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Control in Robotics: Open Problems and Future Directions

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Abstract

This contribution will focus on the state-of-the-art of control problems in robotics. Beyond its tutorial value, the work aims at identifying challenging control problems that must be addressed to meet future needs and demands, as well as at indicating preliminary solutions to the identified problems. Coverage of the various topics will start from the closest issues related to industrial robotics, such as force control, multirobots and dexterous hands, to the farthest advanced issues related to underactuated and nonholonomic systems, as well as to teleoperation, haptic interfaces and visual servoing.

1. Introduction

Robotics has attracted an ever increasing number of control researchers in the latest twenty years, producing a visible cross-fertilization between the two fields. This is rather evident from the number of publications and annual conferences devoting much space to control problems in robotics.

As automation becomes more prevalent in industry and typical bulky robot manipulators are being replaced with new systems which are smaller, faster, lighter and smarter, it should be clear that traditional PID control is no longer a satisfactory means of control in many situations. Optimum performance of industrial automation systems, especially if they include robots, will demand the use of such approaches as robust control, adaptive control, intelligent control and the like.

The goal of this paper is to focus on the state-of-the-art of control problems in robotics. Beyond its tutorial value, the work aims at identifying open problems as well as at indicating future directions of research. The discussion is liberally inspired by the presentations at the *IEEE International Workshop on Control Problems in Robotics and Automation: Future Directions*, held in San Diego, California on December 9, 1997, which are collected in [1]. The reader is also referred to [2] for recent advanced material on robot control.

2. Discussion

Robotic systems have captured the attention of control researchers since the early 70's. In this respect, it can be said that the motion control problem for rigid (industrial) robot manipulators is now completely understood and solved, see e.g. [3]. Nonetheless, practical robotic tasks often require interaction between the manipulator and the environment, and thus a *force control* problem arises. The purpose of force control could be quite diverse, such as applying a controlled force needed for a manufacturing process (e.g. deburring or grinding), pushing an external object using a controlled force, or dealing with geometric uncertainty by establishing controlled contacts (e.g. in assembly). Four major force control approaches have been proposed; namely, *impedance control* [4], *inner/outer position/force control* [5], *parallel force/position control* [6], and *hybrid force/position control* [7]. Impedance control logically derives from position control, in that the force is controlled in an indirect fashion by achieving a suitable dynamic behaviour between the contact force and the end-effector displacement; a force sensor is not strictly needed unless a linear and decoupled behaviour is sought along the task space directions. The key idea of inner/outer position/force control is to close an outer force feedback loop around the inner position feedback loop typically available in an industrial robot controller; in this case, a force sensor should be available at the robot's wrist. Parallel force/position control aims at combining the capability of controlling position of impedance control with the capability of directly controlling the force of inner/outer position/force control. All the previous schemes do not utilize explicit information about the geometry and stiffness/compliance of the environment, although their performance is clearly affected by the characteristics of the environment. On the other hand, hybrid force/position control exploits full information about the environment and a pre-selection of the task space directions is made to decide which ones are to be force-controlled and which others are to be position-controlled. Many successful laboratory implementations of force control schemes have been reported in the literature, demonstrating the practical usefulness of force feedback when the end effector of

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an industrial robot interacts with an environment. Open research issues in the context of force control which are believed to be worthy of investigation are: *modelling of dynamic environments*, *6-dof task control* (position and orientation, force and moment), *modelling of impact phenomena*, *stability of control schemes during transition from non-contact to contact*, and *force/position control of robot manipulators with flexible joints and/or links*. Preliminary results along such directions can be found in e.g. [8–12].

