

The Interplay Between Robotics and Control Theory



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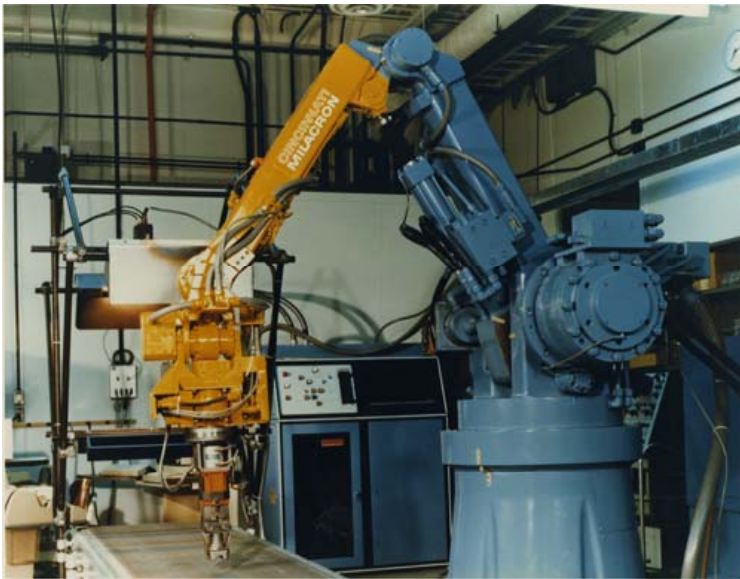
Disclaimer

- This is a personal view based on my own journey into robot control beginning around 1984 and not a comprehensive or even objective survey.
- A greater emphasis is placed on the early years than on recent years as it generally takes time for contributions to be appreciated in a proper perspective.
- The intent is to focus on fundamentals and how control theory has enabled solutions to fundamental problems in robotics and how problems in robotics have motivated the development of new control theory.
- It is impossible to adequately cite even a fraction of the important work in 30 minutes. Citations are therefore sparse - far more people are omitted than are included.
- With thanks to the following people for many useful comments and suggestions on this presentation: Chaouki Abdallah, Karl Astrom, Jessy Grizzle, Seth Hutchinson, Ali Jadbabaie, Frank Lewis, Romeo Ortega, Jean-Jacques Slotine, M Vidyasagar

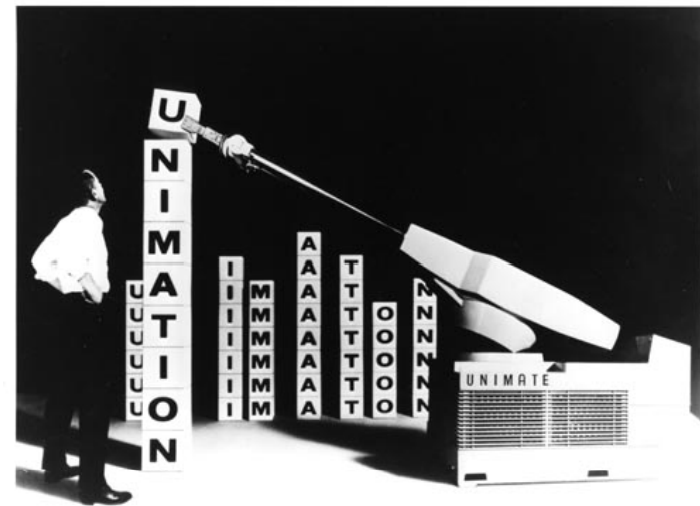


Fifty Years of Robot Control

The Early Years of Robotics - Prior to the 1980's - was largely focused on manipulator arms and simple factory automation tasks; materials handling, welding, painting. Cost of computation, lack of good sensors, and lack of fundamental understanding of robot control were the primary barriers to progress.



Cincinnati Milacron T3 Robot



Unimation 'Unimate' Robot



Fifty Years of Robot Control

Robotics today is a much richer field with far-ranging applications.



