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International Journals/Transactions

1. M. Nakamura, S. R. Munasinghe, S. Goto and N. Kyura, "Enhanced contour control of SCARA robot under torque saturation constraint", *IEEE/ASME Trans. on Mechatronics*, vol. 5, no. 4, pp. 437-440, Dec. 2000.

2. S. R. Munasinghe, M. Nakamura, S. Goto and N. Kyura, "Optimum contouring of industrial robot arms under assigned velocity and torque constraints", *IEEE Tran. on Systems, Man and Cybernetics*, vol. 31, no. 5, pp. 159-167, May, 2001.

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3. S. R. Munasinghe and M. Nakamura, "Teleoperation of welfare robotic systems by motion planning considering assigned velocity and acceleration limit", *Intl. J. Human-Friendly Welfare Robotic Systems*, vol. 3, no. 2, pp. 23-31, June, 2002.

4. S. R. Munasinghe, M. Nakamura, S. Goto and N. Kyura, "Trajectory planning for industrial robot manipulators considering assigned velocity and allowance under joint acceleration limit", *Intl. J. of Control, Automation, and Systems*, vol. 1, no. 1, pp. 68-75, March, 2003.

5. S. R. Munasinghe, M. Nakamura, S. Goto and N. Kyura, "Pole selection of feedforward compensators considering bounded control input of industrial mechatronic systems", *IEEE Tran. on Industrial Electronics, Part-A*, (accepted for publication).

6. S. R. Munasinghe and M. Nakamura, "Determination of maximum end-effector

velocity at trajectory corners in robot manipulator control under joint acceleration constraint", *IEEE Tran. on Systems Man, and Cybernetics* (in review).

International Conference Proceedings

1. M. Nakamura, S. R. Munasinghe, S. Goto and N. Kyura, "Enhanced contour control of SCARA robot under torque constraint", *in Proc. IEEE/RSJ Intl. Conf. on Intelligent Robots and Systems*, pp. 1774-1779, Taejon, Korea, Dec 17-21, 1999.

2. S. R. Munasinghe, M. Nakamura, S. Aoki, S. Goto and N. Kyura, "High speed precise control of robot arms with assigned speed under torque constraint by trajectory generation in joint co-ordinates", *in Proc. IEEE Intl. Conf. on Systems, Man, and Cybernetics*, pp.II-854-857, Tokyo, Japan, Oct. 12-17, 1999.

3. M. Nakamura, S. R. Munasinghe, S. Goto, and N. Kyura, "Feasible method of optimum control of industrial robot arms in operation under speed and torque constraint", *in Proc. 3rd Asian Control Conf.*, pp. 2887-2892, Shanghai, China, July, 2000.

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4. S. R. Munasinghe, M. Nakamura, S. Goto, and N. Kyura, "Precise control of industrial robot arms considering trajectory allowance under torque and speed constraint" *in Proc. IEEE Intl. Conf. on Robotics and Automation*, pp. 3949-3954, Seoul, Korea, May 21-26, 2001.

5. S. R. Munasinghe, M. Nakamura, T. Iwanaga, S. Goto, and N. Kyura, "Precise, Jerk-free contouring of industrial robot arms with trajectory allowance under torque and velocity constraints" *in Proc. IEEE Intl. Conf. on Industrial Electronics*, pp. 204-209, Denver. Colorado, USA, Nov. 29-Dec. 2, 2001.

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1. M. Nakamura, S. R. Munasinghe, S. Goto and N. Kyura, "Effective tracking Control of articulated robot manipulators with torque saturation characteristics", *Annul Conf. of Society of Instrumentation and Cntrol Engineers (SICE), kyushu Branch*, pp 137-140, Okinawa, Japan, Dec. 12-13, 1998.

2. S. R. Munasinghe, M. Nakamura, S. Goto and N. Kyura, "Contouring control of industrial robot arms with trajectory allowance under velocity and torque constraints in three dimensional space", *Annul Conf. of Society of Instrumentation and Cntrol Engineers (SICE), kyushu Branch*, pp. 333-336, Miyazaki, Japan, Nov. 27-28, 2000.

3. S. R. Munasinghe, M. Nakamura, S. Goto, and N. Kyura, "Pole selection for modified data method for mechatronic servo systems by considering bounded control input" *in Proc. Annul Conf. of Society of Instrumentation and Cntrol Engineers (SICE), kyushu Branch*, pp. 183-185, Kumamoto, Japan, Dec. 15-16, 2001.

