International Assessment of Research & Development in Robotics

Control-Software-Architecture

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Major Subtopics

- Algorithm (Control):
  - Nonlinear: model based, neuro-fuzzy
  - Adaptive: model based, learning
  - Optimal: time optimality
  - Hybrid systems: discrete event system
  - Biomimetic based
- Software:
  - Simulation: order *N*, differential-algebraic system, flexibility (FEM), distributed communication
  - Programming: language, user interface, interpolation, demonstration
  - Real-time OS: QoS guarantees, plug & play
- Architecture:
  - Centralized, hierarchical, distributed, decentralized
  - Multi-rate, multi-resolution (quantization)
- Application-specific:
  - industrial manipulators
  - force control
  - parallel robots
  - multi-finger grasping
  - wheeled robots
  - biped locomotion
  - networked robotic system
  - vision feedback
  - haptic feedback
  - micro-robots, precision motion
  - multiple-robot collaboration
  - team robot
  - teleoperation
  - flexible (joint/link) robot
  - (hyper)redundant robot
  - nonholonomic systems
  - failure tolerance

Major Investigators

- US Universities (partial list!):
  - Caltech: J. Burdick, R. Murray (under-actuated systems, nonholonomic systems, hyper-redundant robots, team robot, distributed control).
  - Berkeley: S. Sastry, R. Horowitz, M. Tomizuka, H. Kazerooni (robot control, grasping, hybrid systems, control software, adaptive/learning/nonlinear control).
  - Illinois: M. Spong, S. Hutchinson (flexible joint control, visual servo-control, teleoperation, networked control).
  - CMU: P. Khosla, M. Mason (vision feedback, real-time control architecture, manipulation).
  - Northwestern: M. Peshkin, E. Colgate, K. Lynch (cobot, teleoperation, manipulation).

Major Investigators (Cont.)

- US Universities (partial list!):
  - U. Penn, V. Kumar, G. Pappas (team robot, hybrid system, UAV).
  - Harvard, R. Brockett (nonlinear control, networked control with quantized communication).
  - MIT, J-J. Slotine, H. Asada, S. Dubowsky, N. Hogan, R. Brooks (adaptive control, learning control, non-holonomic systems, impedance control, architecture).
  - RPI, A. Desrochers, A. Sanderson, J. Trinkle, J. Wen (discrete event systems, robot sensor network, robot assembly, nonlinear and adaptive control).
  - Georgia Tech., W. Book, I. Ebert-Uphoff, K-M. Lee, H. Lipkin, W. Singhose, R. Arkin, T. Balch (flexible robots, parallel robots, reactive control, architecture).

Major Advances

- Inverse dynamics: application of feedback linearization to serial robots, now routinely used in industrial manipulators (e.g., ABB)
- Time optimal control: along a path subject to dynamics, velocity and accel constraints, also used in industrial manipulators
- Adaptive robot control: model based adaptive control with global stability guarantee, implemented on ASIC.
- Nonholonomic control: control using time varying feedback or cyclic input, application of differential flat system theory, mostly applied to mobile robots and underactuated robots.

Major Advances (Cont.)

- Flexible joint robot modeling and control: Application of feedback linearization to flexible joint robots, applied to some industrial arms.
- Teleoperation: wave variable based control for delay robustness. Guarantee stability, but user would feel delayed response.
- Order *N* simulation: Application of order *N* computation to forward and inverse dynamics. Essential for large number degrees of freedom, e.g., robot with flexible link, micro-robots.
- Hybrid force/position, impedance control: Simultaneous regulation of motion and force, applied to machining, assembly, haptic feedback, multi-finger control.