Parallel manipulators are gaining popularity over serial-link arms for their higher stiffness-to-weight ratios, speed, and other properties



Robots are exploring Mars and are poised to return to the moon.

Humanoids, like Honda's Asimo, have captured popular attention



Surgical robots, like the DaVinci system, are a reality

Fifty Years of Robot Control

The definition of what constitutes a robot has broadened dramatically.



Robot Swarms



Modular, Reconfigurable
and snake robots



Pilotless aircraft



Micro and Nano Robots
(University of Karlsruhe)



Household robots



Timeline and Overview of the Presentation

- In the Beginning - Pre-1984
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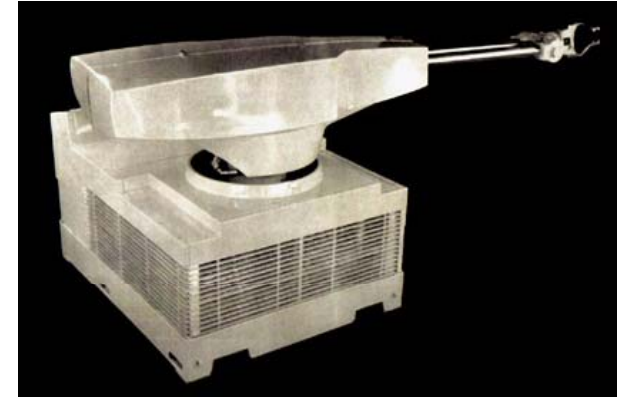
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In the Beginning



Two factors have been the primary drivers in the advancement of robot control:

1. An emphasis on fundamental understanding of dynamics, architecture, and system's level design
 - Early work on robot control was mostly based on approximate linear models and did not exploit knowledge of the natural dynamics.
 - Vision and force control were not well integrated into the overall motion control architecture.
 - Mechanical design and control system design were separate with some well-known design failures.
2. Moore's Law
 - The increasing speed and decreasing cost of computation has been a key enabler for the development and implementation of advanced, sensor-based control.

In the Beginning

- Some early classic papers on robot control developed creative new ideas:

J.S. Albus, “A New Approach to Manipulator Control: The Cerebellar Model Articulation Controller (CMAC),” *J. Dyn. Sys. Meas. and Control*, Vol. 97, pp. 220-227, 1975.

D.E. Whitney, “Resolved Motion Rate Control of Manipulators and Human Prostheses,” *IEEE Trans. Man-Machine Systems*, MMS-10, pp. 47-53, 1969.

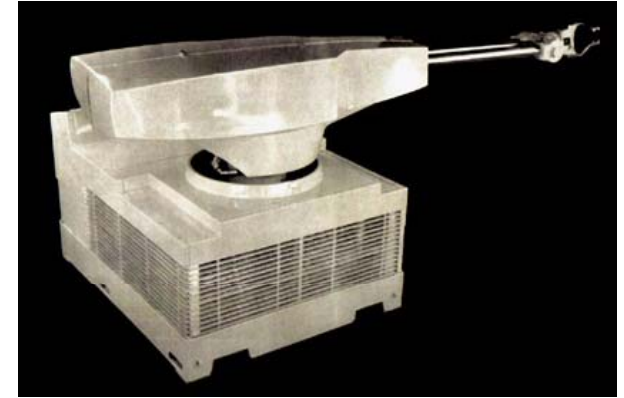
J.Y.S. Luh, M.W. Walker, and R.P.C. Paul, “Resolved Acceleration Control of Mechanical Manipulators,” *IEEE Transactions on Automatic Control*, Vol 25, No. 3, pp. 468-474, 1980.

- Or were innovative applications of well established control methods:

M.E. Kahn and B. Roth, “The Near Minimum-Time Control of Open-Loop Articulated Kinematic Chains,” *J. Dyn. Sys. Meas. and Control*, Vol. 93, pp. 164-172, 1971.

