The Quest for Autonomy

Are We There Yet?

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2015 ACC, Chicago

How does the Google car work

- The "heart of the system" is a laser range finder mounted on the roof of the car. The device, generates a detailed 3D map of the environment. The car then combines the laser measurements with high-resolution maps of the world, producing different types of data models that allow it to drive itself while avoiding obstacles and respecting traffic laws.
- The vehicle also carries other sensors, which include: four radars, mounted on the front and rear bumpers, that allow the car to "see" far enough to be able to deal with fast traffic on freeways; a camera, positioned near the rear-view mirror, that detects traffic lights; and a GPS, inertial measurement unit, and wheel encoder, that determine the vehicle's location and keep track of its movements.

How does the Google car work

- Before sending the self-driving car on a road test, Google engineers drive along the route one or more times to gather data about the environment. The autonomous vehicle compares the data it is acquiring to the previously recorded data, an approach that is useful to differentiate pedestrians from stationary objects like poles and mailboxes.

Autonomy and Degrees of Autonomy

- ***Autonomous*** means having the ability and authority for self-government.

  A system is autonomous regarding a set of goals, and with respect to a set of measures (of intervention by humans or other systems).

  A regular feedback control system could be seen as autonomous regarding stability goals with respect to (certain level or degree of external and internal) disturbances. This is because stability is maintained even when there are internal system parameter variations and external disturbances. This robustness is due to feedback closed-loop mechanism that compensates for uncertainties; on the other hand, an open-loop system with feed-forward control has none of these robustness properties and no autonomy regarding stability with respect to parameter variations and disturbances.

Autonomy and Degrees of Autonomy

A system is autonomous regarding a set of goals, and with respect to a set of measures (of intervention by humans or other systems).

- A system has *high or low degree or level of autonomy regarding a goal*. By high degree/level of autonomy it is meant that the degree/level of human intervention (or perhaps intervention by other engineered systems) is low, while by low degree/level of autonomy, a high degree/level of human intervention is implied.

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Autonomy and Degrees of Autonomy

- **Autonomous Controllers have the power and ability for self governance in the performance of control functions.**

  Autonomous regarding a set of goals, wrt a set of measures.
- **Degrees of Autonomy:**

  Conventional fixed controllers can be considered having low degree of autonomy.

  Adaptive controllers have higher degree of autonomy.

  A Highly Autonomous Controller is highly adaptable to changes in the plant, environment and control objectives and provides High Level of Adaptation.

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Autonomy and Degrees of Autonomy

The system under consideration always has a set of goals to be achieved and a control mechanism to achieve them. This implies that ***every autonomous system is a control system*.**

When one considers humans collaborating with engineered systems, then the overall system that includes humans in the loop may be considered (fully) autonomous with respect to a set of goals. Depending on the role of the humans in the loop and the level of control authority humans exert, the remaining system will have different degrees or levels of autonomy.

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Autonomy and Degrees of Autonomy

In an automobile, if the goal is for example to keep the vehicle inside a lane while travelling with constant speed, the system may consist of the vehicle and the driver where the system attains its goals in the presence of uncertainties/disturbances, such as gust of wind and road incline.

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Autonomy and Degrees of Autonomy

- Degrees of Autonomy

- Need high level decision making techniques for reasoning under uncertainty. These techniques, if used by humans, are attributed to Intelligent Behavior.

  Intelligent Control - High autonomy is the objective, intelligent control provides one way to achieve it.

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Intelligent Control for High Autonomy Systems

- Intelligent Control
  That all encompassing area that tends to include everything that it is not characterized as conventional control. Goes beyond Neural Networks, Fuzzy Logic and Genetic Algorithms.

  IEEE CSS Task Force on "Defining Intelligent Control" in IEEE CSM in June 1994 (Chair PJA).