Whenever a manipulation task exceeds the capability of a single robot, a *multirobot cooperative system* is needed. Various robotic applications require the adoption of two-arm systems in lieu of single robot manipulators. These include, for instance, manipulation of heavy or non-rigid objects and mating of mechanical pieces. In all such cases the two robots should operate in a coordinated way so as to synchronize the relative motions, avoid undesired collisions, maintain the grasp between the arms and the object, etc. The problem of motion coordination of a two-arm robot system was addressed in a number of works including the *leader-follower (or master-slave) strategy* [13], the *symmetric formulation* [14], and the *cooperative task space concept* [15]. In the leader-follower strategy, the kinematic constraints imposed by the closed chain created through the object held by the two manipulators are used to express the motion of one manipulator (follower) as a function of the commanded motion of the other (leader). Instead, the symmetric formulation attributes equal importance to the two robots performing the given task and kineto-static relationships are derived for the absolute (external) and relative (internal) velocities (forces) of the system. As such, this formulation can be naturally extended to multirobot systems [16]; in this case, load-sharing of the grasped object can be achieved if desired [17]. The cooperative task space concept is based on the symmetric formulation in that coordinated motion tasks can be described in terms of a set of meaningful absolute and relative position and orientation variables; in this way, both direct and inverse kinematics of a two-robot system can be obtained in a systematic fashion, and various types of contacts (e.g. rolling, sliding) can be handled. On the other hand, the goal of a controller for cooperative manipulators is twofold: *control of the absolute motion* of the object and *control of the internal forces* arising from the interaction of the end effectors with the commonly held object; the controller can be model-based [18] or of PD-type [19]. Advanced research topics that are currently receiving a great deal of attention include *handling of flexible objects* [20], and *cooperative control of manipulators with flexible joints and/or links* [21].

Multifingered *robot hands* can be regarded as a special class of multirobot systems. The development of mechanical hands for grasping and fine manipulation of objects has been an important part of robotics research since its beginnings [22]. Comparison of the amazing dexterity of the human hand with the extremely elementary functions performed by industrial grippers, compelled many robotics researchers to try and bring some of the versatility of the anthropomorphic model in robotic devices. From the relatively large effort spent by the research community towards this goal, several robot hands sprung out in laboratories all over the world; see e.g. [23] for a survey. Multifingered *dexterous* robot hands often featured very advanced mechanical design, sensing and actuating systems, and also proposed interesting analysis and control problems, concerning e.g. the distribution of control action among several agents (fingers) subject to complex nonlinear bounds. Notwithstanding the fact that hands designed in that phase of research were often superb engineering projects, the community had to face a very poor penetration to the factory floor, or to any other scale application. Among the various reasons for this, there is undoubtedly the fact that dexterous robot hands were too mechanically complex to be industrially viable in terms of cost, weight, and reliability. Reacting to this observation, several researchers started to reconsider the problem of obtaining good grasping and manipulation performance by using mechanically simpler devices. This approach can be seen as an embodiment of a more general *minimalist approach* at robotics design; see e.g. the works collected in [24]. One instance of this process of hardware reduction without sacrificing performance can be seen in devices for power grasping, or whole–arm manipulation, i.e. devices that exploit all their parts to contact and constrain the manipulated part, and not just their end–effectors (or fingertips, in the case of hands). From the example of human grasp, it is evident that power grasps using also the palm and inner phalanges are more robust than fingertip grasping, for a given level of actuator strength. However, using inner parts of the kinematic chain, which have reduced mobility in their operational space, introduces important limitations in terms of controllability of forces and motions of the manipulated part, and ensue nontrivial complications in control [25]. Classical designs achieve dexterity in a hand with rigid, hard-finger, non-rolling and non-sliding contacts. On the other hand, if a rolling contact [26] is allowed, the situation changes dramatically, as *nonholonomy* enters the picture. Although nonholonomy seems to be a promising approach to reducing the complexity, cost, weight, and unreliability of the hardware used in robotic hands, it is true in general that planning and controlling nonholonomic systems is more difficult than holonomic ones.