S. Dubowski and D.T. DesForges, “The Application of Model-Referenced Adaptive Control to Robotic Manipulators,” *J. Dyn. Sys. Meas. and Control*, Vol. 101, pp. 193-200, 1979.

K.-K. D. Young, “Controller Design for a Manipulator Using the Theory of Variable Structure Systems,” *IEEE Trans. Systems, Man, Cybernetics*, SMC-8, No. 2, pp. 101-109, 1978.



Moore's Law

- Pre-1984 papers on robot control invariably contained a calculation of the computational burden of implementation.

Adaptive Controller	Multiplications	Additions
Newton-Euler Equations of Motion	$117n-24$	$103n-21$
Least Squares Identification Algorithm	$30n^2 + 5n + 1$	$30n^2 + 3n - 1$
Control Algorithm	$8n^3 + 2n^2 + 39$	$8n^3 - n^2 - n + 18$
Total Mathematical Operations of Adaptive Controller	$8n^3 + 32n^2 + 5n + 40$	$8n^3 + 29n^2 + 2n + 17$

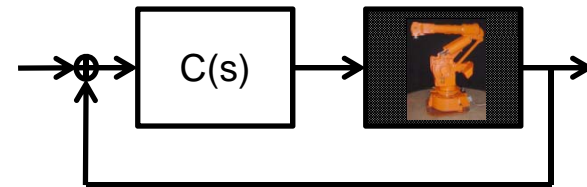
Table 1 Computations of The Adaptive Controller

CSG Lee, MJ Chung, and BH Lee, "Adaptive Control for Robot Manipulators in Joint and Cartesian Coordinates," 1984 IEEE ICRA, pp. 530-539, Atlanta, GA, March 13-15, 1984.



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Computed Torque and Feedback Linearization

- An early example of a non-traditional control idea was the method of computed torque

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.

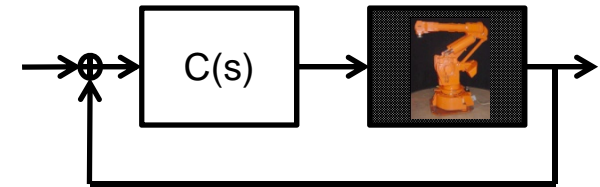
- Although computed offline and implemented as a feedforward scheme, the method of computed torque was a prelude to inverse dynamics control

E. Freund, "A Nonlinear Control Concept for Computer Controlled Manipulators," Proc. IFAC Symp. Multivariable Technol. Syst., pp 395-403, 1977.

- Inverse dynamics, in turn, helped motivate the differential geometric method of feedback linearization that has been applied to numerous practical problems within and outside of robotics

B. Jakubczyk and W. Respondek, "On Linearization of Control Systems," Bull. Acad. Polonaise Sci. Ser. Sci. Math., vol 28, pp. 517-522, 1980.

L.R. Hunt, R. Su, G. Meyer, "Design for Multi-Input Nonlinear Systems," Differential Geometric Control Theory, R.W. Brockett et al., eds, Birkhauser, pp. 268-298, 1983.



Feedback Linearization

- For fully actuated rigid manipulators the methods of feedback linearization and inverse dynamics yield equivalent results

T. J. Tarn, A. K. Bejczy, A. Isidori, Y. Chen, “Nonlinear Feedback in Robot Arm Control,” *IEEE Conference on Decision and Control*, pp. 736 - 751, 1984.

- The first nontrivial application in robotics of feedback linearization was to the problem of joint flexibility in robot manipulators

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.

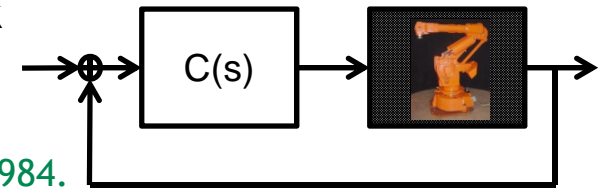
A. De Luca, “Dynamic Control of Robots with Joint Elasticity,” *IEEE Int. Conf. Robotics and Automation*, pp. 152-158, Philadelphia, 1988.

