A Day Without Automatic Control

A Glimpse Behind the Magic

By Panos Antsaklis

First, what does automatic control do? Cruise control in the car keeps the speed constant even when we go up a slope or face a head wind. Automatic control keeps the value of a variable constant (here the speed, but also temperature, pressure, distance and so on in other applications) under a variety of operating conditions, automatically. Amazingly, in the human body automatic control systems are abundant and include regulation of body temperature, of white cell concentration in the blood, of the heart pumping rate, to mention but a few.

But how important is automatic control? Perhaps, to understand and appreciate its importance we need to imagine its absence! We know for example that electric power is important in our everyday life, but we tend to forget this fact or take it for granted. We really appreciate electricity's importance when there is an electric power interruption, a black-out, even a short one, when we realize how much our lives are disrupted. Such electric power disruptions may also put lives at significant risk, because patients in hospitals or at home depend on having readily available electric power. It is similar for telephone communication or the internet, where a loss of service that disrupts our lives clearly shows how dependent we are on these services. So to show clearly what automatic control is and how important it is to us, we will try to imagine what a day without automatic control would be like, before getting into the details of how control works.

We are alive because important quantities in our body like blood pressure, heart beat rate, white and red cell concentrations are regulated automatically and so remain within certain levels. Pace makers are devices that correct abnormal heart beat rates when our body's automatic control system is not behaving normally. We can imagine what may happen without these controls by thinking about the consequences of a control failure; when blood pressure shoots up for example a stroke may occur, while when the pressure is too low, loss of consciousness may occur.

So, if we do away with automatic control even for a very short time, unfortunately you, esteemed reader, will not be alive long enough to enjoy this article!

Yes, automatic control is important; it is serious business and vital to the existence of life in humans, animals, plants. We should care because our very lives, and life on planet earth, depend on it!

But let's now focus on control applications in engineered systems. If there is no automatic control there is no heating or air-conditioning the way we have become accustomed to--where certain temperature and humidity levels are maintained. Refrigerators and stoves would not be able to regulate their operation. Any safety device is a control device. The electric power grid maintains very tight control on the frequency of the AC voltage, and if that fails blackouts occur. Automatic pilots in airplanes are automatic control systems, and helicopters or military aircraft would not be able to fly at all without automatic controls.

Where is the magic? How does automatic control work? It works by using feedback control. Information about the output variable we measure is used to adjust the input variable we can control. When the output is too high, the input level is reduced and when the output is too low the input is increased. In a motor for example, if the rpm (revolutions per minute) of the output (of the shaft's angular velocity) slows down because of a load (lifting a heavy load with a crane or in an elevator) then the input voltage is increased automatically, which makes the rpm go up. To use an example from human biology, if our body temperature is increasing in a hot day, perspiration is used to cool down the body via evaporation.

To control, one needs to know the effect of possible action on the system or process that is to be controlled. One needs to have a cause and effect kind of list, so when the process evolves in an undesirable way we may intervene and correct it.

In an automobile, the automatic speed control system, the cruise control as it is known, detects the speed, calculates how much it is different from the desired speed and increases or decreases the fuel by adjusting the gas pedal. This is exactly how the driver behaves, and the automatic controller imitates the actions of the driver. It is envisioned that in the future sensors will detect that a pedestrian intends to cross the road and will slow down the car, or it will detect that children are playing with a ball too close to the road and slow down the car, in the same way a careful driver would behave. Today, our cars run more efficiently and with cleaner emissions because of control algorithms in the "engine control module." The ABS brakes would not exist without automatic control; the same with the Electronic Stability Control systems. Our cars today are cleaner, safer and more efficient because of automatic control.

