i \leq j$.

Os componentes da matriz de momento de inércia ao longo da coluna jsão então iguais aos torque ou forças geradas na junta. Assim, para $i \leq j$:

$$H_{ij} = \begin{cases} \mathbf{z}_{i-1} \cdot \mathbf{n}_i & \text{Junta } i \text{ rotacional} \\ \mathbf{z}_{i-1} \cdot \mathbf{f}_i & \text{Junta } i \text{ translacional} \end{cases}$$
(A-17)

Para computar M, c_j , e E_j , inicia-se no elo n:

$$\mathbf{M}_n = \mathbf{m}_n \tag{A-18}$$

$$\mathbf{c}_n = \mathbf{s}_n + \mathbf{p}_n^{\star} \tag{A-19}$$

$$\mathbf{E}_n = J_n \tag{A-20}$$

onde,

- $\mathbf{m}_{i} = \text{massa do elo } j.$
 - \mathbf{s}_j = localização do centro de massa do elo j em relção à coordenada do elo j.
- \mathbf{J}_{j} = matriz do momento de inércia do elo j.

Para solucionar \mathbf{M}_i , $\mathbf{c}_i \in \mathbf{E}_i$, pode-se utilizar as seguintes equações recursivas:

$$\mathbf{M}_j = \mathbf{M}_{j+1} + m_j \tag{A-21}$$

$$\mathbf{c}_{j} = \frac{1}{M_{j}} [m_{j}(\mathbf{s}_{j} + \mathbf{p}_{j}^{*}) + M_{j+1}(\mathbf{c}_{j+1} + \mathbf{p}_{j}^{*})]$$
(A-22)

$$\mathbf{E}_{j} = \mathbf{E}_{j+1} + M_{j+1} [(\mathbf{c}_{j+1} + \mathbf{p}_{j}^{*} - \mathbf{c}_{j}) \cdot (\mathbf{c}_{j+1} + \mathbf{p}_{j}^{*} - \mathbf{c}_{j}) \mathbf{I} -(\mathbf{c}_{j+1} + \mathbf{p}_{j}^{*} - \mathbf{c}_{j}) (\mathbf{c}_{j+1} + \mathbf{p}_{j}^{*} - \mathbf{c}_{j})^{T}] + \mathbf{J}_{j} + m_{j} [(\mathbf{s}_{j} + \mathbf{p}_{j}^{*} - \mathbf{c}_{j}) \cdot (\mathbf{s}_{j} + \mathbf{p}_{j}^{*} - \mathbf{c}_{j}) \mathbf{I} -(\mathbf{s}_{j} + \mathbf{p}_{j}^{*} - \mathbf{c}_{j}) (\mathbf{s}_{j} + \mathbf{p}_{j}^{*} - \mathbf{c}_{j})^{T}]$$
(A-23)

onde I é a matriz identidade 3×3 . Da equação (A-22), M_j é a soma da massa do elo j e a massa total do sistema composto do elo j+1 até n. Da equação (A-23), o centro de massa do sistema composto do elo j até elo n pode ser obtido do conhecimento da localização do centro de massa do elo j, s_j e a localização do centro de massa do sistema composto do elo j + 1 até elo n, c_{j+1} . De uma forma análoga, uma vez que c_{j+1}, M_{j+1} , e E_{j+1} foram determinados, usase-se o teorema de eixos paralelos para a matriz de momentos de inércia do sistema composto do elo j até elo n relativo a c_j . O teorema de eixos paralelos é um método para obter a matriz de momentos de inércia J_o de um corpo rígido em relação a uma origem de coordenadas O arbitrária em termos da matriz de inércia J_G relativa ao centro de massa. Seja r o vetor coordenada de G relativo a O, como se mostra na figura A.1, e M a massa, então:

$$\mathbf{J}_0 = \mathbf{J}_G + M(r \cdot rI - rr^T) \tag{A-24}$$

Assim, os primeiros dois termos da equação (A-23) são a contribuição em E_j da composição dos elos j + 1 até n, e os seguintes dois termos são a contribuição E_j pelo elo j, como se mostra na figura A.2.