The general class of *underactuated mechanical systems* include *flexible manipulators* (with elastic joints [27] and flexible links [28]), walking robots [29], mobile robots [30], free-floating robots (space [31] and undersea [32]), and special devices such as a brachiating [33] or a gymnastic robot [34]. The common denominator of all such systems is the availability of fewer control inputs than degrees of freedom. The Lagrangian dynamics of these systems may contain feedforward nonlinearities, nonminimum phase zero dynamics, nonholonomics constraints, and other properties that place this class of systems at the forefront of research in advanced control. Strong control properties such as feedback linearization and passivity holding for fully actuated systems are typically lost when a mechanical system is underactuated. The only property that is not lost is the so-called *partial feedback linearization* property (a consequence of the positive definiteness of the inertia matrix) which can be thought of as input/output linearization [35] with respect to the actuated degrees of freedom; see e.g. [36] for the flexible-link context. Apart from the above-mentioned problems of controlling nonholonomic systems, approximate design techniques such as *singular perturbations* [37], *backstepping* [38], *forwarding* [39] have been successfully applied to certain classes of systems, and are believed to offer a potential for robust and adaptive control of broader classes of underactuated mechanical systems.

Since its introduction in the 40's, the field of *teleoperation* has expanded its scope to include manipulation at different scales and in virtual worlds. Teleoperation has been used in the handling of radioactive materials, in undersea exploration and servicing. Its use has been demonstrated in space [40], in the control of construction/forestry machines of the excavator type [41], in microsurgery and micro-manipulation experiments [42] and other areas. The goal of teleoperation is to achieve *transparency* [43] by mimicking human motor and sensory functions. Within the relatively narrow scope of manipulating a tool, transparency is achieved if the operator cannot distinguish between maneuvering the master controller and maneuvering the actual tool. The ability of a teleoperation system to provide transparency depends largely upon the performance of the master [44] and the performance of its bilateral controller [45]. Ideally, the master should be able to emulate any environment encountered by the tool, from free-space to infinitely stiff obstacles. The demand for force feedback in general purpose computer-user interfaces is even higher today, as performance improvements in computer systems have enabled complex applications requiring significant interaction between the user and the computer. Thus actuated devices with several degrees of freedom can serve as sophisticated input devices that also provide tactile and *kinesthetic feedback* [46] to the user. Such devices, called *haptic interfaces*, have been demonstrated in a number of applications such as surgical training [47], graphical and force-feedback user interfaces [48]. The design of haptic interfaces is quite challenging, as the outstanding motion and sensing capabilities of the human arm are difficult to match. The performance specifications that haptic interfaces must meet are still being developed, based on a number of psychophysical studies and constraints such as manageable size and cost [49]. Peak acceleration, isotropy and dynamic range of achievable impedances are considered to be very important. A design approach that considers the haptic interface controller can be found in [50].

A great many tasks routinely performed by humans (for example machine control, driving, assembly, or fruit picking) are based on visually perceived information. In order for robots to perform such tasks, without extensive instrumentation or re-engineering of the environment, they must also have the ability to perceive and act upon *visual information*. Computer vision is therefore an important sensor for robotic systems since it mimics the human sense of vision and allows for non-contact measurement of the environment. Limited vision capability has been available in commercial robot controllers for many years now. It is used for tasks such as inserting parts with respect to fiducial marks on printed circuit boards, or for grasping unorganized parts moving on conveyor belts. Typically these systems adopt a *look–and–move strategy* — a well calibrated camera and vision system determines the desired robot end-effector pose and the robot system is commanded to make the appropriate motion; see [51] for a tutorial on *visual servo control*. The accuracy of the resulting motion clearly depends directly on the quality of the *camera calibration* [52] and the accuracy of the robot. The systems in operation today are able to achieve the necessary precision using high-quality and expensive components and good system engineering. An alternative promising approach to increasing the performance of the overall system is to use a vision system to continuously guide, or steer, the robot end-effector toward the target. Such a closed-loop position control structure for a robot end-effector is referred to as *visual servoing* system [53]. A visual feedback control loop, like any feedback control system, will increase closed-loop accuracy and robustness to error in the sensor or the robot; see [54] for a taxonomy of visual servo systems. Such a system may include more than one camera, and the cameras can be placed either on the robot observing the target (the so-called *eye–in–hand configuration* [55]), or in the world observing the robot and the target (the so-called *hand–eye coordination* [56]). Future research challenges are in *robust vision* to make systems work in complex real-world environments, and *robust or adaptive control* for improved dynamic performance with possibly variable latency. Preliminary efforts along these guidelines can be found in [57,58].

