Control in Robotics

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Introduction

The interplay between robotics and control theory has a rich history extending back over half a century. We begin this section of the report by briefly reviewing the history of this interplay, focusing on fundamentals—how control theory has enabled solutions to fundamental problems in robotics and how problems in robotics have motivated the development of new control theory. We focus primarily on the early years, as the importance of new results often takes considerable time to be fully appreciated and to have an impact on practical applications. Progress in robotics has been especially rapid in the last decade or two, and the future continues to look bright.

Robotics was dominated early on by the machine tool industry. As such, the early philosophy in the design of robots was to design mechanisms to be as stiff as possible with each axis (joint) controlled independently as a single-input/single-output (SISO) linear system. Point-to-point control enabled simple tasks such as materials transfer and spot welding. Continuous-path tracking enabled more complex tasks such as arc welding and spray painting. Sensing of the external environment was limited or nonexistent.

Consideration of more advanced tasks such as assembly required regulation of contact forces and moments. Higher speed operation and higher payload-to-weight ratios required an increased understanding of the complex, interconnected nonlinear dynamics of robots. This requirement motivated the development of new theoretical results in nonlinear, robust, and adaptive control, which in turn enabled more sophisticated applications.

Today, robot control systems are highly advanced with integrated force and vision systems. Mobile robots, underwater and flying robots, robot networks, surgical robots, and others are playing increasing roles in society. Robots are also ubiquitous as educational tools in K-12 and college freshman experience courses.

The Early Years

The first industrial robot in the United States was the Unimate, which was installed in a General Motors plant in 1961 and used to move die castings from an assembly line and to weld these parts on auto bodies (Fig. 1). Full-scale production began in 1966. Another company with early robot products was Cincinnati Milacron, with companies in Japan and Europe also entering the market in the 1970s. Prior to the 1980s, robotics continued to be focused on manipulator arms and simple factory automation tasks: materials handling, welding, and painting.

From a control technology standpoint, the primary barriers to progress were the high cost of computation, a lack of good sensors, and a lack of fundamental understanding of robot dynamics. Given these barriers, it is not surprising that two factors were the primary drivers in the advancement of robot control in these early days. First, with the realization of the close connection between robot performance and automatic control, a community developed that focused on increasing fundamental understanding of dynamics, architecture, and system-level design. In retrospect, we can see that this

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work had some significant limitations: control schemes were mostly based on approximate linear models and did not exploit knowledge of the natural dynamics of the robot, vision and force control were not well integrated into the overall motion control architecture, and mechanical design and control system design were separate.

(Credit: George Devol)

Figure 1. Unimate, the first industrial robot.

The second factor was exogenous to both the controls and robotics communities, namely, Moore's Law. The increasing speed and decreasing cost of computation have been key enablers for the development and implementation of advanced, sensor-based control.

At the forefront of research, both established control methods were explored in innovative applications for robots, and creative new ideas—some of which influenced control research more generally—were proposed. Especially worth noting is the early work on computed torque and inverse dynamics control [1]. As a sign of those times, it is interesting to note that until the mid-1980s, papers on robot control invariably included a calculation of the computational burden of the implementation.

Control of Manipulators

Robot manipulators have become a "standard" control application, and the synergies were widely recognized and exploited in research. The earlier research on computed torque and inverse dynamics control has been applied to numerous practical problems within and outside of robotics.

Beginning in the mid-1980s, robot manipulators became a "standard" control application, and the synergies were widely recognized and exploited in research. The earlier research on computed torque and inverse dynamics control [1], for example, helped motivate the differential geometric method of feedback linearization that has been applied to numerous practical problems within and outside of robotics [2]. For fully actuated rigid manipulators, the feedback linearization method was put on a firm theoretical foundation and shown to be equivalent to the inverse dynamics method [3]. The first nontrivial application of the feedback linearization method in robotics, in the sense that it requires a nonlinear coordinate transformation based on the solution of a set of PDEs, was to the problem of joint flexibility in robot manipulators [4]. Joint flexibility had previously been identified as the major limiting factor to manipulator performance, and it remains an important component of robot dynamics and control.

Another line of research pursued connections with robust control. Since feedback linearization relies on the exact cancellation of nonlinearities, the question of robustness to parameter uncertainty is immediately raised. Standard H_∞ control cannot adequately address this problem due to the persistent nature of the uncertainty. A solution for the special case of second-order systems, using the small-gain theorem, was worked out in [5], and the general case was presented in [6], which subsequently led to a new area of control now known as L_1-optimal control—a prime example of a robotics control contribution leading to new control theory. Several other methods of robust control, such as sliding modes and Lyapunov methods, have also been applied to the robust control problem for robot manipulators.