Na equação (A-11) até (A-23), tem sido implicado que todos os vetores são referenciados ao sistema coordenado O, e por isso que eles são difíceis de calcular. Como descrito em [6], para aliviar o custo computacional, todas as propriedades de massa do sistema composto do elo j até o elo n serão



Figura A.1: Posição do centro de massa G com respeito à coordenada O



Figura A.2: Centro de massa do sistema composto do el
ojaté o elo \boldsymbol{n}

referenciados para o sistema coordenado j - 1. Assim, a equação usada para computar as propriedades da massa do sistema composto do elo j até elo n, para j = 1, ..., n, torna-se:

$$\mathbf{M}_n = \mathbf{m} \mathbf{J}_n \tag{A-25}$$

$$^{n-1}\mathbf{c}_n = A_{n-1}^n ({}^n s_n + \mathbf{p}_n^*)$$
 (A-26)

$${}^{n-1}\mathbf{E}_n = A_{n-1}^n E_n A_n^{n-1} \tag{A-27}$$

Usando este procedimento para computar a matriz de inércia H e o algoritmo descrito no método 1, encontram-se assim, as acelerações requeridas.

A continuação um resumo dos passos para achar a dinâmica direta aplicando o método 3 do algoritmo WAlker-Orin.

Passo 1: Calcule-se M_j , $^{j-1}\mathbf{c}_j$ e $^{j-1}\mathbf{E}_j$ para j = N...1 com

$$M_i = M_{j+1} + m_j$$
 (A-28)

$${}^{j-1}\mathbf{c}_{j} = \mathbf{A}_{j-1}^{j}{}^{j}\mathbf{c}_{j}$$
$${}^{j-1}\mathbf{c}_{j} = \mathbf{A}_{j-1}^{j}\{\frac{1}{M_{j}}[m_{j}({}^{j}\mathbf{s}_{j} + {}^{j}\mathbf{p}_{j}^{*}) + M_{j+1}({}^{j}\mathbf{c}_{j+1} + {}^{j}\mathbf{p}_{j}^{*})]\}$$
(A-29)

$${}^{j-1}\mathbf{E}_{j} = \mathbf{A}_{j-1}^{j} \{{}^{j}\mathbf{E}_{j+1} + M_{j+1} [({}^{j}\mathbf{c}_{j+1} + {}^{j}\mathbf{p}_{j}^{*} - {}^{j}\mathbf{c}_{j}) \cdot ({}^{j}\mathbf{c}_{j+1} + {}^{j}\mathbf{p}_{j}^{*} - {}^{j}\mathbf{c}_{j})\mathbf{I} - ({}^{j}\mathbf{c}_{j+1} + {}^{j}\mathbf{p}_{j}^{*} - {}^{j}\mathbf{c}_{j})({}^{j}\mathbf{c}_{j+1} + {}^{j}\mathbf{p}_{j}^{*} - {}^{j}\mathbf{c}_{j})^{T}] + {}^{j}\mathbf{J}_{j} + m_{j} [({}^{j}\mathbf{s}_{j} + {}^{j}\mathbf{p}_{j}^{*} - {}^{j}\mathbf{c}_{j}) \cdot ({}^{j}\mathbf{s}_{j} + {}^{j}\mathbf{p}_{j}^{*} - {}^{j}\mathbf{c}_{j})\mathbf{I} - ({}^{j}\mathbf{s}_{j} + {}^{j}\mathbf{p}_{j}^{*} - {}^{j}\mathbf{c}_{j})({}^{j}\mathbf{s}_{j} + {}^{j}\mathbf{p}_{j}^{*} - {}^{j}\mathbf{c}_{j})^{T}] \mathbf{A}_{j}^{j-1}$$
 (A-30)