- Intelligent Control and Intelligent Systems. Autonomous Intelligent Systems
  http://www.nd.edu/~pantsakl/links/

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THE QUEST FOR AUTONOMY

Pervasive theme in engineered systems through the centuries

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Historical Notes

B.C. - A.D: Float Regulators
Ktesibios' water clock
1600 – 1700: Drebbel's Temperature Regulators
Pappin's Pressure Regulators
1769: James Watt's Flyball Governor
Era of Intuitive Invention

1868: J.C. Maxwell. Mathematical Theory, Differential Equation Description of Flyball Governor
Routh 1877 Lyapunov 1890

1930s: Feedback Electronic Amplifier
Nyquist Bode Frequency Response
1940s: Wiener Optimal Filters
Laplace Trans. Complex Plane Root-Locus

1950s: Pontryagin -Max Principle
Bellman – Dynamic Programming
"Classical Control"
1960–Today:
"Modern Era" State Variables
Optimal Control and Estimation
Space Applications
Control of Multi-Input and Multi-Output Systems
Stochastic Control
Adaptive Control
Integration of Time and Frequency Domain Methods in Optimal Control
Nonlinear Control Systems
Computer Advances
Future: Highly Demanding Control Requirements on Highly Complex Systems

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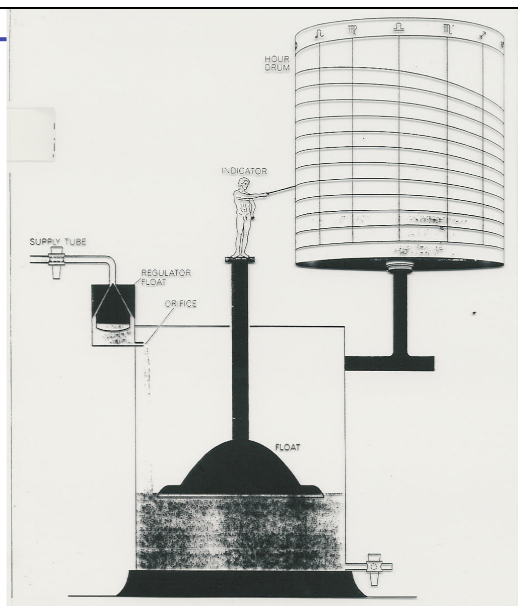

ANCIENT WATER CLOCK is the earliest known device for feed-[illegible]. It was invented in the third century B.C. by a Greek mechanician named Ktesibios, working in Alexandria. This drawing is based on a reconstruction by the German classicist Hermann Diels. The indicator figure is mounted on a large float (*bottom*), which rises inside a tank as a result of a slow trickle of water into the tank. The 12 hours, which vary in length with the seasons of the year, are indicated on the drum at top right. The change in the length of the hours can be represented by simply turning the drum to the proper month. The float regulator at top left controls the rate of water flowing into the main tank by maintaining a constant water level in the adjacent regulator vessel. If the level rises (as a result, say, of an increase of static pressure in the external supply line), the regulator float will rise, throttling the inflow into the regulator vessel. The device is remarkably similar in operation to the carburetor of a modern automobile.

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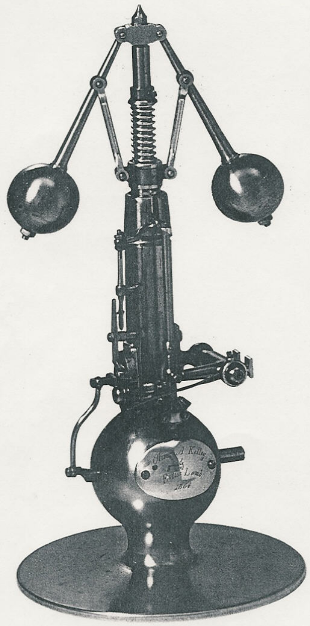

Feedback Mechanisms

IN THE HISTORICAL COLLECTIONS OF THE NATIONAL MUSEUM OF HISTORY AND TECHNOLOGY

By Otto Mayr

SMITHSONIAN INSTITUTION PRESS
CITY OF WASHINGTON
1971

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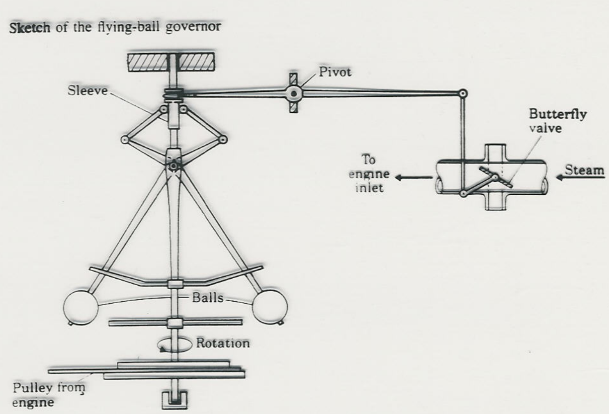