3. Conclusion

The above discussion has touched upon a number of issues related to control problems in robotics. Due to lack of space, the chosen topics could not be analyzed in depth enough, nor other important topics such as fuzzy and neural control, discrete-event control, supervisory control, sensor fusion, hybrid systems, etc. could be surveyed. It is believed that the bibliography hereafter and the references therein should provide some basic sources for further reading and investigation on the ideas discussed in this paper.

References

[1] B. Siciliano and K.P. Valavanis (Eds.), *Control Problems in Robotics and Automation*, Springer-Verlag, London, 1998.

[2] C. Canudas de Wit, B. Siciliano, and G. Bastin, *Theory of Robot Control*, Springer-Verlag, London, 1996.

[3] L. Sciavicco and B. Siciliano, *Modeling and Control of Robot Manipulators*, McGraw-Hill, New York, 1996.

[4] N. Hogan, "Impedance control: An approach to manipulation, Parts I–III," *ASME J. of Dynamic Systems, Measurement, and Control*, vol. 107, pp. 1–24, 1985.

[5] J. De Schutter and H. Van Brussel, "Compliant robot motion II. A control approach based on external control loops," *Int. J. of Robotics Research*, vol. 7, no. 4, pp. 18–33, 1988.

[6] S. Chiaverini and L. Sciavicco, "The parallel approach to force/position control of robotic manipulators," *IEEE Trans. on Robotics and Automation*, vol. 9, pp. 361–373, 1993.

[7] M.H. Raibert and J.J. Craig, "Hybrid position/force control of manipulators," *ASME J. of Dynamic Systems, Measurement, and Control*, vol. 103, pp. 126–133, 1981.

[8] B. Siciliano and L. Villani, "Six-degree-of-freedom impedance robot control," *Proc. 8th Int. Conf. on Advanced Robotics*, Monterey, CA, 1997, pp. 387–392.

[9] A. De Luca and C. Manes, "Modeling robots in contact with a dynamic environment," *IEEE Trans. on Robotics and Automation*, vol. 10, pp. 542–548, 1994.

[10] B. Brogliato, *Nonsmooth Impact Mechanics*, Springer-Verlag, London, 1996.

[11] T.-J. Tarn, Y. Wu, N. Xi, and A. Isidori, "Force regulation and contact transition control," *IEEE Control Systems Mag.*, vol. 16, no. 1, pp. 32–40, 1996.

[12] F. Matsuno and K. Yamamoto, "Dynamic hybrid position/force control of a two degree-of-freedom flexible manipulator," *J. of Robotic Systems*, vol. 11, pp. 355–366, 1994.

[13] J.Y.S. Luh and Y.F. Zheng, "Constrained relations between two coordinated industrial robots for motion control," *Int. J. of Robotics Research*, vol. 6, n. 3, pp. 60–70, 1987.

[14] M. Uchiyama and P. Dauchez, "Symmetric kinematic formulation and non-master/slave coordinated control of two-arm robots," *Advanced Robotics*, vol. 7, pp. 361–383, 1993.

[15] P. Chiacchio, S. Chiaverini, and B. Siciliano, "Direct and inverse kinematics for coordinated motion tasks of a two-manipulator system," *ASME J. of Dynamic Systems, Measurement, and Control*, vol. 118, pp. 691–697, 1996.

[16] P. Chiacchio, S. Chiaverini, L. Sciavicco, and B. Siciliano, "Global task space manipulability ellipsoids for multiple arm systems," *IEEE Trans. on Robotics and Automation*, vol. 7, pp. 678–685, 1991.

[17] I.D. Walker, R.A. Freeman, and S.I. Marcus, "Analysis of motion and internal loading of objects grasped by multiple cooperating manipulators," *Int. J. of Robotics Research*, vol. 10, no. 4, pp. 396-409, 1991.

[18] Z. Li, P. Hsu, and S. Sastry, "Grasping and coordinated manipulation by a multifingered robot hand," *Int. J. of Robotics Research*, vol. 8, no. 4, pp. 33–50, 1989.

[19] J.T. Wen and K. Kreutz, "Motion and force control of multiple robotic manipulators," *Automatica*, vol. 28, pp. 729–743, 1992.