Passo 2: Calcular ${}^{j-1}\mathbf{F}_j,\,{}^{j-1}\mathbf{N}_j$ paraj=1...Nutilizando

$${}^{j-1}\mathbf{F}_j = \mathbf{z}_o \times M_j{}^{j-1}\mathbf{c}_j \tag{A-31}$$

$${}^{j-1}\mathbf{N}_{j} = {}^{j-1}\mathbf{E}_{j}\mathbf{z}_{o} \tag{A-32}$$

(A-33)

Passo 3: Para j = N...1 calcule-se ${}^{i-1}\mathbf{f}_i$, ${}^{i-1}\mathbf{n}_i$, i = j...1 das equações seguintes para uma particular j,

$$^{j-1}\mathbf{f}_j = j_{j-1}\mathbf{F}_j \tag{A-34}$$

$$^{j-1}\mathbf{n}_j = {}^{j-1}\mathbf{N}_j + {}^{j-1}\mathbf{c}_j \times {}^{j-1}\mathbf{F}_j$$
 (A-35)

$$^{i-1}\mathbf{f}_{i} = \mathbf{A}_{i-1}^{i}{}^{i}\mathbf{f}_{i+1} \tag{A-36}$$

$$^{i-1}\mathbf{n}_{i} = \mathbf{A}_{i-1}^{i}(^{i}\mathbf{n}_{i+1} + ^{i}\mathbf{p}_{i}^{*} \times ^{i}\mathbf{f}_{i+1})$$
(A-37)

Utilizando as equações (A-31) até (A-37), seria o procedimento para calcular a matriz H, e com a equação descrito no método 1 acharemos as acelerações para cada valor do torque.

$$\mathbf{H}_{ij} = \begin{cases} z & \text{componente de}^{i-1}\mathbf{n}_i & \text{junta } i \text{ rotativa} \\ z & \text{componente de}^{i-1}\mathbf{f}_i & \text{junta } i \text{ prismática} \end{cases}$$
(A-38)

onde

$$\mathbf{z}_{o} = \begin{bmatrix} 0\\0\\1 \end{bmatrix} \tag{A-39}$$

B Apêndice B

Este apêndice contém as propriedades da modelagem dinâmica do robô manipulador descritas no capítulo 3, importante para os diferentes tipos de algoritmos de controle utilizados neste trabalho.

B.1 Modelagem Dinâmica

Seja a equação da modelagem dinâmica do robô manipulador de n graus de liberdade obtida da expressão (3-22), e seja o vetor \mathbf{q} de $n \times 1$ o deslocamento nas juntas, então:

$$\mathbf{H}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{G}(\mathbf{q}) = \boldsymbol{\tau}$$
(B-1)

B.1.1 Propriedade 1

A matriz de inércia é positiva-definida e simétrica, tal que:

$$\lambda_h \mathbf{I}_n \le \mathbf{H}(\mathbf{q}) \le \lambda_H \mathbf{I}_n \tag{B-2}$$

onde $\lambda_h \in \lambda_H$ são constantes positivas.

B.1.2 Propriedade 2

A matriz $\mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})$ com dimensão $n \times n$ satisfaz:

$$\|\mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\| \le \|c_o \dot{\mathbf{q}}\| \tag{B-3}$$

limitada por alguma constante c_o

B.1.3 Propriedade 3

O vetor força/torque gravitacional satisfaz:

$$\|\mathbf{G}(\mathbf{q})\| \le g_o \tag{B-4}$$

limitada por alguma constante g_o .

