Bibliography

[AHLM95] S. Akella, W. H. Huang, K. M. Lynch, and M. T. Mason. Planar manipulation on a conveyor with a one joint robot. In *7th Int. Symposium of Robotics Research*, 1995.

[Ara96] H. Arai. Controllability of a 3-dof manipulator with a passive joint under a nonholonomic constraint. In *1996 IEEE Int. Conf. on Robotics and Automation(ICRA'96)*, pages 3707–3713, Minneapolis, MN, April 1996.

[AS93] T. Akiyama and Y. Sakawa. Path planning of space robots by nonlinear programming. In *RSJ 3rd Robot Symposium*, pages 191–196, 1993. (in Japanese).

[AS96] A. Astolfi and W. Schaufelberger. State and output feedback stabilization of multiple chained systems with discontinuous control. In *35th IEEE Conf. on Decision and Control(CDC'96)*, pages 1443–1448, Kobe, Japan, December 1996.

[AT91] H. Arai and S. Tachi. Position control of a manipulator with passive joints using dynamic coupling. *IEEE Trans. on Robotics and Automation*, 7(4):528–534, 1991.

[Bai93] J. Baillieul. Stable average motions of mechanical systems subject to periodic forcing. In *Dynamics and Control of Mechanical Systems: The Falling Cat and Related Problems: Fields Institute Communications*, volume 1, Providence, R.I., 1993. Americal Mathematical Society.

[BG+96] A. Bicchi, Ken. Goldberg, et al. Minimalism in robot manipulation. In *Workshop WS1 in 1996 IEEE Int. Conf. on Robotics and Automation*, Minneapolis, MN, April 1996.

[BKG+95] E. Barreto, E. J. Kostelich, C. Grebogi, E. Ott, and J. A. Yorke. Efficient switching between controlled unstable periodic orbits in higher dimensional chaotic systems. *Physical Review E*, 51(5):4169–4172, May 1995.

[BRM92] A. Bloch, M. Reyhanoglu, and N. McClamroch. Control and stabilization of nonholonomic dynamic systems. *IEEE Trans. on Automatic Control*, 37(11):1746–1757, 1992.

[Bro83] R. W. Brockett. Asymptotic stability and feedback stabilization. In R. W. Brockett, R. S. Millman, and H. J. Sussmann, editors, *Differential Geometric Control Theory*, volume 27 of *Progress in Mathematics*, pages 181–208. Birkhäuser, Boston, 1983.

[BS95] A. Bicchi and R. Sorrentino. Dexterous manipulation through rolling. In *1995 IEEE Int. Conf. on Robotics and Automation(ICRA'95)*, pages 452–457, Nagoya, Japan, 1995.

[CD93a] G. Chen and X. Dong. Controlling chua's circuit. *J. of Circuits, Systems, and Computers*, 3(1):139–149, 1993.

[CD93b] G. Chen and X. Dong. On feedback control of chaotic continuous-time systems. *IEEE Trans. on Circuits and Systems -I: Fundamental Theory and Applications*, 40(9):591–601, September 1993.

[CdWS92] C. Canudas de Wit and O. J. Sørdalen. Exponential stabilization of mobile robots with nonholonomic constraints. *IEEE Trans. on Automatic Control*, pages 1791–1797, 1992.

[Cho92] J. C. K. Chou. Quaternion kinematic and dynamic differential equations. *IEEE Transactions on Robotics and Automation*, 8(1):53–64, 1992.

[CLBW91] J. F. Canny, Z. X. Li, J. Burdick, and J. T. Wen. Nonholonomic motion planning: Theory, algorithms and applications. In *Workshop F2 in 1991 IEEE Int. Conf. on Robotics and Automation*, Sacramento, CA, 1991.

[CN96] W. J. Chung and Y. Nakamura. Motion planning of a nonholonomic manipulator -parametric minimization of kinematic overshoots for chained form systems-. In *2nd ECPD Int. Conf. on Advanced Robotics, Intelligent Automation and Active Systems*, pages 585–590, Vienna, Austria, September 1996.

[CNS95a] W. J. Chung, Y. Nakamura, and O. J. Sørdalen. Experimental reserach of a nonholonomic manipulator. In *4th Int. Symposium on Experimental Robotics*, pages 458–466, Stanford, California, July 1995.

[CNS95b] W. J. Chung, Y. Nakamura, and O. J. Sørdalen. Prototyping a nonholonomic manipulator. In *1995 IEEE Int. Conf. on Robotics and Automation(ICRA'95)*, pages 2029–2036, Nagoya, Japan, May 1995.

[Cor92] J.-M. Coron. Links between local controllability and local continuous stabilization. In *Nonlinear Control Systems Desigm Symposium '92 (NOLCOS'92)*, pages 477–482, Bordeaux, F., 1992.

[Far94] Miklós Farkas. *Periodic Motions*, volume 104 of *Applied Mathematical Sciences (F. John and J. E. Marsden and L. Sirovich eds.)*. Springer-Verlag, New York, 1994.

[Fro79] C. Frohlich. Do springboard divers violate angular momentum conservation ? *American J. of Physics*, 47:583–592, 1979.

[Gol80] H. Goldstein. *Classical Mechanics*. Addison-Wesley, second edition, 1980.

[HJ93] E. R. Hunt and G. Johnson. Keeping chaos at bay. *IEEE Spectrum*, pages 32–36, November 1993.

[IKY96a] J. Imura, K. Kobayashi, and T. Yoshikawa. Exponential stabilization problem of nonholonomic chained systems with specified transient response. In *35th IEEE Conf. on Decision and Control(CDC'96)*, pages 4733–4738, Kobe, Japan, December 1996.

[IKY96b] J. Imura, K. Kobayashi, and T. Yoshikawa. Nonholonomic control of 3 link planar manipulator with a free joint. In *35th IEEE Conf. on Decision and Control(CDC'96)*, pages 1435–1436, Kobe, Japan, December 1996.

[KCdW95] H. Khennouf and C. Canudas de Wit. On the construction of stabilizing discontinuous controllers for nonholonomic systems. In *Proc. of NOLCOS'95*, pages 747–752, 1995.