- Joint flexibility had previously been identified as the major limiting factor to manipulator performance

L. M. Sweet and M. C. Good, “Redefinition of the Robot Motion Control Problem: Effects of Plant Dynamics, Drive System Constraints, and User Requirements,” *Proc. of 23rd IEEE Conf on Decision and Control*, Las Vegas, NV. pp. 724-730, 1984.

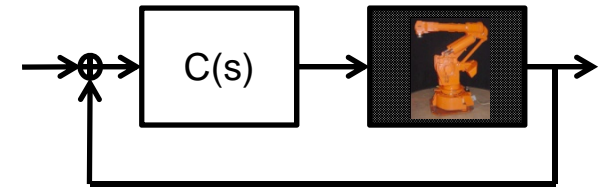
and remains an important component of robot dynamics and control

A. Albu-Schäffer and G. Hirzinger: State feedback controller for flexible joint robots: A globally stable approach implemented on DLR's light-weight robots. *IROS*, Vol 2., pp. 1087-1094, 2000.



Robust Control of Manipulators

•Feedback Linearization relies on exact cancellation of nonlinearities, which immediately raises the question of robustness to parameter uncertainty. Standard H^∞ control is inadequate to 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



Spong, M.W., and Vidyasagar, M., “Robust Linear Compensator Design for Nonlinear Robotic Control,” *IEEE Journal of Robotics and Automation*, Vol. RA 3, No. 4, pp. 345-350, Aug., 1987.

and the general case was presented in

M. Vidyasagar , “Optimal rejection of persistent bounded disturbances,” *IEEE Trans. Auto. Control*, AC-31(6), 527-534, June 1986

which subsequently led to a new area of control now known as L1-optimal control theory - a prime example of a practical application leading to new theory.

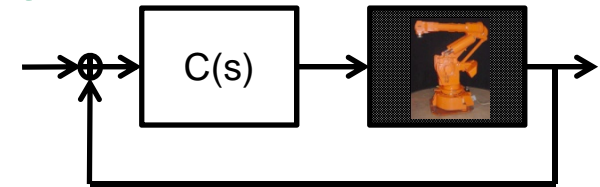
•Several other methods of robust control, such as sliding modes, and Lyapunov methods have been applied to this problem as surveyed in

C. Abdallah, P. Dorato, and M. Jamshidi, “Survey of the Robust Control of Robots,” American Control Conference, pp. 718 - 721, 1990.



Adaptive Control of Manipulators

The fundamental breakthrough in adaptive control of rigid manipulators occurred in



Slotine, J.J.E., and Li, W., “On the Adaptive Control of Robot Manipulators,” *Int. J. Robotics Res.*, Vol 6, No. 3, pp. 147-157, Fall, 1987.

The key to the solution of the adaptive control problem was the recognition of two important properties of Lagrangian dynamical systems, namely,

1. linearity in the inertia parameters

An, C.H., Atkeson C.G. and Hollerbach, J.M., “Estimation of inertial parameters of rigid body links of manipulators,” *IEEE Conf. Decision and Control*, Fort Lauderdale, 1985.

P. Khosla and T. Kanade, “Parameter Identification of Robot Dynamics,” *IEEE Conf. Decision and Control*, Fort Lauderdale, 1985.

2. the skew-symmetry property of the robot inertia

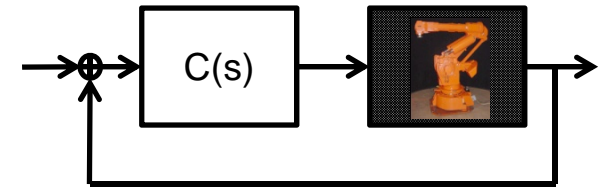
S. Arimoto and F. Miyazaki, “On the stability of PID Feedback with Sensory Information,” *Robotics Research*, M. Brady and R. Paul, eds., MIT Press, 1984.