B.1.4 Propriedade 4

Da propriedade (B-2), lembre-se que a matriz $\mathbf{H}(\mathbf{q})$ é simétrica $(H_{ij} = H_{ji})$ e seja $\mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})$ a matriz das forças de Coriolis e Centrífugas. Então, representando para o *i*-ésimo elemento $\mathbf{C}\dot{\mathbf{q}}$ como

$$\sum_{j=1}^{n} C_{ij} \dot{q}_j = \frac{1}{2} \sum_{j=1}^{n} \sum_{k=1}^{n} \frac{\partial H_{ij}}{\partial q_k} \dot{q}_j \dot{q}_k + \frac{1}{2} \sum_{k=1}^{n} \sum_{j=1}^{n} \left(\frac{\partial H_{ij}}{\partial q_k} - \frac{\partial H_{jk}}{\partial q_i} \right) \dot{q}_k \dot{q}_j$$

e simplificando a expressão obtém-se:

$$C_{ij} = \frac{1}{2} \sum_{k=1}^{n} \frac{\partial H_{ij}}{\partial q_k} \dot{q}_k + \frac{1}{2} \sum_{k=1}^{n} \left(\frac{\partial H_{ik}}{\partial q_j} - \frac{\partial H_{jk}}{\partial q_i}\right) \dot{q}_k$$

$$C_{ij} = \frac{1}{2}\dot{H}_{ij} + \frac{1}{2}\sum_{k=1}^{n}\left(\frac{\partial H_{ik}}{\partial q_j} - \frac{\partial H_{jk}}{\partial q_i}\right)\dot{q}_k$$

Seja $\mathbf{N}(\mathbf{q}, \dot{\mathbf{q}}) = \mathbf{H}(\mathbf{q}) - 2\mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})$, então

$$N_{ij} = \sum_{k=1}^{n} \left(\frac{\partial H_{jk}}{\partial q_i} - \frac{\partial H_{ik}}{\partial q_j}\right) \dot{q}_k$$

Da expressão anterior, obtemos que:

$$N_{ij} = -N_{ji}$$

Isto significa que a matriz $\mathbf{N}(\mathbf{q}, \dot{\mathbf{q}})$ é uma matriz anti-simétrica, e assim

$$\dot{\mathbf{q}}^T \mathbf{N}(\mathbf{q}, \dot{\mathbf{q}}) \dot{\mathbf{q}} \equiv 0$$

$$\dot{\mathbf{q}}^T (\dot{\mathbf{H}} - 2\mathbf{C}) \dot{\mathbf{q}} \equiv 0$$
(B-5)

para qualquer vetor $\dot{\mathbf{q}}$ de dimensões $n \times 1$

B.1.5 Propriedade 5

Um balanço de energia para o robô manipulador de juntas rígidas é dado por:

$$E_{manipulador} = E_{cinética} + E_{potencial}$$

onde

$$E_{cinética} = \frac{1}{2} \dot{\mathbf{q}}^T \mathbf{H} \dot{\mathbf{q}}$$
$$E_{potencial} = \mathbf{U}(\mathbf{q})$$

então

$$E_{manipulador} = \frac{1}{2} \dot{\mathbf{q}}^T \mathbf{H} \dot{\mathbf{q}} + \mathbf{U}(\mathbf{q})$$

Derivando a expressão da energia,

$$\frac{d}{dt}(E_{manipulador}) = \dot{\mathbf{q}}^T \mathbf{H} \ddot{\mathbf{q}} + \frac{1}{2} \dot{\mathbf{q}}^T \dot{\mathbf{H}} \dot{\mathbf{q}} + \frac{\partial \mathbf{U}(\mathbf{q})}{\partial t} \frac{\partial q}{\partial q}$$
$$\frac{d}{dt}(E_{manipulador}) = \dot{\mathbf{q}}^T \mathbf{H} \ddot{\mathbf{q}} + \frac{1}{2} \dot{\mathbf{q}}^T \dot{\mathbf{H}} \dot{\mathbf{q}} + \dot{\mathbf{q}}^T \mathbf{G}$$