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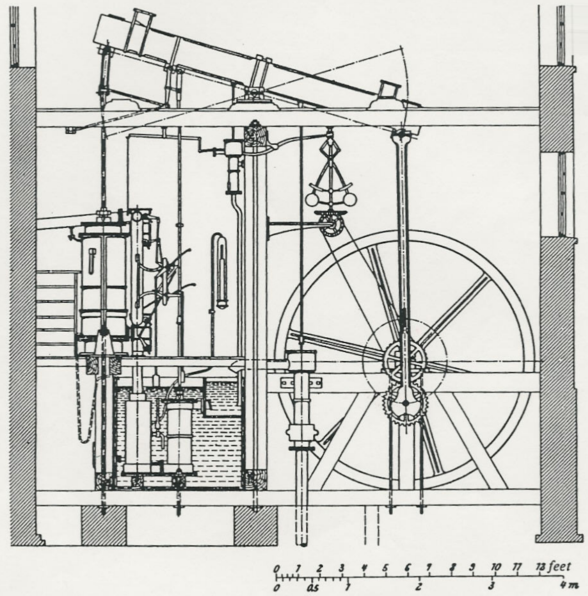
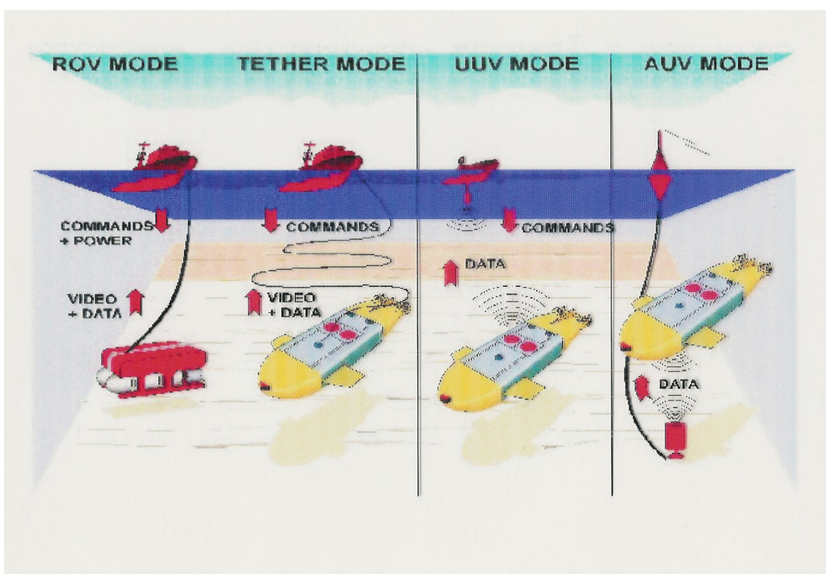


Figure 1 Watt steam engine (1789-1800) with centrifugal governor.



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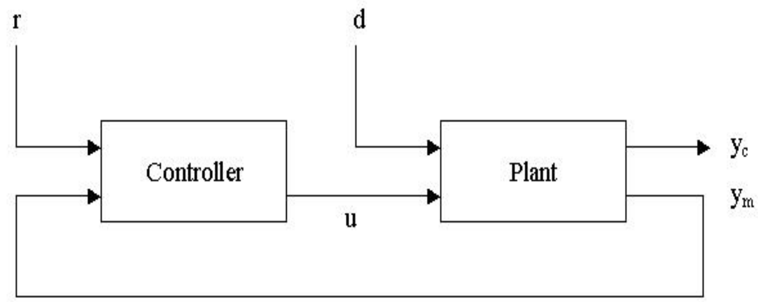
Fixed Controllers. Robust Control Systems Linear and Nonlinear Systems



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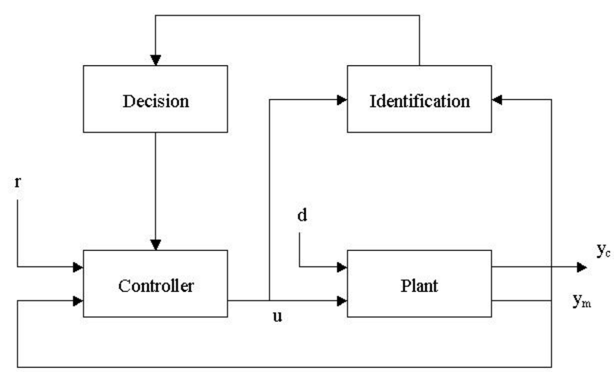
Adaptive Controllers Direct and Indirect Linear Systems. Nonlinear.