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4. S. R. Munasinghe, M. Nakamura, S. Goto, and N. Egashira, "Advanced motion planning and supervised control for teleoperated welfare robots" *in Proc. Annul Conf. of Society of Instrumentation and Cntrol Engineers (SICE), kyushu Branch*, pp. 309-312, Oita, Japan, Dec. 7-8, 2002.

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Appendix A

Actuator Saturation in Servo Control

Industrial robotics is mostly based on servo dynamics with kinematic control [16]. Awareness of the actuator saturation characteristics is essential in order to set the torque/acceleration saturation constraint of these control models. It is therefore necessary to be considered in trajectory planning as well. All practical trajectory planners should have this limit and it is a must-have constraint. A simple test to experimentally determine this limit has been developed for Performer MK3s manipulator. The method can be customized to other manipulators also. It determines the actual acceleration limit of a single servo joint. The test set-up is illustrated in Fig. A.1 Performer MK3s manipulator has a built-in torque monitor that monitors

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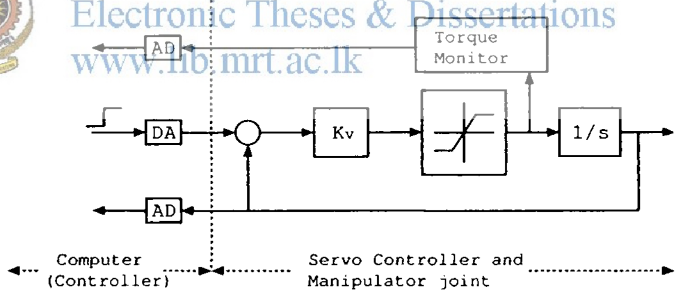

Figure A.1: Test set-up to determine joint acceleration limit

motor torque. This signal can be used to observe torque saturation characteristics. Pulse counter output reads the joint velocity which can be differentiated to observe joint acceleration saturation. In a test, the three joints of the Performer MK3s manipulator were individually exited with step inputs $VOLT_{in}$ =0.4[Volt] to 2.6[Volt] in 0.2[Volt] steps. The torque monitor signals for these inputs are recorded as illustrated in Fig. A.2. Actuator saturation phenomena can be clearly observed from the above results. Corresponding joint velocity signals were obtained as shown in Fig. A.3. Differentiation of joint velocity results reveal joint acceleration information and they can be plotted with torque monitor results as shown in Fig. A.4 Torque monitor signal shows saturation limit approximately equal to 1.6[V/s], The unit is [V/s] as it was differentiated from joint velocity signal. And, joint accelerations show corresponding saturation limits approximately equal to 90[V]. These limits are common to all three joints. Joint acceleration limit can be used to represent joint torque saturation so that enough accuracy can be obtained with the servo controller as shown in Fig. 2.2. The physical quantities of these voltage limits can be determined using servo parameters given in Fig. 2.3.

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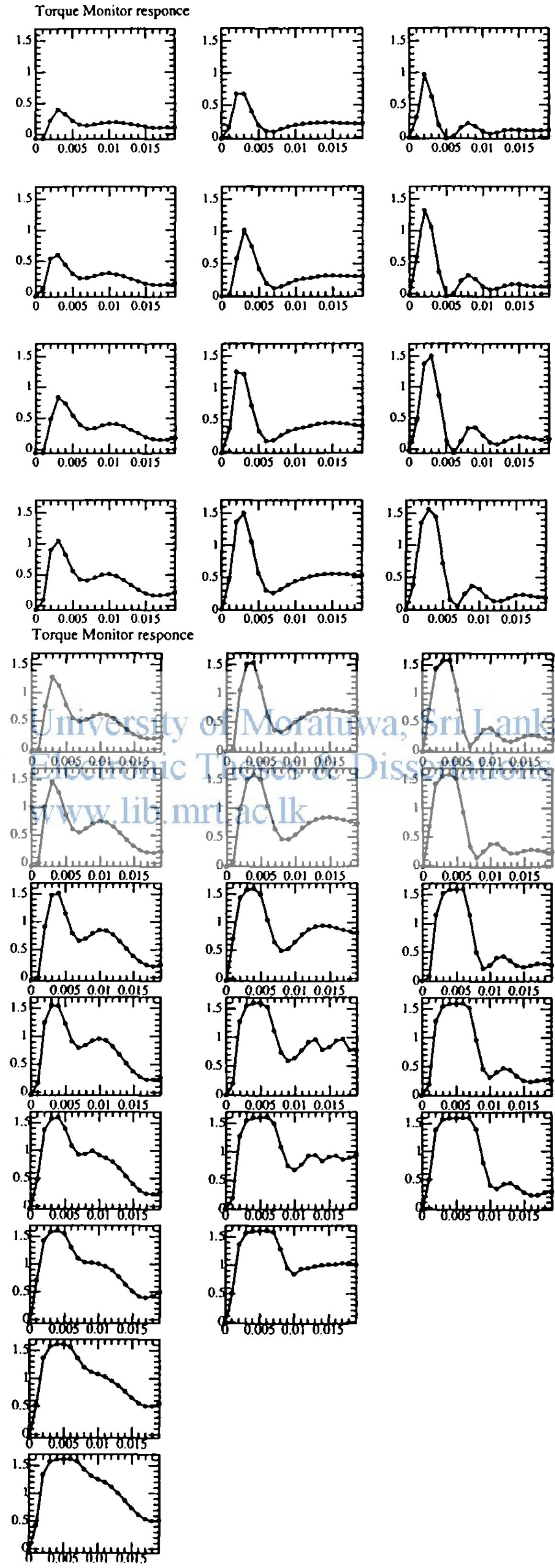