[KCdW96] H. Khennouf and C. Canudas de Wit. Quasi-continuous exponential stabilizers for nonholonomic systems. In *IFAC 13th World Congress*, pages 2b–174. International Federation of Automatic Control, 1996.

[KHY72] T. R. Kane, M. R. Headrick, and J. D. Yatteau. Experimental investigation of an astronaut maneuvering scheme. *J. of Biomechanics*, 5:313–320, 1972.

[KKMN90] Y. Kanayama, Y. Kimura, F. Miyazaki, and T. Noguchi. A stable tracking control method for an autonomous mobile robot. In *1990 IEEE Int. Conf. on Robotics and Automation(ICRA'90)*, pages 384–389, Cincinnati, Ohio, 1990.

[KKMN91] Y. Kanayama, Y. Kimura, F. Miyazaki, and T. Noguchi. A stable tracking control method for a nonholonomic mobile robot. In *IEEE/RSJ Int. Workshop on Intelligent Robots and Systems '91(IROS'91)*, pages 1236–1241, Osaka, November 1991.

[KR86] J. Kerr and B. Roth. Analysis of multifingered hands. *Int. J. of Robotics Research*, 4(4):3–17, 1986.

[KRM94] I. V. Kolmanovsky, M. Reyhanoglu, and N. H. McClamroch. Discontinuous feedback stabilization of nonholonomic systems in extended power form. In *33rd IEEE Conf. on Decision and Control*, pages 33469–3474, Lake Buena Vista, FL, 1994.

[KS69] T. R. Kane and M. P. Scher. A dynamical explanation of the falling cat phenomenon. *Int. J. of Solids and Structures*, 5:663–670, 1969.

[KS70] T. R. Kane and M. P. Scher. Human self-rotation by means of limb movements. *J. of Biomechanics*, 3:39–49, 1970.

[KS92] Jong Hyun Kim and John Stringer, editors. *Applied Chaos*. Wiley Interscience, New York, 1992.

[Lap91] V. V. Lapshin. Motion control of a legged machine in the supportless phase of hopping. *Int. J. of Robotics Research*, 10(4):327–337, 1991.

[Lau87] J.-P. Laumond. Feasible trajectories for mobile robots with kinematic and environment constraints. In O. L. Hertzberger and F. C. A. Groen, editors, *Intelligent Autonomous Systems*, pages 346–354, 1987.

[Lau90] J.-P. Laumond. Nonholonomic motion planning versus controllablity via the multibody car system example. Technical Report STAN-CS-90-1345, Stanford University, December 1990.

[Lau91] J.-P. Laumond. Controllability of a multibody mobile robot. In *Int. Conf. on Advanced Robotics*, Pisa, Italy, 1991.

[LC90] Z. Li and J. Canny. Motion of two rigid bodies with rolling constraint. *IEEE Trans. on Robotics and Automation*, 6(1):62–71, 1990.

[LCH90] Z. Li, J. Canny, and G. Heinzinger. Robot motion planning with nonholonomic constraints. In *Robotics Research: the 5th Int. Symposium (August 1989, Tokyo)*, pages 309–316. MIT press, 1990.

[LDG93] Y.-V. Lai, M. Ding, and C. Grebogi. Controlling hamiltonian chaos. *Physical Review E*, 47(1):86–92, January 1993.

[LdN96] W. Leroquais and B. d'Andréa Novel. Modeling and control of wheeled mobile robots not satisfying ideal velocity constraints : unicycle case. In *35th IEEE Conf. on Decision and Control(CDC'96)*, pages 1437–1442, Kobe, Japan, December 1996.

[LM95] K.M. Lynch and M.T. Mason. Controllability of pushing. In *1995 IEEE Int. Conf. on Robotics and Automation(ICRA'95)*, pages 112–119, Nagoya, Japan, 1995.

[LM96] K. M. Lynch and M. T. Mason. Dynamic underactuated nonprehensile manipulation. In *IEEE/RSJ Int. Workshop on Intelligent Robots and Systems (IROS'96)*, 1996.

[LM97] A. D. Lewis and R. M. Murray. Configuration controllability of simple mechanical control systems. *SIAM J. of Control and Optimization*, 35(3):766–790, 1997.

[LMO96a] A. De Luca, R. Mattone, and G. Oriolo. Control of underactuated mechanical systems: Applicatiopn to the planar 2r robot. In *35th IEEE Conf. on Decision and Control(CDC'96)*, pages 1455–1460, Kobe, Japan, December 1996.

[LMO96b] A. De Luca, R. Mattone, and G. Oriolo. Dynamic mobility of redundant robots using end-effector commands. In *1996 IEEE Int. Conf. on Robotics and Automation(ICRA'96)*, pages 1760–1767, Minneapolis, MN, April 1996.

[Lon90] R. W. Longman. The kinetics and workspace of a satellite-mounted robot. *Journal of the Astronautical Sciences*, 38(4):423–440, 1990.

[LS90] G. Lafferriere and H. J. Sussmann. Motion planning for controllable systems without drift. In *Prep. of Workshop F2,Nonholonomic Motion Planning: Theory,Algorithms and Applications (at 1991 IEEE Int. Conf. on Robotics and Automation)*, pages 1148–1153, Sacramento, CA, 1990.

[LS93] G. Lafferriere and H.J. Sussmann. A differential geometric approach to motion planning. In Z. X. Li and J. F. Canny, editors, *Nonholonomic Motion Planning*, pages 235–270. 1993.

[Lyn96] K. M. Lynch. *Nonprehensile Robotic Manipulation: Controllability and Planning*. PhD thesis, The Robotics Institute, Carnegie Mellon Univ., March 1996.

[Mar94] M. Marey. Des mouvements que certains animaux exécutent pour retomber sur leurs pieds, lorsqu'ils sont pr/'ecipités d'un lieu élevé. *C. r. hebd. Seanc. Acad. Sci.*, 119:714–717, 1894.

[ML93] M. T. Mason and K. M. Lynch. Dynamic manipulation. In *IEEE/RSJ Int. Workshop on Intelligent Robots and Systems (IROS'93)*, pages 152–159, 1993.

[MLF97] K. Machida, Z. H. Luo, and M. Funaki. Prototyping and control experiments of a cartesian nonholonomic robot. *J. of Robotic Society of Japan*, 15(2):243–248, 1997. (in Japanese).