The mid-1980s were also a time of development in adaptive control, and again the connection with robotics was pursued. The fundamental breakthrough in the adaptive control of rigid manipulators was made by Slotine and Li [7]. The key to the solution of the adaptive control problem was the recognition of two important properties of Lagrangian dynamical systems: linearity in the inertia parameters and the skew-symmetry property of the robot inertia matrix [8].

Subsequently, the skew symmetry property was recognized as being related to the fundamental property of passivity. The term *passivity-based control* was introduced in the context of adaptive control of manipulators [9]. Passivity-based control has now become an important design method for a wide range of control engineering applications.

A final notable trend during this phase of the evolution of robot control was teleoperation—the control of robotic manipulators by possibly remotely located human operators. The obvious challenge that results is accommodating the delays involved, both for communication of sensory feedback and for transmission of the operator's command to the manipulator. That instability could be induced by time delays in so-called bilateral teleoperators, which involves feedback of sensed forces to the master, was recognized as a problem as early as the mid-1960s. Passivity-based control provided a breakthrough and enabled delay-independent stabilization of bilateral teleoperators [10], [11]. The key concept was to represent a master-slave teleoperator system as an interconnection of two-port networks and then encode the velocity and force signals as so-called scattering variables before transmitting them over the network. This approach renders the time-delay network element passive and the entire system stable independent of the time delay.

A state-of-the-art teleoperated robot is the Da Vinci surgical system from Intuitive Surgical, which integrates advances in micromanipulators, miniature cameras, and a master-slave control system to enable a surgeon to operate on a patient via a console with a 3-D video feed and foot and hand controls. However, neither force feedback nor remote operations are supported as yet; the surgeon's console is typically by the patient's side.

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Mobile Robots

The problem of kinematic control of mobile robots received much attention starting in the 1980s as an application of differential geometric methods. The difficulty of the problem was dramatically revealed by Brockett's theorem, which showed that smooth time-invariant stabilizing control laws for such systems do not exist [12]. Brockett's theorem stimulated the development of alternative control methods , including hybrid switching control and time-varying approaches to stabilization of nonholonomic systems.

Mobile robots are now regularly used in many applications. One prominent application is aiding disaster recovery efforts in mines and after earthquakes. Military uses, such as for roadside bomb detection, form another broad category. Recently, products have been developed for consumer applications, such as the Roomba® and other robots from iRobot. Finally, wheeled mobile robots are exploring Mars and are poised to return to the moon.

Market Sizes and Investment

The robotics industry was slow getting started. Unimation did not show its first profit until 1975, almost a decade after it began full-scale production of its pioneering Unimate robot. Today, the Robotic Industries Association estimates that more than one million robots are in use worldwide; Japan has the largest deployment, with the United States having the second largest.

According to one recent market research report from Electronics.ca Publications, the global market for robotics was worth $17.3 billion in 2008 and is projected to increase to $21.4 billion in 2014, a compound annual growth rate (CAGR) of 4.0%. The largest segment of the market is industrial applications, worth $11.5 billion. Industrial robots, with their heavy reliance on the automotive industry, were especially hard hit with the recent global recession—2009 shipments were down 50% from year-ago levels, according to the Robotic Industry Association. Projected growth is lower for this segment than for professional service (market size of $3.3 billion in 2008) and military ($917 million) applications. Domestic services, security, and space applications constitute smaller segments, although the huge success of the Roomba floor-cleaning robot has demonstrated the enormous potential of consumer robotics.

Research Challenges

Underactuation

Underactuated robots have fewer control inputs than degrees of freedom and are a natural progression from flexible-joint and flexible-link robots. Underactuation leads naturally to a consideration of partial or output feedback linearization as opposed to full-state feedback linearization. Consideration of normal forms and zero dynamics is important in this context [13]. Energy/passivity methods are fundamental for the control of underactuated systems.

Visual Servo Control and Force Control

The idea of using imaging or video sensors for robot control is not new; it predates the availability of low-cost, high-quality digital cameras and advances in computational platforms enabling real-time processing of digital video signals. These latter developments have significantly increased interest in the topic.