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Control Systems - Higher Level Adaptation

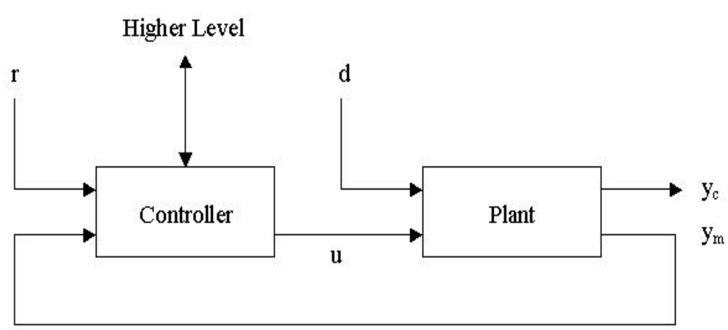
- **When Significant Changes Occur in Plant, Environment, Control Goals and Constraints:**

  Conventional Control Systems are not Adequate to Adapt to Failures, Design a New Control Law, Set New Control Goals in order to cope with the changes

- **To Be Able to Adapt to Such Changes Without Human Intervention :**

  Need to Take into Consideration Information Beyond the Math Plant Model and Current Control Goals and Need to Add Decision Making Capabilities Under Significant Uncertainties.

Highly Adaptive Controller
Autonomous Intelligent Control



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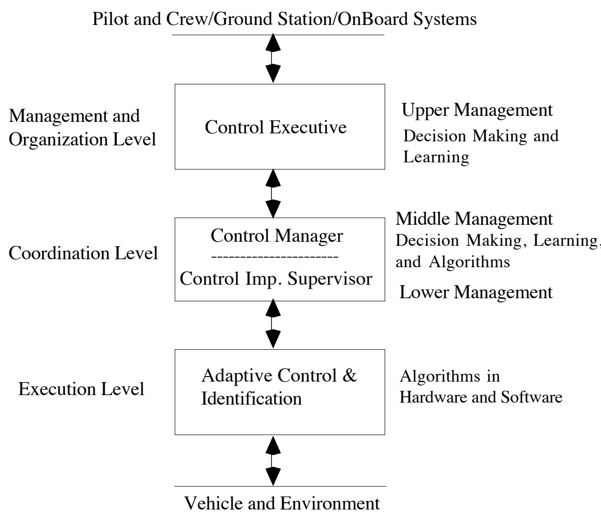

Autonomous Controller Functional Architecture – Spacecraft JPL

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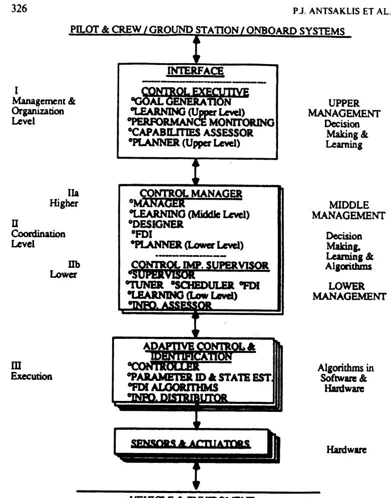

Fig. 1. Autonomous controller architectural schematic.

be operated and tested independently. The autonomous controller performs many of the functions currently performed by the pilot, crew, or ground station. The pilot and crew are thus relieved from mundane tasks and some of the ground station functions are brought aboard the vehicle. In this way the vehicle becomes more autonomous.

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Execution Level (III)

Its main function is to generate, via the use of numeric algorithms, low level control actions as dictated by the higher levels of the controller, and apply them to the vehicle. It senses the responses of the vehicle and environment, processes it to identify parameters, estimates states, or detects vehicle failures, and passes this information to the higher levels.