[MLS94a] R. M. Murray, Z. Li, and S. S. Sastry. *A Mathematical Introduction to Robotic Manipulation*. CRC Press, Boca Raton, 1994.

[MLS94b] R. M. Murray, Z. Li, and S. S. Sastry. *A Mathematical Introduction to Robotic Manipulators*. CRC Press, 1994.

[MR96] H. Michalska and F. U. Rehman. Discontinuous feedback stabilization using guiding functions: the fire truck example. In *35th IEEE Conf. on Decision and Control(CDC'96)*, pages 1712–1713, Kobe, Japan, December 1996.

[MS91] R.M. Murray and S.S. Sastry. Steering nonholonomic systems in chained form. In *IEEE Conf. on Decision and Control(CDC'91)*, pages 1121–1126, Brighton, UK, 1991.

[MS96] P. Morin and C. Samson. Time-varying exponential stabilization of chained form systems based on a backstepping technique. In *35th IEEE Conf. on Decision and Control(CDC'96)*, pages 1449–1454, Kobe, Japan, December 1996.

[MZ94] R. Mukherjee and M. Zurowski. Pseudo-holonomic behavior of planar space robots. In *1994 IEEE Int. Conf. on Robotics and Automation(ICRA'94)*, pages 2405–2410, 1994.

[NI93] Y. Nakamura and R. Iwamoto. Space multibody structure connected with free joints and its shape control. In *32nd Conf. on Decision and Control(CDC'93)*, San Antonio, Texas, 1993.

[NIY95] Y. Nakamura, R. Iwamoto, and K. Yoshimoto. Control of nonholonomic mechanisms with drift. *Journal of Robotic Society of Japan*, 13(6):830–837, 1995. (in Japanese).

[NM89] Y. Nakamura and R. Mukherjee. Redundancy of space manipulator on free-flying vehicle and its nonholonomic path planning. In *NASA Conf. on Space Telerobotics*, pages 181–190, Pasadena, CA, 1989.

[NM90] Y. Nakamura and R. Mukherjee. Bi-directional approach for nonholonomic path planning of space robots. In *Robotics Research: the 5th Int. Symposium(August 1989, Tokyo)*, pages 405–416. MIT press, 1990.

[NM91] Y. Nakamura and R. Mukherjee. Nonholonomic path planning of space robots via a bidirectional approach. *IEEE Trans. on Robotics and Automation*, 7(4):500–514, 1991.

[NM97] Y. Nakamura and R. Mukherjee. Noetherian perspective of eulerian motion of a free rigid body. *AIAA Journal of Guidance, Control, and Dynamics*, 20(1):193–196, 1997.

[NS91] Y. Nakamura and S. Savant. Nonholonomic motion control of an autonomous underwater vehicle. In *IEEE/RSJ Int. Workshop on Intelligent Robots and Systems '91(IROS'91)*, pages 1254–1259, Osaka, November 1991.

[NS92] Y. Nakamura and S. Savant. Nonholonomic tracking control of autonomous underwater vehicles. In *1992 IEEE Int. Conf. on Robotics and Automation(ICRA'92)*, Nice, France, May 1992.

[NT93] E. Nakano and M. Tsuchiya. A study on the control of the rotational maneuvers of a robot in midair. *J. of Robotic Society of Japan*, 11(1):91–99, 1993.

[NvdS90] H. Niemeijer and A. J. van der Schaft. *Nonlinear dynamical Control Systems*. Springer-Verlag, 1990.

[OGY90] E. Ott, C. Grebogi, and J. A. Yorke. Controlling chaos. *Physical Review Letters*, 64(11):1196–1199, March 1990.

[ON91a] G. Oriolo and Y. Nakamura. Control of mechanical systems with second-order nonholonomic constraints: Underactuated manipulators. In *IEEE Conf. on Decision and Control(CDC'91)*, Brighton, UK, 1991.

[ON91b] G. Oriolo and Y. Nakamura. Free-joint manipulators: Motion control under second-order nonholonomic constraints. In *IEEE/RSJ Int. Workshop on Intelligent Robots and Systems (IROS'91)*, pages 1248–1253, Osaka, November 1991.

[P+96] M. Peshkin et al. Nonholonomic haptic display. In *1996 Int. Conf. on Robotics and Automation*, Minneapolis, MN, 1996.

[Pom92] J.-B. Pomet. Explicit design of time-varying stabilizing control laws for a class of controllable systems without drift. *System and Control Letters*, 18:139–145, 1992.

[RM96] M. Rathinam and R. M. Murray. Configuration flatness of lagrangian systems underactuated by one control. In *35th IEEE Conf. on Decision and Control(CDC'96)*, pages 1688–1693, Kobe, Japan, December 1996.

[RvdSMK96] M. Reyhanoglu, A. van der Schaft, N. H. McClamroch, and I. Kolmanovsky. Nonlinear control of a class of underactuated systems.

In *35th IEEE Conf. on Decision and Control(CDC'96)*, pages 1682–1687, Kobe, Japan, December 1996.

[SAA90] C. Samson and K. Ait-Abderrahim. Mobile robot control part 1 : feedback control of a nonholonomic wheeled cart in cartesian space. Technical Report 1228, INRIA Sophia-Antipolis, France, June 1990.

[SAA91] C. Samson and K. Ait-Abderrahim. Feedback stabilization of a nonholonomic wheeled mobile robot. In *IEEE/RSJ Int. Workshop on Intelligent Robots and Systems '91(IROS'91)*, pages 1242–1247, Osaka, November 1991.

[Sal82] J. K. Salisbury. *Kinematic and force analysis of articulated hands.* PhD thesis, Dept. of Mechanical Engineering, Stanford Univ., 1982.

[Sam91a] C. Samson. Time-varying feedback stabilization of nonholonomic car-like mobile robots. Technical Report 151, INRIA Sophia-Antipolis, 1991.

[Sam91b] C. Samson. Velocity and torque feedback control of a nonholonomic cart. In *Advanced Robot Control, Lecture Notes in Control and Information Sciences No.162*, pages 125–151. Springer-Verlag, 1991.

[Sam93] C. Samson. Time-varying feedback stabilization of a car-like wheeled mobile robot. *Int. J. of Robotics Research*, 12(1):55–64, 1993.