[20] M.M. Svinin and M. Uchiyama, "Coordinated dynamic control of a system of manipulators coupled via a flexible object," *Prepr. 4th IFAC Symp. on Robot Control*, Capri, Italy, 1994, pp. 1005–1010.

[21] M. Yamano, J.S. Kim, and M. Uchiyama, "Experiments on cooperative control of two flexible manipulators working in 3D space," *Asia-Pacific Vibration Conf.*, Kyongju, Korea, 1997.

[22] M.T. Mason and J.K. Salisbury, *Robot Hands and the Mechanics of Manipulation*, MIT Press, Cambridge, MA, 1985.

[23] R.A. Grupen, T.C. Henderson, and I.D. McCammon, "A survey of general–purpose manipulation," *Int. J. of Robotics Research*, vol. 8, no. 1, pp. 38–62, 1989.

[24] A. Bicchi and K. Goldberg (Eds.), Proceedings of the 1996 Workshop on Minimalism in Robotic Manipulation, *1996 IEEE Int. Conf. on Robotics and Automation*, Minneapolis, MA, 1996.

[25] D. Prattichizzo and A. Bicchi, "Dynamic analysis of mobility and graspability of general manipulation systems," *ASME J. of Dynamic, Systems, Measurement, and Control*, vol. 119, pp. 760–767, 1997.

[26] A.C. Cole, J.E. Hauser, and S. Sastry, "Kinematics and control of multifingered hands with rolling contact," *IEEE Trans. on Automatic Control*, vol. 34, pp. 398–404, 1989.

[27] M.W. Spong, "Modeling and control of elastic joint robots," *ASME J. of Dynamic Systems, Measurement, and Control*, vol. 109, pp. 310–319, 1987.

[28] W.J. Book, "Recursive Lagrangian dynamics of flexible manipulator arms," *Int. J. of Robotics Research*, vol. 3, no. 3, pp. 87–101, 1984.

[29] T. McGeer, "Passive dynamic walking," *Int. J. of Robotics Research*, vol. 9, no. 2, 1990.

[30] R.M. Murray and S.S. Sastry, "Nonholonomic motion planning: Steering using sinusoids," *IEEE Trans. on Automatic Control*, vol. 38, pp. 700–716, 1993.

[31] S. Dubowsky and E. Papadopoulos, "The kinematics, dynamics, and control of free-flying and free-floating space robotic systems," *IEEE Trans. on Robotics and Automation*, vol. 9, pp. 531–543, 1993.

[32] T.I. Fossen, *Guidance and Control of Ocean Vehicles*, Wiley, Chichester, UK, 1996.

[33] F. Saito, T. Fukuda, and F. Arai, "Swing and locomotion control for a two-link brachiation robot," *IEEE Control Systems Mag.*, vol. 14, no. 1, pp. 5–12, 1994.

[34] M.W. Spong, "The swingup control problem for the acrobot," *IEEE Control Systems Mag.*, vol. 15, no. 1, pp. 49–55, 1995.

[35] A. Isidori, *Nonlinear Control Systems* (3rd Ed.), Springer-Verlag, London, 1995.

[36] A. De Luca and B. Siciliano, "Inversion-based nonlinear control of robot arms with flexible links," *AIAA J. of Guidance, Control, and Dynamics*, vol. 16, pp. 1169–1176, 1993.

[37] B. Siciliano and W.J. Book, "A singular perturbation approach to control of lightweight flexible manipulators," *Int. J. of Robotics Research*, vol. 7, no. 4, pp. 79–90, 1988.

[38] M. Krstic, I. Kanellakopoulos, and P.V. Kokotović, *Nonlinear and Adaptive Control Design*, Wiley, New York, 1995.

[39] R. Sepulchre, M. Janković, and P.V. Kokotović, *Constructive Nonlinear Control*, Springer-Verlag, London, 1997.

[40] G. Hirzinger, B. Brunner, J. Dietrich, and J. Heindl, "Sensor-based space robotics – ROTEX and its telerobotic features," *IEEE Trans. on Robotics and Automation*, vol. 9, pp. 649–663, 1993.