The human body has designed its automatic control mechanisms guided by genetics as humans evolved, perhaps modifying these mechanisms in a more or less "real-time" fashion, to a certain degree as needed, guided by environmental influences and interactions. It should be mentioned that feedback control is a central mechanism in early forms of life seeking food: sensors detect the relative position to the food source and controllers adjust motion accordingly using existing actuators (fins, flagella etc.). We are aware of the control we use to grasp a water glass, where we use feedback information from eyesight and also touch to move our hand, but we may not be as aware or familiar with the automatic control mechanisms mentioned above--body temperature control for instance-although they are easily observable. But even in the case of the motor control of the hand, we typically do not think about the underlying control mechanism until the automatic control fails in some nervous system disorders (e.g. Parkinson's or a traumatic brain injury), where the lack of control makes its importance obvious often very dramatically.

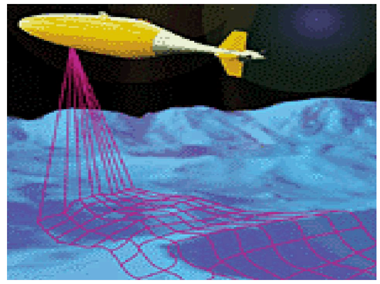
In engineering (man-made) systems, automatic control mechanisms are designed based on models of the behavior that needs to be controlled. These models are typically mathematical models that capture the behavior of interest. The study of the models leads to identifying the variables that need to be manipulated and by how much, in order to achieve given desired specifications. In aircraft flight, when the automatic pilot is engaged, particular control surfaces are used (the ailerons, the elevators, or the rudder) to ascend, descend or turn. Detailed mathematical models are used to decide what action should be taken, and the decision mechanisms are implemented via algorithms coded in software that runs on digital hardware. These algorithms process sensor information such as speed, direction, altitude together with information regarding desire altitude, speed or direction and issue control commands to electric motors or hydraulic actuators that move the control surfaces just the right amount.

The control specifications may refer to a static value, as in keeping the room temperature at 68 degrees or the aircraft speed at .8 Mach, or they may refer to dynamic, time-changing values, as in having an aircraft follow a particular trajectory over time, or a radar beam following, "locking on," an aircraft that flies overhead. Designing controllers that make complex systems exhibit desired behaviors can be very challenging. This is because the mathematical models, which can be quite complicated (e.g. nonlinear or partial differential equations, automata or Petri nets) only approximately describe the behavior of interest, and in addition, non-measurable external disturbances (e.g. load disturbances, measurement noise) may affect the behavior in an adverse way. These ever-present uncertainties that may be internal or external to the plant (the system to be controlled) are the principal reasons for using feedback information in the control of systems.

What is the research relevant to accomplishing the control goals then? What are the topics researchers in control work on and publish? Certainly the center-pieces are the decision mechanisms, that have knowledge of the plant behavior, encapsulated in its mathematical model, and by processing sensor information regarding the actual behavior (as opposed to the predicted behavior the model provides), decide how to apply corrective action in view of the desired behavior. Optimization methods are often researched and used together with a great number of other control design approaches that are heavily influenced by the type of mathematical models used -- they may be ordinary or partial linear or nonlinear differential equations describing dynamic behavior, transfer functions and Laplace transforms, frequency response and complex analysis, algebraic equations describing some steady state behavior, difference equations and z-transform, logic models, automata and Petri or hybrid models, and so on. Mathematical modeling is very important, and model parameter estimation and identification is an important research area. More recently there is significant effort dedicated to modeling biological processes. Analyzing the behavior of complex systems and extracting properties is very important because it leads to better ways to control their behavior; research in the area of dynamical systems is of significant interest here. State estimation is also important because the plant states are very useful in control; many times they can only be estimated from existing measurements and the plant equations. The sensor data may need to be processed to extract information usable by the controller. And so areas such as sensor fusion, signal processing become important. The areas of sampled data systems and digital control become important when the control algorithms are implemented via a digital device. Difference equations and z-transform may then be used. When the information from the sensors (and information sent to the actuators) is transmitted over a network, research in networked control is of interest, which combines concepts from control, communication networks and information theory. When many systems interact with each other, distributed control and research in multi-agent systems become important. There the information available to individual agents is only local, but the control implemented by each agent affects the global behavior. As the systems to be controlled become more complex, identifying faults early on is very important. So fault diagnosis, identification and isolation together with control reconfiguration are of interest. Adaptation and learning are also very important at higher levels of complexity. Certainly the control implementation depends on hardware and software, and their availability or absence influence the research in control algorithms.