[SB94] D. Seto and J. Baillieul. Control problems super-articulated mechanical systems. *IEEE Trans. on Automatic Control*, 39(12):2442–2453, 1994.

[SCdW92] O.J. Sørdalen and C. Canudas de Wit. Path following and stabilization of a mobile robot. In *Proc. IFAC Nonlinear Control Systems Design Symp.*, pages 513–518, Bordeaux, France, 1992.

[Sch80] B. F. Schutz. *Geometrical method of mathematical physics.* Cambridge University Press, 1980.

[SDE93] O. J. Sørdalen, M. Dalsmo, and O. Egeland. An exponentially convergent control law for a nonholonomic underwater vehicle. In *IEEE Transaction*, 1993.

[SGOY93] T. Shinbrot, C. Grebogi, E. Ott, and J. A. Yorke. "using small perturbations to control chaos". Nature, 363:411–417, 1993.

[SIKK94] M. Sampei, M. Ishikawa, H. Kiyota, and M. Koga. Time-state control form and its application to non-holonomic systems. In *12th Annual Conf. of Robotic Society of Japan*, pages 437–438, 1994. (in Japanese).

[SKI95] M. Sampei, H. Kiyota, and M. Ishikawa. Time-state control form and its application to a non-holonomic space robot. In *NOLCOS'95*, 1995.

[SKKS96] M. Sampei, H. Kiyota, M. Koga, and M. Suzuki. Necessary and sufficient conditions for transformation of nonholonomic system into time-state control form. In *35th IEEE Conf. on Decision and Control(CDC'96)*, pages 4745–4746, Kobe, Japan, December 1996.

[SMO91] K. Senda, Y. Murotsu, and M. Ozaki. A method of attitude control for space robots (an approach using a neural network). *Trans. of the Japan Society of Mechanical Engineers*, 57(539(C)):2356–2362, 1991. (in Japanese).

[SNC94] O.J. Sørdalen, Y. Nakamura, and W.J. Chung. Design of a nonholonomic manipulator. In *1994 IEEE Int. Conf. on Robotics and Automation(ICRA'94)*, pages 8–13, San Diego, CA, 1994.

[SNC95a] O. J. Sørdalen, Y. Nakamura, and W. J. Chung. Application of nonholonomic constraints design of controllable mechanisms. In *European Control Conference(ECC'95)*, pages 1876–1881, Roma, Italy, September 1995.

[SNC95b] O. J. Sørdalen, Y. Nakamura, and W. J. Chung. Path planning and stabilization of a nonholonomic manipulator. In *European Control Conference(ECC'95)*, pages 2636–2641, Roma, Italy, September 1995.

[Sør93] O.J. Sørdalen. Conversion of the kinematics of a car with n trailers into a chained form. In *1993 IEEE Inter. Conf. on Robotics and Automation(ICRA'93)*, pages 1/382–1/387, Atlanta, Georgia, 1993.

[Spr86] K. W. Spring. Euler parameters and the use of quaternion algebra in the manipulation of finite rotations: a review. *Mechanism and Machine Theory*, 21(5):365–373, 1986.

[Sre90] N. Sreenath. Nonlinear control of multibody systems in shape space. In *1990 IEEE Int. Conf. on Robotics and Automation(ICRA'90)*, pages 1776–1781, Cinncinati, OH, 1990.

[Sus87] H. J. Sussmann. A general theorem on local controllability. *SIAM J. Control and Optimization*, 25(1), January 1987.

[SV85] J. A. Sanders and F. Verhulst. *Averaging Methods Nonlinear Dynamical Systems*. Springer-Verlag, 1985.

[Tab89] M. Tabor. *Chaos and integrability in nonlinear dynamics – an introduction.* Wiley Inter-Science, 1989.

[UY87] Y. Umetani and K. Yoshida. Continuous path control of space manipulators mounted on omv. *Acta Astron*, 15(12):981–986, 1987.

[UY89] Y. Umetani and K. Yoshida. Resolved motion rate control of space manipulators with generalized jacobian matrix. *IEEE Trans. on Robotics and Automation*, 5:303–314, 1989.

[Vaf87] Z. Vafa. *The Kinematics, Dynamics and Control of Space Manipulators: the Virtual Manipulator Concept.* PhD thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology, 1987.

[Var84] V. S. Varadarajan. *Lie Groups, Lie Algebras, and Their Representations.* Springer-Verlag, 1984.

[VD90] Z. Vafa and S. Dubowsky. On the dynamics of space manipulators using the virtual manipulator, with applications to path planning. *Journal of the Astronautical Sciences*, 38(4):441–472, 1990.

[Wig90] S. Wiggins. *Introduction to Applied Nonlinear Dynamical Systems and Chaos.* Springer-Verlag, 1990.

[WSE95] K.Y. Wichlund, O.J. Sørdalen, and O. Egeland. Control properties of underactuated vehicles. In *1995 IEEE Int. Conf. on Robotics and Automation(ICRA'95)*, pages 2009–2014, Nagoya, Japan, 1995.

[Yam93] K. Yamada. Arm path planning for a space robot. In *1993 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems(IROS'93)*, pages 2049–2055, 1993.

[Yam96] K. Yamada. Feedback control of space robot attitude by cyclic motion of arm. *J. of Institute of System Control and Information Engineers*, 9(6):296–304, 1996. (in Japanese).

[YKK92] K. Yamafuji, T. Kobayashi, and T. Kawamura. Elucidation of twisting motion of a falling cat and its realization by a robot. *J. of Robotic Society of Japan*, 10(5):648–655, 1992. (in Japanese).

Published Papers by the Author and his Colleagues

[Journal Papers] (in English)

[1] Y. Nakamura and T. Suzuki, "Planning Spiral Motions of Nonholonomic Free-Flying Space Robots," *AIAA Journal of Spacecraft and Rockets*, Vol. 34, No. 1, pp. 137–143, Jan.-Feb. (1997).

[2] Y. Nakamura, T. Suzuki and M. Koinuma, "Nonlinear Behavior and Control of A Nonholonomic Free-Joint Manipulator," *IEEE Trans. on Robotics and Automation*, Vol. 13, No. 6, pp. 853–862, Dec. (1997).