D. Koditschek, “Natural Motion of Robot Arms,” *IEEE Conf. Decision and Control*, Las Vegas, 1984.



Passivity-Based Control

- Later it was recognized that the skew symmetry property was related to the fundamental property of passivity. The term *Passivity-Based Control* was introduced in the context of adaptive control of manipulators in



R. Ortega and M.W. Spong, “Adaptive Control of Robot Manipulators: A Tutorial,” *Automatica*, Vol. 25, No. 6, pp. 877-888, 1989.

- A pioneering early application of passivity-based control was contained in

M. Takegaki and S. Arimoto, “A New Feedback Method for Dynamic Control of Manipulators,” *J. Dyn. Sys. Meas. and Cont.*, Vol 102, pp. 119-125, 1981.

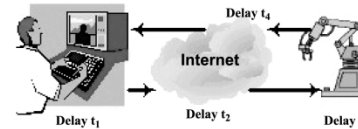
- Passivity-Based Control has become an important design method for a wide range of control engineering applications.

A. Astolfi, R. Ortega and R. Sepulchre, “Passivity-Based Control of Nonlinear Systems,” in *Control of Complex Systems*, eds. K. Astrom, P. Albertos, M. Blanke, A. Isidori, W. Schaufelberger and R. Sanz, Springer, London, 2000.



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Teleoperation

- Time delay induced instability of force reflection teleoperators was known as a major impediment from the 1960's to the 1980's.

- Passivity-based control enabled delay-independent stabilization of bilateral teleoperators in

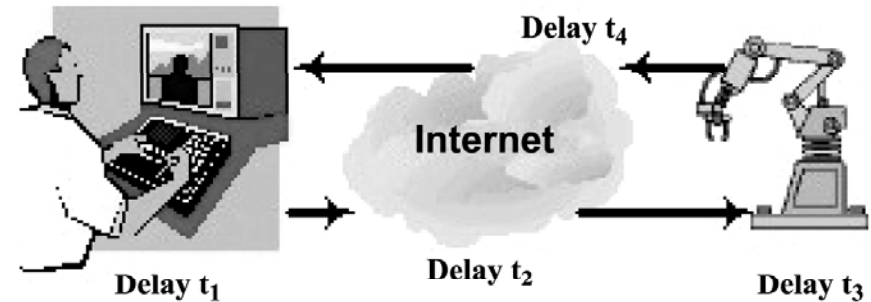
R. Anderson and M. W. Spong, "Bilateral Teleoperation with Time Delay," *IEEE Trans. Aut. Cont.*, Vol. 34, No. 5, pp. 494-501, May, 1989.

G. Niemeyer and J.-J. E. Slotine, "Stable adaptive teleoperation," *IEEE Journal of Oceanographic Engineering*, Vol. 16, No. 1, pp. 152-162, 1991.

- The key concept was to represent a master-slave teleoperator system as an interconnection of two-port networks

B. Hannaford, "A design framework for teleoperators with kinesthetic feedback," *IEEE Transactions on Robotics and Automation*, Vol 5, No. 4, pp. 426-434, 1989.

and then encode the position and velocity signals using so-called *Scattering Variables* [Anderson and Spong] or *Wave Variables* [Niemeyer and Slotine], which renders the time-delay network element passive independent of the time delay.



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Mobile Robots

- The problem of kinematic control of mobile robots received a great deal of interest starting in the 1980's as an application of differential geometric methods

H. Sussmann and G. Lafferriere, "Motion planning for controllable systems without drift," *IEEE Conf. Robotics and Automation*, Sacramento, CA, April 1991, pp. 1148-1153, 1991.

- The difficulty of the problem was dramatically revealed by Brockett's Theorem, which showed that smooth stabilizing control laws for such systems do not exist

R. W. Brockett, "Asymptotic stability and feedback stabilization," in *Differential Geometric Control Theory*, R. W. Brockett, R. S. Millman, and H. J. Sussmann, eds, pp. 181-191. Birkhauser, 1983.