There are many application domains for control, each with their own particular models and requirements. Control concepts, theories, and algorithms are used in manufacturing, in chemical processes, refineries, nuclear and non nuclear electric energy plants, pipelines, electric transmission and distribution, transportation (air, ground water, underwater, space), economics, political science, psychology, physics, biology. More recently the area of Cyber-Physical Systems attempts to encapsulate the tight integration of computers and the physical world in control. The common denominator of control in all these very diverse areas is the concept of Feedback.

A more detailed description of what automatic control systems are and do is included below. This material comes from the IEEE Control Systems Society Website and it originates from the earlier CSS brochure titled *“Control Systems: Meet the Challenge, Put Control in your Future.”*

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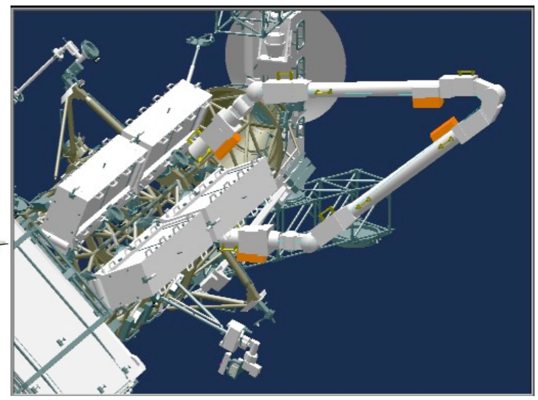

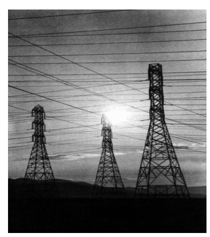

What is Automatic Control All About

Control and Its Applications

Control methods are used whenever some quantity, such as temperature, altitude or speed, must be made to behave in some desirable way over time. For example, control methods are used to make sure that the temperature in our homes stays within acceptable levels in both winter and summer; so that airplanes maintain desired heading, speed and altitude; and so automobile emissions meet specifications.

The thermostat that regulates the operation of the furnace in a typical home is an example of a device that controls the heating system, so that the temperature is maintained at a specified level. The autopilot in a passenger aircraft that maintains speed, altitude and heading is an example of a more sophisticated automatic control system. The cruise control in a car, which maintains constant speed independently of road inclines, is yet another example of a control system. Control methods in biomedical applications make possible the use of electrical nerve signals to control prosthetics, and precision robots for cutting holes in bone for implanting artificial joints, resulting in much tighter fits than previously thought possible.

Control is All Around Us

Control is a common concept, since there always are variables and quantities, which must be made to behave in some desirable way over time.

In addition to the engineering systems, variables in biological systems such as the blood sugar and blood pressure in the human body, are controlled by processes that can be studied by the automatic control methods. Similarly, in economic systems variables such as unemployment and inflation, which are controlled by government fiscal decisions can be studied using control methods.

Our technological demands today impose extremely challenging and widely varying control problems. These problems range from aircraft and underwater vehicles to automobiles and space telescopes, from chemical processes and the environment to manufacturing, robotics and communication networks.

The Practice of Control

A large fraction of engineering designs involves automatic control features. Frequently, control operations are implemented in an embedded microprocessor that observes signals from sensors and provides command signals to electromechanical actuators. Applications may range from washing machines to high performance jet engines. Designers frequently use computer-aided-design (CAD) software that embodies theoretical design algorithms, and permits tradeoff comparisons among various performance measures such as speed of response, operating efficiency and sensitivity to uncertainties in the model of the system. Proposed control designs, especially those for complex and expensive applications, are usually tested using computer based simulations.