[Journal Papers] (in Japanese) (和文)

[3] T. Suzuki and Y. Nakamura, "Spiral Motion of Nonholonomic Space Robots," *Journal of the Robotics Society of Japan*, Vol. 13, No. 7, pp. 1020–1029 (1995).
(鈴木, 中村: 「非ホロノミック宇宙ロボットのスパイラルモーション」, 日本ロボット学会誌, Vol. 13, No. 7, pp. 1020–1029 (1995).)

[4] Y. Nakamura, M. Koinuma and T. Suzuki, "Chaotic Behavior and Nonlinear Control of a Two-Joint Planar Arm with a Free Joint -Control of Nonholonomic Mechanisms with Drift-" Journal of the Robotics Society of Japan, Vol.14, No.4, pp.602–611 (1996). (in Japanese)
(中村, 濃沼, 鈴木: 「自由関節を持つ平面アームのカオス的挙動と非線形制御－ドリフトを持つ非ホロノミック機械の制御－」, 日本ロボット学会誌, Vol. 14, No. 4, pp. 602–611 (1996).)

[5] Y. Nakamura and T. Suzuki, "Behavior Analysis and Control by Amplitude Modulation of Nonholonomic Mechanical Systems via the Averaging Method - Positioning Control of A Planar 2R Free-Joint Manipulator -," *The Journal of Robotic Society of Japan*, Vol. 16, No. 4 (1998). (to appear)
(中村, 鈴木: 「非ホロノミック機械系の平均化法による挙動解析と振幅変調制御－平面 2R 自由関節マニピュレータの位置制御－」, 日本ロボット学会誌, Vol. 16, No. 4 (1998).(掲載予定))

Conference Papers (Reviewed)

[6] Y. Nakamura, T. Suzuki, M. Koinuma, "Nonlinear Behavior and Control of Underactuated Robotic Mechanisms," *The Seventh International Symposium of Robotics Research*, Herrsching am Ammersee, Germany, Oct. (1995) (published as *ROBOTICS RESEARCH : The seventh International Symposium*, (G. Giralt and G. Hirzinger Eds.), pp. 67–77, Springer-Verlag, London (1996))

[7] T. Suzuki and Y. Nakamura, "Planning Spiral Motion of Nonholonomic Space Robots," *Proc. of 1996 IEEE Int. Conf. on Robotics and Automation*, Vol. 1, pp. 718–725, Minneapolis, MN, April (1996).

[8] T. Suzuki, M. Koinuma and Y. Nakamura, "Chaos and Nonlinear Control of a Nonholonomic Free-Joint Manipulator," *Proc. of 1996 IEEE Int. Conf. on Robotics and Automation*, Vol. 3, pp. 2668–2693, Minneapolis, MN, April (1996).

[9] T. Suzuki and Y. Nakamura, "Nonlinear Control of A Nonholonomic Free Joint Manipulator with the Averaging method," *Proc. of 1996 IEEE Conf. on Decision and Control(CDC'96)*, pp. 1694–1699, Kobe, Japan, Dec. (1996).

[10] T. Suzuki and Y. Nakamura, "Control of Manipulators with Free-Joints via the Averaging Method," *Proc. of 1997 IEEE Int. Conf. on Robotics and Automation(ICRA'97)*, pp. 2998–3005, Albuquerque, NM, April (1997).

[11] T. Suzuki and Y. Nakamura, "Analysis and Control of Underactuated Mechanisms via the Averaging Method," *Proc. of 2nd Asian Control Conference(ASCC'97)*, pp. 273–276, Seoul, Korea, July (1997).

[12] T. Suzuki and Y. Nakamura, "Control of 2R Free-Joint Manipulators via the Averaging Method," *The 3rd Int. Conf. on Advanced Mechatronics(ICAM'98)*, Okayama, Japan, Aug. (1998) (in review).

Conference Papers (without review) (in Japanese) (和文)

[12] T. Suzuki and Y. Nakamura, "Non-holonomic Motion Planning of a Space Robot by Spiral Motion," *Prepr. 11th Annual Conf. of Robotic Society of Japan*, pp. 49–52, Chofu, Tokyo, Nov. (1993).
(鈴木, 中村: 「スパイラルモーションによる宇宙ロボットの非ホロノミック運動の計画」, 第 11 回日本ロボット学会学術講演会予稿集, No. 1, pp. 49–52, 調布, Nov. (1993).)

[13] T. Suzuki and Y. Nakamura, "Approximating Infeasible Trajectory of Nonholonomic Space Robot via Spiral Motion," *Prepr. JSME Annual Conf. on Robotics and Mechatronics(ROBOMEC'94)*, pp. 931–936, Kobe, July (1994).
(鈴木, 中村: 「非ホロノミック宇宙ロボットにおける不可能運動のスパイラルモーションによる近似」, 日本機械学会ロボティクス・メカトロニク

ス講演会'94 講演論文集 (ROBOMEC'94), Vol. B, No. 940-21, pp. 931–936, 神戸, July (1994).)

[14] T. Suzuki and Y. Nakamura, "Optimization of Spiral Motion of Nonholonomic Space Robots," *Prepr. 12th Annual Conf. on Robotic Society of Japan*, pp. 29–30, Fukuoka, Nov. (1994).
(鈴木, 中村: 「非ホロノミック宇宙ロボットのスパイラルモーションの最適化」, 第 12 回日本ロボット学会学術講演会予稿集, No. 1, pp. 29–30, 福岡, Nov. (1994).)

[15] T. Suzuki, M. Koinuma and Y. Nakamura, "Control of Nonholonomic Phenomena," *Prepr. 1st Symp. on Theory of Machines and Mechanisms*, pp. 13-18 (1995).
(鈴木, 濃沼, 中村: 「非ホロノミック現象の制御」, 第 1 回日本 IFToMM 会議シンポジウム前刷集, pp. 13–18, 東京, May (1995).)

[16] Y. Nakamura, M. Koinuma and T. Suzuki, " Chaotic Behavior of Nonholonomic Robots with Drift Terms," *Prepr. JSME Annu. Conf. on Robotics and Mechatronics(ROBOMEC'95)*, pp. 925-928, Kawasaki, June (1995).
(中村, 濃沼, 鈴木: 「ドリフト項をもつ非ホロノミックロボットのカオス現象」, 日本機械学会ロボティクス・メカトロニクス講演会'95 (ROBOMEC'95), Vol. B, pp. 925–928, 川崎, June (1995).)