Major Papers

- **Inverse dynamics:** Luh, Walker, Paul, "Resolved acceleration control," IEEE Trans. Auto. Contr., 25(3), 468-474, 1980. (278 cites)
- **Sliding mode control:** Slotine, Sastry, "Tracking control of non-linear systems using sliding surfaces, with application to robot manipulators," Int. J. Control, 38(2), 465-492, 1983. (314 cites)
- **Impedance control:** Hogan, "Impedance control: An approach to manipulation," ASME J. Dyn. Sys. Meas. & Contr., 107(1), 1-24, 1985. (168 cites)
- **Time optimal control:** Shin, McKay, "Minimum-time control of a robotic manipulator with geometric path constraints," IEEE Trans. Auto. Contr., 30, 531-541, 1985. (134 cites); Bobrow, Dubowsky, Gibson, "Time-optimal control of robotic manipulators along specified paths," Int. J. Robotics Res., 4(3) 3-17, 1985. (139 cites)
- **Flexible joint robot:** Cannon, Schmitz, "Initial experiments on the endpoint control of a flexible one-link robot," Int. J. Robotics Res., 3(3), 62-75, 1984. (328 cites); Book, "Recursive Lagrangian dynamics of flexible manipulator arms," Int. J. Robotics Research 3(3), 87-101, 1984. (207 cites); Spong, "Modeling and control of elastic joint robots," ASME J. Dyn. Sys. Meas. & Contr., 109(4), 310-319, 1987. (93 cites)
- **Adaptive control:** Slotine, Li, "On the adaptive control of robot manipulators," Int. J. Robotics Res., 6(3), 49-59, 1987. (261 cites)

Major Papers (Cont.)

- **Order N simulation:** Featherstone, “Calculation of robot dynamics using articulated-body inertias,” Int. J. Robotics Res., 2(1), 13-30, 1983. (96 cites)
- **Fine motion:** Lozano-Perez, Mason, Taylor, “Automatic synthesis of fine-motion strategies for robots,” Int. J. Robotics Res., 3(1), 3-24, 1984. (110 cites)
- **Subsumption architecture:** Brooks, “A robust layered control system for a mobile robot,” IEEE J. R & A, 2(1), 14-23, 1986. (607 cites)
- **Operational space:** Khatib, “A unified approach for motion and force control of robot manipulators: The operational space formulation,” IEEE J. R & A, 3(1), 43-53, 1987. (228 cites)
- **Teleoperation:** Anderson, Spong, “Bilateral control of operators with time delay,” IEEE Trans. Auto. Contr., 34(5), 494-501, 1989. (65 cites)
- **Nonholonomic system:** Li, Canny, “Motion of two rigid bodies with rolling constraints,” IEEEE Trans. R & A, 6(1), 62-72, 1990. (56 cites)
- **Visual servo control:** Espiau, Chaumette, Rives, “A new approach to visual servoing in robotics,” IEEE Trans. R & A, 8(3), 313-326, 1992. (132 cites); Papnikolopoulos, Khosla, Kanade, “Visual tracking of a moving target by a camera mounted on a robot: A combination of control and vision,” IEEE Trans. R & A, 9(1), 14-35, 1993. (76 cites)
- **Fault-tolerant architecture:** Parker, “ALLIANCE: An architecture for fault tolerant multirobot cooperation,” IEEE Trans. R & A, 14(2), 220-240 1998. (34 cites)

Major Unsolved Problem

- Reliable assembly: robotic assembly (especially of microsystems) with imprecise geometric and dynamic models and environment
- Distributed operation: coordinated robot control with information and actuation distribution, communication bandwidth limitation, indirect communication through shared dynamics (stigmergy)
- Fault detection and mitigation: satisfactory controller performance in the face of drastic changes in the system dynamics.
- Modeling, control, and design of complex multi-body systems (e.g., protein folding, material design, surgical simulation)

Research Goals

- Motion and force control in microsystem assembly.
- Distributed robot transport, manipulation, assembly in the presence of delay, quantization, and noise.
- Simulation, analysis, and design of complex multi-body systems
- Real-time, fault-tolerant, plug & play software systems with QoS guarantees
- Control of emergent behavior

Major Accomplishments in Other Countries

- Micro-robot manipulation: Fukuda, Arai, Nagoya University (novel locomotion, optical tweezer cell manipulation)
- Micro-robot, precision engineering: Clavel, EPFL (high speed parallel robot design/control)
- Multi-robot collaboration: Uchiyama, Tohoku University (multi-robot load transport, manipulation)

International Collaboration

- Research into micro-robot modeling, design, and control.
- Networked based control: e.g., recent work by N. Xi with collaboration with Nagoya and HK Science & Tech Univ.
- OROCOS (Open Robot Control Software): European collaboration with H. Bruyninckx (Katholieke Universiteit Leuven), R. Chatila (Centre National de la Recherche Scientifique), H. Christensen, (Kungliga Tekniska Hogskolan)
- Industry-University collaboration like Lund-ABB