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Figure A.2: Torque monitor signal for step voltage inputs 0.2[V] to 2.6[V] in 0.2[V] steps.

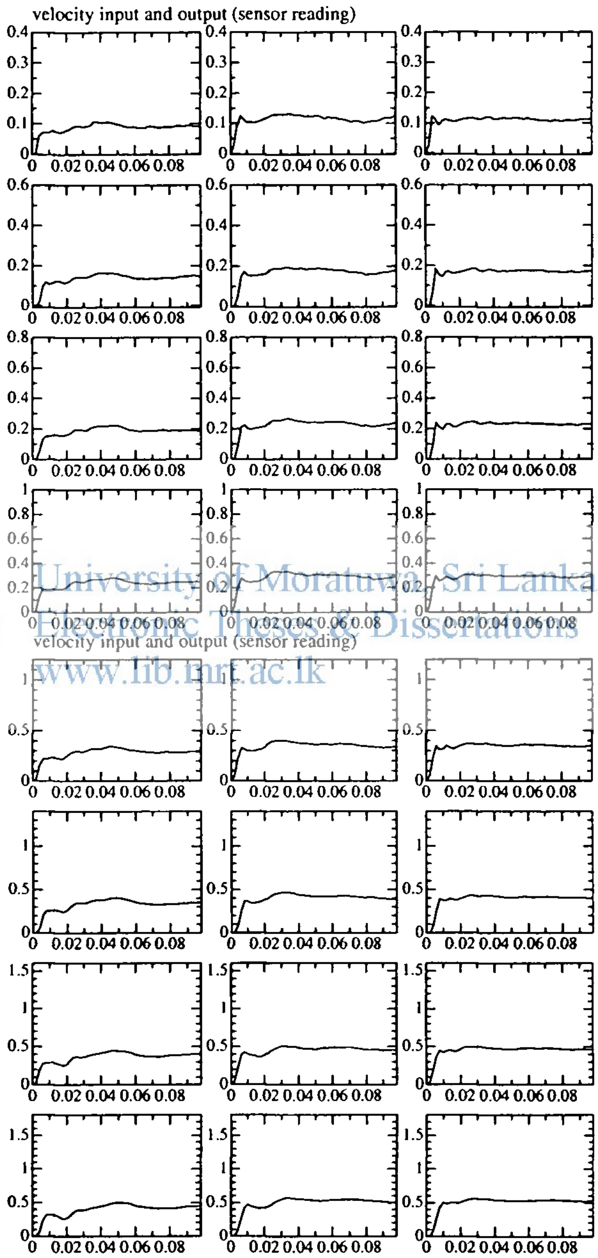

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Figure A.3: Joint velocity signals for step voltage inputs.

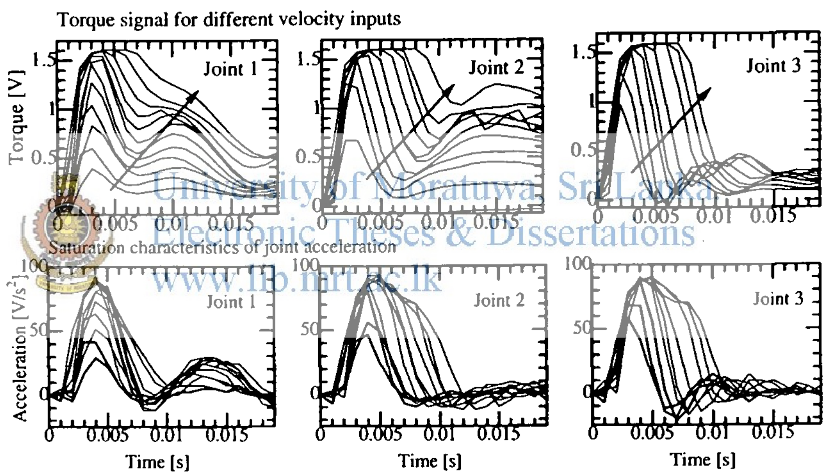

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Figure A.4: Saturation characteristics of torque and joint acceleration.