[41] P.D. Lawrence, S.E. Salcudean, N. Sepehri, D. Chan, S. Bachmann, N. Parker, M. Zhu, and R. Frenette, "Coordinated and force-feedback control of hydraulic excavators," in *Experimental Robotics IV*, O. Khatib and J.K. Salisbury (Eds.), Springer-Verlag, London, 1995, pp. 181–194.

[42] M. Mitsuishi, H. Watanabe, H. Nakanishi, H. Kubota, and Y. Iizuka, "Dexterity enhancement for a tele-micro-surgery system with multiple macro-micro co-located operation point manipulators and understanding of the operator's intention," *Proc. 1st Joint Conf. CVRMED II & MRCAS*, Grenoble, France, 1997, pp. 821–830.

[43] D.A. Lawrence, "Stability and transparency in bilateral teleoperation," *IEEE Trans. on Robotics and Automation*, vol. 9, pp. 624–637, 1993.

[44] S.E. Salcudean, N.M. Wong, and R.L. Hollis, "Design and control of a force-reflecting teleoperation system with magnetically levitated master and wrist," *IEEE Trans. on Robotics and Automation*, vol. 11, pp. 844–858, 1995.

[45] Y. Yokokohji and T. Yoshikawa, "Bilateral control of master-slave manipulators for ideal kinesthetic coupling," *IEEE Trans. on Robotics and Automation*, vol. 10, pp. 605–620, 1994.

[46] B. Hannaford, "A design framework for teleoperators with kinesthetic feedback," *IEEE Trans. on Robotics and Automation*, vol. 5, pp. 426–43, 1989.

[47] R.M. Satava and S.B. Jones, "Virtual environments for medical training and education," *Presence*, vol. 6, pp. 139–146, 1997.

[48] A.J. Kelley and S.E. Salcudean, "The development of a force feedback mouse and its integration into a graphical user interface," *Proc. 1994 ASME Int. Mechanical Engineering Congr. Exposition*, Chicago, IL, 1994, DSC-vol. 55-1, pp. 287–294.

[49] V. Hayward and O.R. Astley, "Performance measures for haptic interfaces," in *Robotics Research: The Seventh International Symposium*, G. Giralt and G. Hirzinger (Eds.), Springer-Verlag, London, 1996.

[50] D.A. Lawrence and J.D. Chapel, "Performance trade-offs for hand controller design," *Proc. 1994 IEEE Int. Conf. on Robotics and Automation*, San Diego, CA, 1994, pp. 3211–3216.

[51] S. Hutchinson, G. Hager, and P. Corke, "A tutorial on visual servo control," *IEEE Trans. on Robotics and Automation*, vol. 12, pp. 651–670, 1996.

[52] R.Y. Tsai and R.K. Lenz, "Techniques for calibration of the scale factor and image center for high accuracy 3D machine vision metrology," *IEEE Trans. on Pattern Analysis and Machine Intelligence*, vol. 10, pp. 713–720, 1988.

[53] P.I. Corke, *Visual Control of Robots*, Research Studies Press and Wiley, New York, 1996.

[54] A.C. Sanderson and L.E. Weiss, "Image-based visual servo control using relational graph error signals," *Proc. IEEE*, pp. 1074–1077, 1980.

[55] B. Nelson and P.K. Khosla, "Increasing the tracking region of an eye-in-hand system by singularity and joint limit avoidance," *Proc. 1993 IEEE Int. Conf. on Robotics and Automation*, Atlanta, GA, 1993, vol. 3, pp. 418–423.

[56] G.D. Hager, "A modular system for robust hand-eye coordination," *IEEE Trans. on Robotics and Automation*, vol. 13, pp. 582–595, 1997.

[57] N.P. Papanikolopoulos and P.K. Khosla, "Adaptive robot visual tracking: Theory and experiments," *IEEE Trans. on Automatic Control*, vol. 38, pp. 429–445, 1993.

[58] P. Sharkey and D. Murray, "Delays versus performance of visually guided systems," *IEE Proc. on Control Theory and Applications*, vol. 143, pp. 436–447, 1996.