[17] Y. Nakamura, T. Suzuki and M. Koinuma, "Nonlinear Control of Nonholonomic Robots with Drift Terms," *Prepr. JSME Annu. Conf. on Robotics and Mechatronics(ROBOMEC'95)*, Vol. B, pp. 929-932, Kawasaki, June (1995).
(中村, 鈴木, 濃沼: 「ドリフト項をもつ非ホロノミックロボットの非線形制御」, 日本機械学会ロボティクス・メカトロニクス講演会'95 (ROBOMEC'95), Vol. B, pp. 929–932, 川崎 ,June (1995).)

[18] T. Suzuki and Y. Nakamura, "Spiral Motion of Nonholonomic Space Robots," *1995 ISAS 5th Workshop pn Astrodynamics and Flight Mechanics*, pp. 50–57 (1995).
(鈴木, 中村: "非ホロノミック宇宙ロボットのスパイラルモーション," アストロダイナミクスシンポジウム講演後刷り集, pp. 50–57, 相模原, Aug. (1995).)

[19] T. Suzuki, M. Koinuma and Y. Nakamura, "Chaos and Nonlinear Control of Nonholonomic Free Joint Arm," *Prepr. 13th Annual Conf. of Robotic Society of Japan*, No. 3, pp. 695–696, Kawasaki, Nov. (1995).
(鈴木, 濃沼, 中村: 「非ホロノミック自由関節アームのカオスと非線形制御」, 第 13 回日本ロボット学会学術講演会予稿集, No. 3, pp. 695–696, 川崎, Nov. (1995).)

[20] T. Suzuki and Y. Nakamura, "Nonholonomic Control of Multi-link System with Unactuated Joints," *13th Annual Conf. of the Robotic Society of Japan*, No. 3, pp. 707–708 (1995).
(鈴木, 濃沼, 中村: 「受動関節を持つ多リンク系の非ホロノミック制御」, 第 13 回日本ロボット学会学術講演会予稿集, No. 3, pp. 707–708, 川崎, Nov. (1995).)

[21] T. Suzuki and Y. Nakamura, "Nonlinear Control of Nonholonomic Dynamical Systems – Analysis of Behaviors with Periodic Inputs using the Averaging Method and Design of Feedback Control based on it –," *Prepr. JSME Annual Conf. on Robotics and Mechatronics (ROBOMEC'96)*, pp. 1101–1104, Ube (1996).
(鈴木, 中村: 「非ホロノミック動力学システムの非線形制御 – 平均化法を用いた周期入力に対する挙動の解析とそれに基づくフィードバック制御系の設計 –」, 日本機械学会ロボティクス・メカトロニクス講演会'96 (ROBOMEC'96), Vol. B, pp. 1101–1104, 宇部, June (1996).)

[22] T. Suzuki and Y. Nakamura, "Analysis of Second-Order Nonholonomic Systems via Averaging Method," *Prepr. 14th Annual Conf. of the Robotic Society of Japan*, pp. 767–768, Niigata (1996).
(鈴木, 中村: 「2 階非ホロノミックシステムの平均化法による解析」, 第 14 回日本ロボット学会学術講演会予稿集, No. 3, pp. 767–768, 新潟, Nov. (1996).)

[23] T. Suzuki and Y. Nakamura, "Control of A 3-Joint Manipulator with 2 Free Joints — Analysis of Behaviors and Design of Control via the Averaging Method —," *Prepr. JSME Annual Conf. on Robotics and Mechatronics (ROBOMEC'97)*, pp. 817–820, Atsugi, June (1997).
(鈴木, 中村: 「2 自由関節を持つ 3 関節マニピュレータの制御 – 平均化法による挙動解析と制御設計 –」, 日本機械学会ロボティクス・メカトロニクス講演会'97 (ROBOMEC'97), pp. 817–820, 厚木, June (1997).)

[24] Y. Nakamura and T. Suzuki, "NONHOLONOMIC ROBOTS — Averaging Method: a Tool for Behavioural Analysis —," Keynote speech in: *Prepr. JSME Annual Conf. on Robotics and Mechatronics (ROBOMEC'97)*, pp. 1221–1224, Atsugi, June (1997).
(中村, 鈴木: 「非ホロノミックロボット – 非線形挙動解析法としての平均化法 –」, 日本機械学会ロボティクス・メカトロニクス講演会'97 (ROBOMEC'97 キーノート講演, pp. 1221–1224, 厚木, June (1997).)

[25] T. Suzuki and Y. Nakamura, "Control of 3R Free-Joint Manipulator with only One Actuator – Stabilization to a Manifold via Conservations of its Averaged Motion –," *Prepr. of 15th Annual Conf. of Robotic Society of Japan*, pp. 21–22, Tokyo, Sept. (1997).
(鈴木, 中村: 「3 R 自由関節マニピュレータの 1 駆動関節による制御 – 平均化挙動における保存量による多様体への安定化 –」, 第 15 回日本ロボット学会学術講演会, pp. 21–22, 東京, Sept. (1997))

Appendix

A Euler Parameters

A.1 Definition and properties

The Euler parameters are defined as a *quaternion* and are represented by a point on the surface of 4-dimension unit hypersphere $\boldsymbol{S}^3$. The Euler parameters $\boldsymbol{\epsilon}$, namely, orientation from the standard orientation is expressed by the rotation axis $\boldsymbol{n}$ and the rotation angle θ about the axis as follows [Spr86, Cho92]:

$$\boldsymbol{\epsilon} = \left\{ \begin{array}{c} e_0 \\ e_1 \\ e_2 \\ e_3 \end{array} \right\} = \left\{ \begin{array}{c} \cos\frac{\theta}{2} \\ \sin\frac{\theta}{2}\boldsymbol{n} \end{array} \right\} \in \boldsymbol{S}^3 \tag{7.1}$$