Coordination Level (IIb)

It receives commands to perform predetermined specific control tasks from the control manager in the level above. It provides the appropriate sequence of control and identification algorithms to the Execution Level below. Its ability to deal with extensive uncertainties is limited.

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Coordination Level (IIa)

It receives commands from the management level and determines how to execute them using the designer and planner and considering information from FDI IIa and the control implementation supervisor.

Management and Organization Level (I)

It interfaces with the pilot, crew, ground station, and other onboard systems and performs the highest level control functions. It oversees and directs all the activities at both the Coordination and Execution levels. It is the most "intelligent" of the three levels.

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Characteristics of Hierarchical Autonomous Intelligent Control Systems

- Successive delegation of duties from the higher to lower levels. Number of distinct tasks increases
- Higher levels concerned with slower and broader aspects of system's behavior. Also with longer time horizons.
- Lower levels concerned with smaller contextual horizons and control decisions are made faster based on less information. Also shorter time horizons.

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Characteristics of Hierarchical Autonomous Intelligent Control Systems

- Increasing precision at lower levels and decreasing precision at higher levels.
- Principle of Increasing Intelligence with Decreasing Precision. Increasing intelligence from lower to higher levels needed for high level decision making abilities higher levels in the hierarchy.
- Decreasing precision in higher levels is reflected by decrease in time scale density, bandwidth or system rate and the decision (control action) rate.
- These characteristics lead to a decrease in granularity of models used at higher levels or to an increase in model abstractness.

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People do change, and change comes like a little wind that ruffles the curtains at dawn, and it comes like the stealthy perfume of wildflowers hidden in the grass.

John Steinbeck

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An important scientific innovation rarely makes its way by gradually winning over and converting its opponents:

It rarely happens that Saul becomes Paul

What does happen is that its opponents gradually die out and that the growing generation is familiarized with the idea from the beginning.

Max Planck
1858-1947

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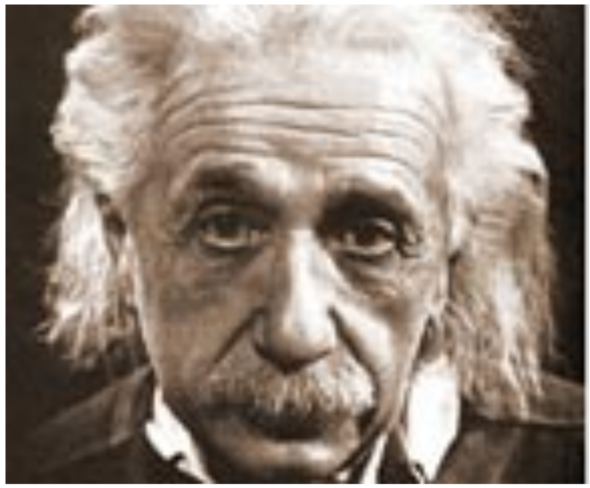

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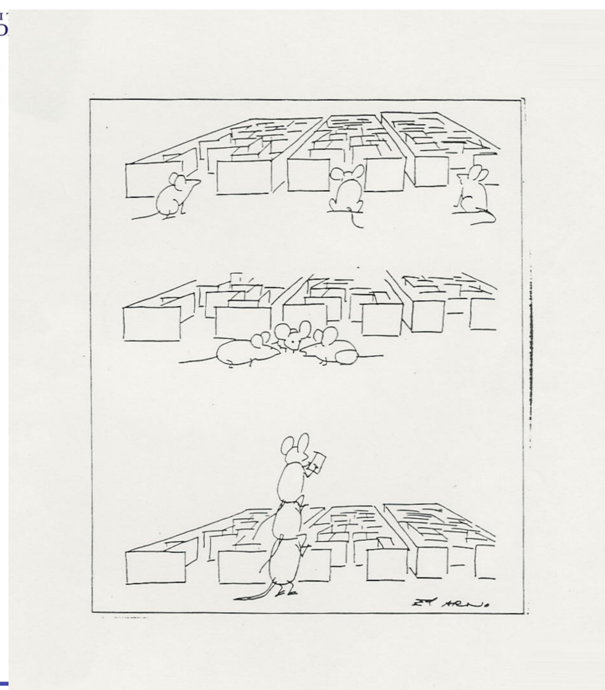

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Cyber-Physical Systems (CPS)

-As computers become ever-faster and communication bandwidth ever-cheaper, computing and communication capabilities will be embedded in all types of objects and structures in the physical environment.