Appendix B

Planning Steps of a Circular Arc at a Sharp Corner

Figure B.1, illustrates a circular arc that replaces a sharp trajectory corner.

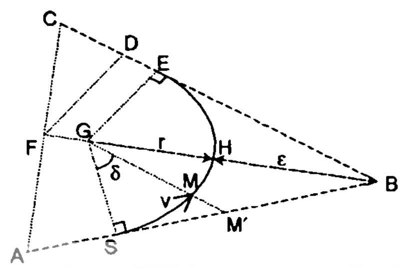

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Figure B.1: Planning of a Cartesian corner.

The steps of planning the circular arc can be itemized as follows:

1. Calculate AB, BC, and AC.
2. $\hat{B} = \cos^{-1}\{[(AB)^2 + (BC)^2 - (AC)^2]/(2AB \times BC)\}$
3. $r = \epsilon \sin(\hat{B}/2)/(1 - \sin(\hat{B}/2))$
4. $\hat{C} = \cos^{-1}\{[(BC)^2 + (AC)^2 - (AB)^2]/(2BC \times AC)\}$
5. $CF = BC \tan(\hat{B}/2) \sec \hat{C}/(\tan \hat{C} + \tan \hat{B}/2)$
6. Calculate co-ordinates of F using $\lambda - rule$ on AC.
7. Calculate BF
8. Calculate co-ordinates of G using $\lambda - rule$ on BF.
9. $\hat{A} = \cos^{-1}\{[(AB)^2 + (AC)^2 - (BC)^2]/(2AB \times AC)\}$
10. $SB = EB = (r + \epsilon) \cos \hat{B}/2$
11. Calculate co-ordinates of S and E using $\lambda - rule$ on AB and BC.

Planning of circular arc SHE involves determination of co-ordinates of M, $\forall \delta \in [0, \pi - \hat{B}]$. Considering ΔSBG, half arc from S to H can be planned according to following steps.

For a given δ.

1. $SM' = r \tan \delta$
2. Calculate co-ordinates of M' using $\lambda - rule$ on SB
3. $GM' = r \sec \delta$
4. Calculate co-ordinates of M using $\lambda - rule$ on GM'

The above procedure can be applied on ΔEBG to plan the half arc from H to E.

Appendix C

Manipulator Kinematics

C.1 Position

Position kinematics relates end-effector position (in Cartesian co-ordinates) to arm configuration (in joint co-ordinates). Referring to Fig. 4.3(a), which illustrates manipulator arm configuration with respect to a specified Cartesian co-ordinate system, let's define the end-effector position tensor in Cartesian co-ordinates as $\boldsymbol{x} = [x^1\ x^2\ x^3]^T$, and the tensor for arm configuration as $\boldsymbol{\theta} = [\theta^1\ \theta^2\ \theta^3]^T$, $i = 1, 2, 3$. Trigonometrically, the relationship between $\boldsymbol{x}$ and $\boldsymbol{\theta}$ can be written as

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$$\boldsymbol{x} = \boldsymbol{f}(\boldsymbol{\theta}), \tag{B.1}$$

in that the vector $\boldsymbol{f}(\boldsymbol{\theta}) = [f^1(\boldsymbol{\theta}) f^2(\boldsymbol{\theta}) f^3(\boldsymbol{\theta})]^T, i = 1, 2, 3$ can be written as

$$\boldsymbol{f}(\theta) = \begin{bmatrix} (L^1 + L^2S^1 + L^3S^{23})C^1 \\ (L^1 + L^2S^1 + L^3S^{23})S^1 \\ L^2C^2 + L^3C^{23} \end{bmatrix}$$

in that $C^i = \cos(\theta^i)$, $S^i = \sin(\theta^i)$, $C^{ij} = \cos(\theta^i + \theta^j)$, and $S^{ij} = \sin(\theta^i + \theta^j)$. Symbol L^i stands for the length of ith link.