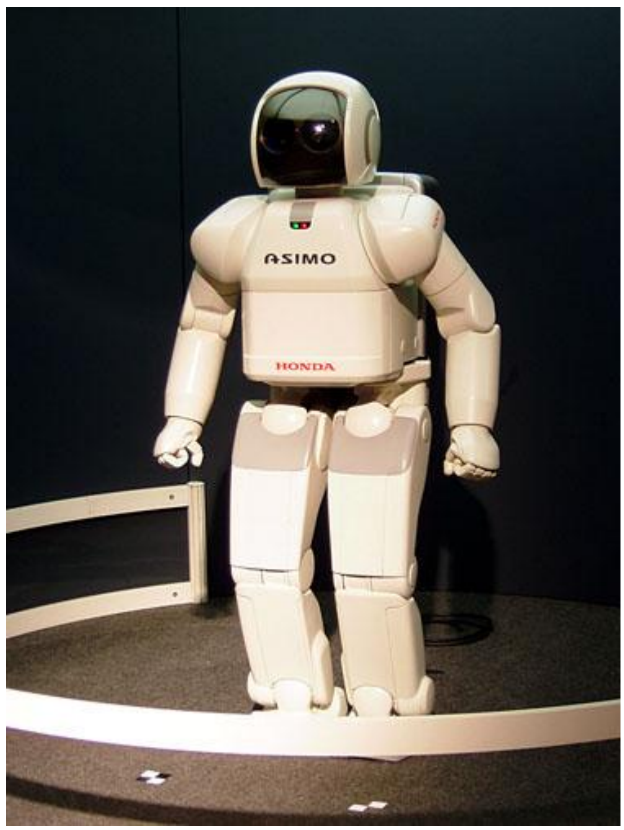
Visual servo control has traditionally used two methodologies, namely, position-based control and image-based control [14]. Position-based control uses vision to estimate the absolute position of the robot and uses the computed position error in the control algorithm. Image-based control, on the other hand, is based on computing the error directly in the image plane of the camera and avoids calculation of the robot position; thus, it is less sensitive to kinematic and calibration errors. Recently, both position-based and image-based methods have been incorporated into hybrid switching control strategies in order to take advantage of the strengths and avoid the weaknesses of both approaches.

Similar to vision-based control, force control in robotics has also traditionally been divided into two fundamental strategies, in this case, called hybrid position/force control and impedance control, respectively. Hybrid position/force control is based on the observation that one cannot simultaneously control both the position of a robot and the force it imparts to the environment. Thus, the task at hand can be decomposed into “directions” along which either position or force (but not both) is controlled. Conversely, impedance control does not attempt to control or track positions and forces. Rather the “mechanical impedance,” which is the suitably defined Laplace transform of the velocity/force ratio, is the quantity to be controlled.

Locomotion

The development of legged robots is motivated by the fact that wheeled robots are not useful in rough terrain or in built structures. The number of legs involved is a free parameter in this research, with robots with as few as one (hopping robots) and as many as eight having been developed by multiple research groups. Bipedal robots are a particularly popular category, both for the anatomical similarity with their creators and because of the research challenges posed by their dynamic instability. An understanding of the dynamics and control of bipedal locomotion is also useful for the development of prosthetic and orthotic devices to aid humans with disabilities or missing limbs.

Readers who have seen videos of Honda’s Asimov robots (Fig. 2) (readers who have not can check YouTube) or other humanoid robots may think that bipedal robots are “for real” now. The accomplishments of this research are indeed impressive. These robots can walk up and down ramps and stairs, counteract pushes and pulls, change gait, roll carts, play table tennis, and perform other functions. But the transition from research laboratory to commercial practice has not been made as yet. In particular, challenges remain for control engineers in the locomotion aspects specifically.



(Credit: Gnsin)

Figure 2. Honda’s Asimov humanoid robot at Expo 2005 in Aichi, Japan.

Control of bipedal locomotion requires consideration of three difficult issues: hybrid nonlinear dynamics, unilateral constraints, and underactuation. The hybrid nature of the control problem results from impacts of the foot with the ground, which introduce discrete transitions between phases of continuous dynamic motion. Unilateral constraints arise from the fact that the foot can push but not pull on the ground and so the foot/ground reaction forces cannot change sign. Underactuation results again from the foot/ground interaction; there is no actuation torque between the foot and the ground. All these difficult issues require advanced methods of control to address them adequately. Energy/passivity methods, geometric nonlinear control, partial feedback linearization, zero dynamics, and hybrid control theory are all fundamental tools for designing rigorous control algorithms for walking [15], [16].

Multi-Agent Systems and Networked Control

Networked control systems and multi-agent systems are important recent application areas for robotics (Fig. 3). Synchronization, coordination, cooperative manipulation, flocking, and swarming combine graph theoretic methods with nonlinear control.

The emerging "hot topic" of cyber-physical systems is also closely related to networked control. Cyber-physical systems will get their functionality through massive networking. Sensors, actuators, processors, databases, and control software will work together without the need to be collocated.

Figure 3. Coordinated robots competing in the international RoboCup soccer competition in 2003. The Cornell team, led by controls researcher Raffaello D'Andrea, won the competition in 1999, 2000, 2002, and 2003.