- Brockett's Theorem stimulated the development of hybrid, switching control and time varying approaches to stabilization of nonholonomic systems

R. M. Murray and S. Sastry, "Nonholonomic motion planning: Steering using sinusoids," *IEEE Trans. on Automatic Control*, vol. 38, no. 5, pp. 700-716, 1993.

O.J. Sordalen, and O. Egeland, "Exponential stabilization of nonholonomic chained systems," *IEEE Transactions on Automatic Control*, Vol. 40, No. 1, pp. 35-49, 1995.



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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.

Spong, M.W., "Partial Feedback Linearization of Underactuated Mechanical Systems," IROS'94, Munich, Germany, Sep. 1994.

- Consideration of normal forms and zero dynamics are important in this context

A. Isidori and C.I. Byrnes, "Output regulation of nonlinear systems," *IEEE Transactions on Automatic Control*, Vol. 35, No. 2, pp. 131-140, 1990.

- Energy/passivity methods are fundamental for control of underactuated systems

R. Ortega, M.W. Spong, F. Gomez-Estern, G. Blankenstein, "Stabilization of a class of underactuated mechanical systems via interconnection and damping assignment," *IEEE Transactions on Automatic Control*, Vol. 47, No. 8, pp.1218 - 1233, 2002.



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Bipedal Locomotion

- Control of (Bipedal) Locomotion requires consideration of one or more of the following difficult issues:
 - hybrid nonlinear dynamics
 - unilateral constraints
 - underactuation
- Energy/Passivity methods, geometric nonlinear control, partial feedback linearization, zero dynamics, and hybrid control theory tools to design rigorous control algorithms for walking.



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.

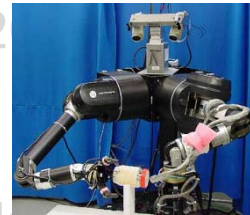
Aaron D. Ames and Shankar Sastry, “Hybrid Geometric Reduction of Hybrid Systems,” *IEEE Conference on Decision and Control, San Diego, CA, 2006*.

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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Visual Servo Control

- An important consequence of Moore's law has been the advent of cameras as inexpensive sensors and visual servo control as a viable method for real-time robot control.

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.

L. Weiss, A. Sanderson, C. Neuman, "Dynamic sensor-based control of robots with visual feedback," *IEEE Transactions on Robotics and Automation*, vol.3, no.5, pp.404-417, Oct. 1987.

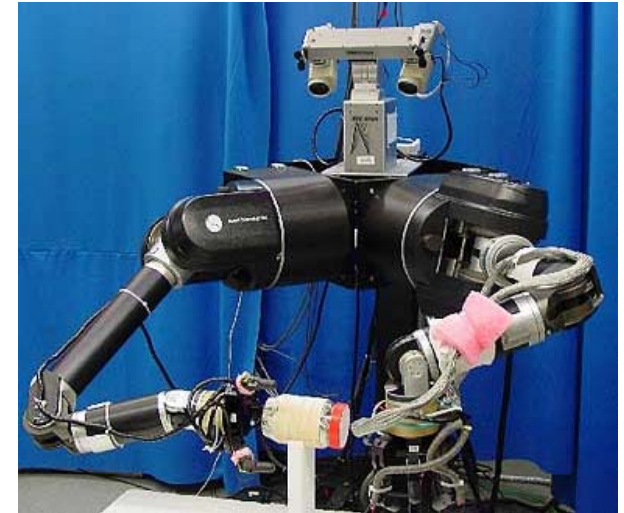
J.T. Feddema, O.R. Mitchell, "Vision-guided servoing with feature-based trajectory generation," *IEEE Transactions on Robotics and Automation*, vol.5, no.5, pp.691-700, Oct. 1989.