C.2 Velocity

Velocity kinematics relates end-effector velocity $\dot{\boldsymbol{x}} = [\dot{x}^1\ \dot{x}^2\ \dot{x}^3]^T$ to joint velocities $\dot{\boldsymbol{\theta}} = [\dot{\theta}^1\ \dot{\theta}^2\ \dot{\theta}^3]^T$ and arm configuration $\boldsymbol{\theta}$. To find out velocity kinematics, we differentiate (B.1) that results

$$\dot{\boldsymbol{x}} = \boldsymbol{f}_{\boldsymbol{\theta}}(\boldsymbol{\theta})\dot{\boldsymbol{\theta}}, \tag{B.2}$$

where the matrix $\boldsymbol{f}_{\boldsymbol{\theta}}(\boldsymbol{\theta}) \triangleq \{\partial f^i(\boldsymbol{\theta})/\partial\theta^j\}, i, j = 1, 2, 3$. Matrix $\boldsymbol{f}_{\boldsymbol{\theta}}(\boldsymbol{\theta})$ is also called the Jacobian $\mathbf{J}$, which can be written as

$$\mathbf{J} = \begin{bmatrix} -S^1(L^1 + L^2S^2 + L^3S^{23}) & C^1(L^2C^2 + L^3C^{23}) & L^3C^1C^{23} \\ -C^1(L^1 + L^2S^2 + L^3S^{23}) & S^1(L^2C^2 + L^3C^{23}) & L^3S^1C^{23} \\ 0 & -L^2S^2 - L^3S^{23} & -L^3S^{23} \end{bmatrix}$$

C.3 Acceleration

Acceleration kinematics relates end-effector acceleration $\ddot{\boldsymbol{x}} = [\ddot{x}^1 \; \ddot{x}^2 \; \ddot{x}^3]^T$ to joint accelerations $\ddot{\boldsymbol{\theta}} = [\ddot{\theta}^1 \; \ddot{\theta}^2 \; \ddot{\theta}^3]^T$, joint velocities $\dot{\boldsymbol{\theta}}$ and arm configuration $\boldsymbol{\theta}$. To get acceleration kinematics, we differentiate (B.2) that results

$$\ddot{\boldsymbol{x}} = \boldsymbol{f}_{\theta}(\boldsymbol{\theta})\ddot{\boldsymbol{\theta}} + \sum_{i=1}^{3} \psi^i \dot{\boldsymbol{\theta}}^T \boldsymbol{f}^i_{\theta\theta}(\boldsymbol{\theta})\dot{\boldsymbol{\theta}}, \tag{B.3}$$

where the matrix $\boldsymbol{f}^i_{\theta\theta}(\boldsymbol{\theta}) = \left\{\partial^2 f^i / \partial\theta^j \partial\theta^k\right\}, i, j, k = 1, 2, 3$. Matrix $\boldsymbol{f}^i_{\theta\theta}(\boldsymbol{\theta})$ is also called Hessian $H^i(\boldsymbol{\theta}), i = 1, 2, 3$, which can be derived as follows:

$$\mathbf{H}^1(\theta) = \begin{bmatrix} -C^1(L^1 + L^2S^2 + L^3S^{23}) & -L^2C^2S^1 + L^3S^1C^{23} & -L^3S^1C^{23} \\ -S^1(L^2C^2 + L^3C^{23}) & -L^2C^1S^2 - L^3C^1S^{23} & -L^3C^1S^{23} \\ L^3C^{23}S^1 & -L^3C^1S^{23} & -L^3C^1S^{23} \end{bmatrix}$$

$$\mathbf{H}^2(\theta) = \begin{bmatrix} -S^1(L^1 + L^2S^2 + L^3S^{23}) & -L^2C^1C^2 + L^3C^1C^{23} & L^3C^1C^{23} \\ C^1(L^2C^2 + L^3S^{23}) & -L^2S^1S^2 - L^3S^1S^{23} & -L^3S^1S^{23} \\ L^3C^1C^{23} & -L^3S^1S^{23} & -L^3S^1S^{23} \end{bmatrix}$$

$$\mathbf{H}^3(\theta) = \begin{bmatrix} 0 & 0 & 0 \\ 0 & -L^2C^2 - L^3C^{23} & -L^3C^{23} \\ 0 & -L^2C^{23} & -L^3C^{23} \end{bmatrix}$$

The symbol ψ^i represents joint selection column vector where $\psi^1 = [1 \; 0 \; 0]^T, \psi^2 = [0 \; 1 \; 0]^T$, and $\psi^3 = [0 \; 0 \; 1]$.

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