Conclusions

Robotics today is a much richer field than even a decade or two ago, with far-ranging applications. Developments in miniaturization, in new sensors, and in increasing processing power have all opened new doors for robots.

As we reflect on the progress made in the field and the opportunities now lying ahead, it is clear that robotics is not a “closed” discipline. The definition of what constitutes a robot has broadened considerably, perhaps even leading to categorical confusion! A Roomba robot is a robot, but is a drone aircraft a robot or an airplane? And as increasingly many “robotic” features are added to automobiles—such as collision avoidance or steering feedback for lane departure warning—should we start thinking of our personal vehicles as robots too? Even in this report some of this redundancy or ambiguity exists. But the problems are similar in many respects, and these different communities have much to gain by building bridges, even nominal ones. Seeking out fundamental problems is the best way to make an impact.

Selected recommendations for research in robotics control:

- Approaches integrating position-based and image-based methods represent a promising research direction for solving the visual servo control problem.
- Control advances are needed for making legged robot locomotion practical; the problem is characterized by hybrid nonlinear dynamics, unilateral constraints, and underactuation.
- With the increasing interest in multivehicle robotics—under/in sea, on land, and in the air—multi-agent and networked control systems have become, and will continue to be, a key research area.

References

[1] B.R. Markiewicz. “Analysis of the Computed Torque Drive Method and Comparison with Conventional Position Servo for a Computer-Controlled Manipulator,” NASA-JPL Technical Memo, 33-61, Mar. 1973.

[2] L.R. Hunt, R. Su, and G. Meyer. “Design for multi-input nonlinear systems,” in *Differential Geometric Control Theory,* R.W. Brockett et al., eds. Boston-Basel-Stuttgart: Birkhauser, 1983, pp. 268-298.

[3] T. J. Tarn, A. K. Bejczy, A. Isidori, and Y. Chen. “Nonlinear feedback in robot arm control,” in Proc. IEEE Conference on Decision and Control, Las Vegas, 1984, pp. 736-751.

[4] M.W. Spong. “Modeling and control of elastic joint robots,” *Transactions of the ASME, J. Dynamic Systems, Measurement and Control,* vol. 109, pp. 310-319, Dec. 1987.

[5] M.W. Spong and M. Vidyasagar. “Robust linear compensator design for nonlinear robotic Control,” *IEEE Journal of Robotics and Automation,* vol. RA 3, no. 4, pp. 345-350, Aug. 1987.

[6] M. Vidyasagar. “Optimal rejection of persistent bounded disturbances,” *IEEE Trans. Auto. Control,* vol. AC-31, no. 6, pp. 527-534, June 1986.

[7] J.-J.E. Slotine and W. Li. “On the adaptive control of robot manipulators,” *Int. J. Robotics Res.,* vol. 6, no. 3, pp. 147-157, Fall 1987.

[8] D. Koditschek. “Natural motion of robot arms,” in Proc. IEEE Conference on Decision and Control, Las Vegas, 1984.

[9] R. Ortega and M.W. Spong. “Adaptive control of robot manipulators: A tutorial,” *Automatica,* vol. 25, no. 6, pp. 877-888, 1989.

[10] R. Anderson and M. W. Spong. “Bilateral teleoperation with time delay,” *IEEE Trans. Aut. Cont.,* vol. 34, no. 5, pp. 494-501, May 1989.

[11] G. Niemeyer and J.-J.E. Slotine. “Stable adaptive teleoperation,” *IEEE Journal of Oceanographic Engineering,* vol. 16, no. 1, pp. 152–162, 1991.

[12] R. W. Brockett. “Asymptotic stability and feedback stabilization,” in *Differential Geometric Control Theory,* R.W. Brockett, R.S. Millman, and H. J. Sussmann, eds. Boston-Basel-Stuttgart: Birkhauser, 1983, pp. 181-191.

[13] A. Isidori and C.I. Byrnes. “Output regulation of nonlinear systems,” *IEEE Transactions on Automatic Control,* vol. 35, no. 2, pp. 131-140, 1990.

[14] S. A. Hutchinson, G.D. Hager, and P.I. Corke. “A tutorial on visual servo control,” *IEEE Transactions on Robotics and Automation,* vol. 12, no. 5, pp. 651-670, 1996.

[15] E.R. Westervelt, J.W. Grizzle, and D.E. Koditschek. “Hybrid zero dynamics of planar biped walkers,” *IEEE Transactions on Automatic Control,* vol. 48, no. 1, pp. 42-56, 2003.

[16] M.W. Spong and F. Bullo. “Controlled symmetries and passive walking,” *IEEE Transactions on Automatic Control,* vol. 50, no. 7, pp 1025-1031, 2005.

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