The above expression is based upon quaternion algebra as

$$\left\{ \begin{array}{c} e_0 \\ e_1 \\ e_2 \\ e_3 \end{array} \right\} \stackrel{\mathrm{def}}{=} \begin{pmatrix} e_0 & -e_1 & -e_2 & -e_3 \\ e_1 & e_0 & -e_3 & e_2 \\ e_2 & e_3 & e_0 & -e_1 \\ e_3 & -e_2 & e_1 & e_0 \end{pmatrix} = \begin{pmatrix} e_0 & -\boldsymbol{e}^T \\ \boldsymbol{e} & e_0\boldsymbol{E} + \boldsymbol{e}^{\times} \end{pmatrix} \tag{7.2}$$

where $\boldsymbol{e} = \begin{pmatrix} e_1 \\ e_2 \\ e_3 \end{pmatrix}$, $\boldsymbol{E}$ denotes a 3×3 identity matrix and $\boldsymbol{e}^{\times}$ denotes a cross product matrix of $\boldsymbol{e}$. Quaternion is a linear algebra which doesn't satisfy the commutative law. Note that the Euler parameters have the following constraints:

$$\boldsymbol{\epsilon}^T\boldsymbol{\epsilon} = e_0^2 + e_1^2 + e_2^2 + e_3^2 = \cos^2\frac{\theta}{2} + \sin^2\frac{\theta}{2}\boldsymbol{n}^T\boldsymbol{n} = 1 \tag{7.3}$$

Namely, the orientation space is a non-Euclidean space $\boldsymbol{S}^3$.

The relation between Euler parameters and angular velocity is expressed as:

$$\boldsymbol{\omega} = 2\dot{\boldsymbol{\epsilon}}\boldsymbol{\epsilon}^* \tag{7.4}$$

A.2 Numerical differentiation with Euler parameters

We perform numerical differentiation using the *Gibbs vector* and its transformation $\frac{\partial}{\partial\epsilon} = \frac{d\xi}{d\epsilon}\frac{\partial}{\partial\xi}$. The relationship between the Gibbs vector and the Euler parameters is as follows:

For $\epsilon = \begin{Bmatrix} e_0 \\ e_1 \\ e_2 \\ e_3 \end{Bmatrix}$, ξ is given as $\xi = \frac{1}{e_0}\begin{pmatrix} e_1 \\ e_2 \\ e_3 \end{pmatrix}$.

Then

$$\frac{\partial\xi}{\partial\epsilon} = \frac{1}{{e_0}^2}\begin{pmatrix} -e_1 & e_0 & 0 & 0 \\ -e_2 & 0 & e_0 & 0 \\ -e_3 & 0 & 0 & e_0 \end{pmatrix} \tag{7.5}$$

B The Yamada's algorithm of Optimization [Yam93]

B.1 Optimization

Yamada considered the change of satellite orientation when the manipulator makes a closed trajectory motion in joint space. When the manipulator joints follow a closed trajectory of $\boldsymbol{q} = \boldsymbol{a}_q s_1 + \boldsymbol{b}_q s_2 + \boldsymbol{c}_q$ where parameters s_1 and s_2 make a closed path in their space, the satellite orientation change $\Delta\epsilon$ is obtained as

$$\Delta\epsilon = \boldsymbol{a}_q^T \boldsymbol{D}_q \boldsymbol{b}_q \tag{7.6}$$

where $\boldsymbol{D}_q$ denotes a 6×6 tensor whose (i, j) element is defined as

$$\boldsymbol{D}_{q,ij} = \int_E \left(\frac{\partial \boldsymbol{f}_i}{\partial q_j} - \frac{\partial \boldsymbol{f}_j}{\partial q_i} + \boldsymbol{f}_i \times \boldsymbol{f}_j\right) \epsilon dE \tag{7.7}$$

where $\boldsymbol{f}_i$ is defined by the equation between the satellite angular velocity and joint velocity as

$$\omega = -\sum_{i=1}^{n} \boldsymbol{f}_i \dot{q}_i \tag{7.8}$$

Let the criterion Q as

$$Q = \boldsymbol{a}_q^T \boldsymbol{a}_q + \boldsymbol{b}_q^T \boldsymbol{b}_q \tag{7.9}$$

Adding this criterion Q and the constraint $\epsilon = \epsilon_d$ and using Lagrange multiplier $\boldsymbol{\lambda}$, the augmented criterion J is represented by

$$J = \boldsymbol{a}_q^T \boldsymbol{a}_q + \boldsymbol{b}_q^T \boldsymbol{b}_q + \boldsymbol{\lambda}^T (\Delta\epsilon - \Delta\epsilon_d) \tag{7.10}$$

which is to be minimized with the variational method.

The necessary condition of optimal solution is that J has a stationary value at $\boldsymbol{a}_q, \boldsymbol{b}_q$. Then it is expressed as

$$\begin{aligned} \left(\frac{\partial J}{\partial \boldsymbol{a}_q}\right)^T &= 2\boldsymbol{a}_q + \left(\frac{\partial \Delta\epsilon}{\partial \boldsymbol{a}_q}\right)^T \boldsymbol{\lambda} = \mathbf{o} \\ \left(\frac{\partial J}{\partial \boldsymbol{b}_q}\right)^T &= 2\boldsymbol{b}_q + \left(\frac{\partial \Delta\epsilon}{\partial \boldsymbol{b}_q}\right)^T \boldsymbol{\lambda} = \mathbf{o} \\ \Delta\epsilon - \Delta\epsilon_d &= \mathbf{o} \end{aligned} \tag{7.11}$$

On the basis of the assumption that the integrand of Eq.(7.7) is constant and invariant to $\boldsymbol{a}_q$ and $\boldsymbol{b}_q$, Eq.(7.11) can be rewritten as

$$\begin{aligned} 2\boldsymbol{a}_q + \boldsymbol{D}_{q\lambda}\boldsymbol{b}_q &= \mathbf{o} \\ 2\boldsymbol{b}_q - \boldsymbol{D}_{q\lambda}\boldsymbol{a}_q &= \mathbf{o} \end{aligned} \tag{7.12}$$

where $\boldsymbol{D}_{q\lambda}$ denotes a 6×6 matrix whose (i, j) element is

$$D_{q\lambda,ij} \stackrel{\text{def}}{=} \sum_k D_{q,ijk}\lambda_k \tag{7.13}$$

and $\boldsymbol{D} = q\lambda$ is *skew-symmetric* from Eq.(7.7).