B. Espiau, F. Chaumette, and P. Rives, "A new approach to visual servoing in robotics," *IEEE Transactions on Robotics and Automation*, vol.8, no.3, pp.313-326, Jun 1992

- The traditional methods of image-based and position-based visual servo control are now incorporated into hybrid, switching control strategies in order to take advantage of the strengths and avoid the weaknesses of both approaches

P.I. Corke, and S.A. Hutchinson, "A new hybrid image-based visual servo control scheme," *IEEE Conference on Decision and Control*, pp. 2521-2526, 2000.

E. Malis, F. Chaumette, and S. Boudet, "2½D visual servoing," *IEEE Transactions on Robotics and Automation*, Vol. 15, No. 2, pp. 238-350, 1999.



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Multi-Agent Systems and Networked Control

- Networked Control Systems and Multi-Agent Systems are important recent applications. Synchronization, coordination, cooperative manipulation, flocking, and swarming, combine graph theoretic methods with nonlinear control methods.



I. Suzuki and M. Yamashita, “Distributed anonymous mobile robots: Formation of geometric patterns,” *SIAM J. Comput.*, vol. 28, no. 4, pp. 1347-1363, 1999.

J.P. Desai, J.P. Ostrowski, and V. Kumar, “Modeling and control of formations of nonholonomic mobile robots,” *IEEE Transactions on Robotics and Automation*, Vol 17, No. 6, pp. 905-908, 2001.

Y. Liu, K. M. Passino, and M. Polycarpou, “Stability analysis of one-dimensional asynchronous swarms,” *American Control Conference*, pp. 716-721, Arlington, VA, June 2001.

N. Leonard and E. Fiorelli, “Virtual leaders, artificial potentials and coordinated control of groups,” *IEEE Conf. Decision Control*, Orlando, FL, 2001.

R. Olfati and R. M. Murray, “Distributed structural stabilization and tracking for formations of dynamic multi-agents,” *IEEE Conf. Decision Control*, Las Vegas, NV, 2002.

A. Jadbabaie, J. Lin, and A.S. Morse, “Coordination of groups of mobile autonomous agents using nearest neighbor rules,” *IEEE Conf. Decision and Control*, pp. 2953 - 2958, Las Vegas, NV, 2002.



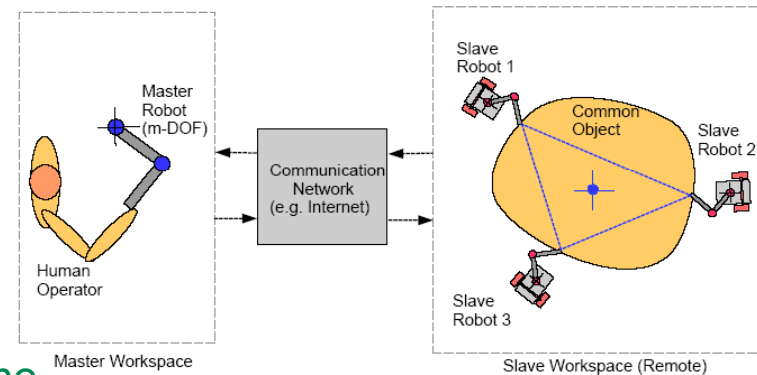
The Future: Cyberphysical Systems



Cyber-physical systems will get their functionality through massive networking. Sensors, actuators, processors, databases, control software will work together without the need to be collocated.



Semi-Autonomous Driving



Remote Manipulation

What are the fundamental control problems that the next generation of researchers will identify and solve to advance the field?



Conclusions

- The synergy between robotics and control theory has greatly benefited both fields.
- Seeking out fundamental problems is the best way to make an impact.
- Due to constraints of time, I have omitted several interesting and important areas of research. These include
 - Flexible Link Robots
 - Dextrous Robots: juggling, gymnastics, air hockey, ping-pong
 - Force Control and Grasping
 - Neural Networks and Fuzzy Logic Control
 - Learning Control
 - Time-Optimal Control
 - Multi-Legged Robots
 - Humanoid Robots
 - Haptics
 - Human-Robot Interaction
- I invite you to continue this discussion and fill in missing details



THANK YOU! QUESTIONS?