Substituindo a equação dinâmica do manipulador, obtemos

$$\frac{d}{dt}(E_{manipulador}) = \dot{\mathbf{q}}^T \boldsymbol{\tau} - \dot{\mathbf{q}}^T \mathbf{C} \dot{\mathbf{q}} - \dot{\mathbf{q}}^T \mathbf{G} + \frac{1}{2} \dot{\mathbf{q}}^T \dot{\mathbf{H}} \dot{\mathbf{q}} + \dot{\mathbf{q}}^T \mathbf{G}$$
$$\frac{d}{dt}(E_{manipulador}) = \dot{\mathbf{q}}^T \boldsymbol{\tau} + \dot{\mathbf{q}}^T (\frac{1}{2} \dot{\mathbf{H}} - \mathbf{C}) \dot{\mathbf{q}}$$

Então, utilizando a propriedade (B-5), finalmente obtemos

$$\frac{d}{dt}(E_{manipulador}) = \dot{\mathbf{q}}^T \boldsymbol{\tau}$$
(B-6)

Se observa que os termos de Coriolis e das forças centrífugas não contribuem para a variação temporal da energia total. Além disso, a potência necessária para o movimento do robô manipulador é aquela potência transmitida pelo atuador de cada junta. As forças de Coriolis e Centrífuga não contribuem na potência do sistema.

C Apêndice C

C.1 Instalação do CHAI3D em MVS2008

Para experimentar os exemplos demo do CHAI3D no MVS2008 fazemos o seguinte:

• Execute o Visual Studio 2008 e abre um Projeto Solution assim, no menu File- >Open- >Project\Solution... ou tecle Ctrl+Shift+O como se mostra na figura C.1.

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Figura C.1: Microsoft Visual Studio 2008

• Aparecerá uma nova janela para abrir o arquivo com extensão .sln, Esse arquivo se encontra na pasta de exemplos\msvc9 do CHAI3D com o nome CHAI3D.sln. Logo compilamos o programa teclando Ctrl+F7 e todos os exemplo demo ficaram pronto para sua experimentação como mostra a figura C.2 e C.3.

Os seguintes passos descrevem a configuração um novo projeto utilizando as bibliotecas que o CHAI3D utiliza. Isto serve para poder programar um próprio código para desenvolver o entorno virtual com a aplicação descrita para este trabalho.



Figura C.2: Compilação dos exemplos demo do CHAI3D

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Figura C.3: Exemplo 01-devices do CHAI3D

- Execute o Visual Studio 2008 e crie um novo projeto no menu File->New->Project ou tecle Ctrl+Shift+N. Guarde o nome projeto na pasta de exemplos\msvc9 do CHAI3D. Para a aplicação utilizamos Win32 Console Application e com um empty project, como mostramos na figura C.4.
- Logo no MSV2008 na parte do menu Project- >Project Properties ou teclando Alt+F7 abrimos uma janela onde configuraremos os arquivos para utilizar o CHAI3D.
- 3. Em Configuration Propierties— >C/C++- >General— >Additional Include Directories escrevemos D:\chai3d-2.0.0\src e D:\chai3d-

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Figura C.4: Criando novo projeto no MVS2008

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4. Em Configuration Propierties— >C/C++- >Preprocessor— >Preprocessor Definitions escrevemos:

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 ${\rm como\ mostra\ a\ figuraC.5.}$

- 5. Em Configuration Propierties— >Linker— >General— >Additional Include Directories escrevemos D:\chai3d-2.0.0\external\ODE\lib\msvc D:\chai3d-2.0.0\external\OpenGL\msvc D:\chai3d-2.0.0\lib\msvc9
- 6. Em Configuration Propierties— >Linker— >General— >Ouput File escrevemos D:\chai3d-2.0.0\bin\project1.exe, figuraC.6.
- 7 Em Configuration Propierties— >Linker— >Input— >Additional Dependencies, escrevemos:

```
winmm.lib opengl32.lib chai3d-debug.lib
glu32.lib odbc32.lib odbccp32.lib ode_double.lib
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Finalmente compilamos nosso primeiro projeto, mostrado na figura C.7.

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Figura C.5: Enlace de arquivos cabeçalhos .
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Figura C.6: Enlace de arquivos .lib (Passos 5 e 6)



Figura C.7: Compilação de um projeto com Chai3D