From Eq.(7.12), we have $\boldsymbol{b}_q = \frac{1}{2}\boldsymbol{D}_{q\lambda}\boldsymbol{a}_q$, and Eq.(7.11) yields the nonlinear simultaneous equations as

$$\boldsymbol{D}_{qa}{}^T\boldsymbol{D}_{qa}\boldsymbol{\lambda} + 2\Delta\epsilon_d = \mathbf{o} \tag{7.14}$$

$$\left(\boldsymbol{I} + \frac{1}{4}\boldsymbol{D}_{q\lambda}{}^2\right)\boldsymbol{a}_q = \mathbf{o} \tag{7.15}$$

where $\boldsymbol{D}_{qa}$ denotes a 6×4 matrix whose (i, k) element is

$$D_{qa,ik} \stackrel{\text{def}}{=} \sum_j D_{q,ijk}a_{q,j} \tag{7.16}$$

Solving Eqs.(7.14) and (7.15), we find solutions $\boldsymbol{a}_q$, $\boldsymbol{b}_q$, $\boldsymbol{\lambda}$ satisfying Eq.(7.11).

C Definition of Chaos

The definition of chaos is rigorously presented by Wiggins [Wig90](pp. 608) as follows:

Lemma 1: We consider a $\boldsymbol{C}^r$ ($r \geq 1$) autonomous vector field on $\boldsymbol{R}^n$ and represent it by

$$\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}) \tag{7.17}$$

We denote the flow generated by Eq.(7.17) by $\phi(t, \boldsymbol{x})$ ($\forall t > 0$) and assume that $\Lambda \subset \boldsymbol{R}^n$ is a compact set invariant under $\phi(t, \boldsymbol{x})$, i.e., $\phi(t, \Lambda) \subset \Lambda$ for all $t \in \boldsymbol{R}$. Then Λ is said to be *chaotic* if

(1) Sensitive dependence on initial conditions (s.d.i.c.) : there exists $\varepsilon > 0$ such that, for any $\boldsymbol{x} \in \Lambda$ and any neighborhood U of $\boldsymbol{x}$, there exist $\boldsymbol{y} \in U$ and $t > 0$ such that

$$|\phi(t, \boldsymbol{x}) - \phi(t, \boldsymbol{y})| > \varepsilon$$

(2) Topological transitivity : for any two open sets $U, V \subset \Lambda$, there exists $t \in \boldsymbol{R}$ such that

$$\phi(t, U) \cap V \neq \emptyset$$

□

D Averaging Method

D.1 Theorem for periodic averaging

Theorem 3 (periodic averaging) Consider the initial value problems

$$\dot{x} = \epsilon f(t, x), \quad x(0) = x_0,$$

with $f : \boldsymbol{R}^{n+1} \mapsto \boldsymbol{R}^n$ and

$$\dot{y} = \epsilon f^o(y), \quad y(0) = x_0,$$

with

$$f^o(y) = \lim_{T \to \infty} \frac{1}{T} \int_0^T f(t, y)dt$$

$$x, y, x_0 \in D \subset \boldsymbol{R}^n, t \in [0, \infty), \epsilon \in (0, \epsilon_0]$$

Suppose

a) f has period T;

b) f is Lipschitz-continuous in x on $D \subset \boldsymbol{R}^n$, $t \geq 0$, continuous in t and x on $\boldsymbol{R}^+ \times D$ and with average f^o;

c) $y(t)$ belongs to an interior subset of D on the time-scale $\dfrac{1}{\epsilon}$;

then,

$$x(t) - y(t) = O(\epsilon) \text{ as } \epsilon \downarrow 0 \text{ on the time-scale } \frac{1}{\epsilon}\ .$$

□

D.2 Theorem for second-order averaging

Theorem 4 (second-order averaging for periodic system)
Consider a periodic-perturbed system as

$$\dot{x} = \varepsilon f_T(x,t) + \varepsilon^2 g_T(x,t) + O(\varepsilon^3)$$

and an averaged system as

$$\dot{y} = \varepsilon f^o(y) + \varepsilon^2 f^{1o}(y) + \varepsilon^2 g^o(y)$$

where

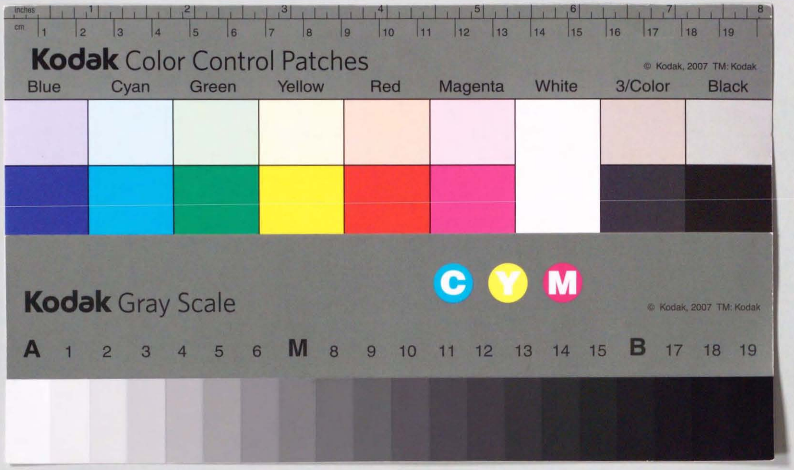
$$f^1(x,t) = \frac{\partial f_T}{\partial x} y^1(x,t) - \frac{\partial y^1}{\partial x} f^o(x)$$

$$y^1(x,t) = \int_0^t (f_T(x,\tau) - f^o(x))\, d\tau + a(x)$$

and $a(x)$ is a smooth function of x such that the average of y^1 becomes 0. Then,

$$x = y + \varepsilon y^1(y(t),t) + O(\varepsilon^2)$$

as $\epsilon \downarrow 0$ on the time-scale $\frac{1}{\epsilon}$. □


Kodak Color Control Patches
© Kodak, 2007 TM: Kodak
Blue
Cyan
Green
Yellow
Red
Magenta
White
3/Color
Black
Kodak Gray Scale
C
Y
M
© Kodak, 2007 TM: Kodak
A 1 2 3 4 5 6 M 8 9 10 11 12 13 14 15 B 17 18 19