-***Cyber-physical systems (CPS)*** are physical, biological and engineered systems whose ***operations are monitored, coordinated,* controlled *and integrated by a computing and communication core***.

-This intimate coupling between the cyber and physical will be manifested from the nano-world to large-scale wide-area systems of systems. And at multiple time-scales.

-Applications with enormous societal impact and economic benefit will be created.

-Cyber-physical systems will transform how we interact with the physical world just like the Internet transformed how we interact with one another.

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- Next generation healthcare -- biomedical devices and systems engineering (wearable/implantable, minimally-invasive, bio-aware, bio-compatible, patient-specific, open, configurable, portable, universal point-of-care safety)
- Next generation energy systems (distributed, intermittent, renewable sources; shifting topology for generation, storage/transfer/transmission, distribution; smart loads, better control of dynamic demand-response; new sources/sinks: cars, buildings)
- Next generation environmental systems (in situ co-generation, multi-source energy harvesting, geo-thermal/ground-source heating and cooling; integrated environmental control: light, thermal, air- and water-quality, noise abatement, physical access)
- Next generation transportation (autonomous systems, energy-efficient, high-performance, multi-modal: air, automotive, rail, maritime systems, enhanced and affordable personal mobility and transport)
- Next generation manufacturing (flexible/configurable, multi-scale, interoperable line components, self-assembly, multi-process bio/chemical/mechanical engineering; precision next-generation - laser/thermal/EMF/bio/mechanical tooling and monitoring)
- Next generation agriculture (pervasive sensing, precision micro-climates/micro-cultures, pervasive animal health monitoring and veterinary medicine),
- Next generation water systems (atmospheric sources, reuse, quality sensing, exploration, hazard alerts)
- …

Source: NSF

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Quest for Autonomy

From Ancient Water Clocks to Autonomous Spacecrafts

Personal Quest

- **Linear Feedback Control & Polynomial / Fractional Descriptions.**
- **High Autonomy and Intelligent Control Systems.**
- **Neural Networks.**
- **Supervisory Control of Discrete Event Systems-Petri Nets.**
- **Hybrid Dynamical Control Systems. ODE & Automata/Petri Nets.**
- **Networked Control Systems.**
- **Cyber-Physical Systems.**

Autonomous Intelligent Control - Publications

"Defining Intelligent Control," (PJA)
Report of the IEEE CSS Task Force on Intelligent Control, P.J.Antsaklis, Chair.
In *IEEE Control Systems Magazine*, pp. 4-5 & 58-66, June 1994.

An Introduction to Intelligent and Autonomous Control, (PJA, Passino, Eds.),
448 pages, Kluwer, 1993. http://www.nd.edu/~pantsakl/

"Intelligent Control," (PJA),
Encyclopedia of Electrical and Electronics Engr.. John Wiley & Sons. Inc. 1999 & 2007.

"Intelligent Learning Control," (PJA),
Guest Editor's Introduction, Special Issue on 'Intelligence and Learning,'
IEEE CSM, Vol.15, No.3, pp. 5-80, June 1995.

"Introduction to Intelligent Control Systems with High Degree of Autonomy," (PJA, Passino) *An Introduction to Intelligent and Autonomous Control*, (PJA, Passino, Eds.) Chapter 1, Kluwer, 1993.

"Learning to be Autonomous: Intelligent Supervisory Control," (PJA, Lemmon, Stiver),
in *Intelligent Control: Theory and Practice*, Gupta & Sinha Eds., pp. 28-62, IEEE Press, 1995.

"An Introduction to Autonomous Control Systems," (PJA, Passino, Wang),
IEEE Control Systems Magazine, Vol 11, No 4, pp 5-13, June 1991.

"Towards Intelligent Autonomous Control Systems: Architecture and Fundamental Issues,"
(PJA, Passino, Wang), *Journal of Intelligent and Robotic Systems*, Vol. 1, pp. 315-342, 1989.