Control engineering experts keep up with the latest theoretical developments. Most control systems are put together by practical minded engineers who have a thorough understanding of application areas such as automotive engines, factory automation, robot dynamics, heating, ventilating and air conditioning.

Methodology

The first step in understanding the main ideas of control methodology is realizing that we apply control in our everyday life; for instance, when we walk, lift a glass of water, or drive a car. The speed of a car can be maintained rather precisely, by carefully observing the speedometer and appropriately increasing or decreasing the pressure on the gas pedal. Higher accuracy can perhaps be achieved by looking ahead to anticipate road inclines that affect the speed. This is the way the average driver actually controls speed. If the speed is controlled by a machine instead of the driver, then one talks about automatic speed control systems, commonly referred to as cruise control systems. An automatic control system, such as the cruise control system in an automobile, implements in the controller a decision process, also called the control law, that dictates the appropriate control actions to be taken for the speed to be maintained within acceptable tolerances. These decisions are taken based on how different the actual speed is from the desired, called the error, and on the knowledge of the car's response to fuel increases and decreases. This knowledge is typically captured in a mathematical model. Information about the actual speed is fed back to the controller by sensors, and the control decisions are implemented via a device, the actuator, that increases or decreases the fuel flow to the engine.

Foundations and Methods

Central in the control systems area is the study of dynamical systems. In the control of dynamical systems, control decisions are expected to be derived and implemented over real time. Feedback is used extensively to cope with uncertainties about the system and its environment.

Feedback is a key concept. The actual values of system variables are sensed, fed back and used to control the system. Hence the control law decision process is based not only on predictions about the plant behavior derived from the system model (as in open-loop control), but also on information about the actual system behavior (closed-loop feedback control).

The theory of control systems is based on firm mathematical foundations. The behavior of the system variables to be controlled is typically described by differential or difference equations in the time domain; by Laplace, Z and Fourier transforms in the transform (frequency) domain. There are well understood methods to study stability and optimality. Mathematical theories from partial differential equations, topology, differential geometry and abstract algebra are sometimes used to study particularly complex phenomena.

Control system theory research also benefits other areas, such as Signal Processing, Communications, Biomedical Engineering and Economics.

Challenges in Control

The ever increasing technological demands of society impose needs for new, more accurate, less expensive and more efficient control solutions to existing and novel problems.

Typical examples are the control demands for passenger aircraft and automobiles. At the same time, the systems to be controlled often are more complex, while less information may be available about their dynamical behavior; for example such is the case in large flexible space structures. The development of control methodologies to meet these challenges will require novel ideas and interdisciplinary approaches, in addition to further developing and refining existing methods.

Emerging Control Areas

The increasing availability of vast computing power at low cost, and the advances in computer science and engineering, are influencing developments in control. For instance, planning and expert systems can be seen as decision processes serving purposes analogous to control systems and so lead naturally to interdisciplinary research and to intelligent control methods. There is significant interest in better understanding and controlling manufacturing processes typically studied in disciplines such as Operations Research, and this has led to interdisciplinary research to study the control of discrete-event systems (DES) that cannot be described by traditional differential or difference equations; and to the study of hybrid control systems that deal with the control of systems with continuous dynamics by sequential machines. Fuzzy control logic and neural networks are other examples of methodologies control engineers are examining to address the control of very complex systems.

Future Control Goals

What does the future hold? The future looks bright. We are moving toward control Systems that are able to cope and maintain acceptable performance levels under significant unanticipated uncertainties and failures, systems that exhibit considerable degrees of autonomy. We are moving toward autonomous underwater, land, air and space vehicles; highly automated manufacturing; intelligent robots; highly efficient and fault tolerant voice and data networks; reliable electric power generation and distribution; seismically tolerant structures; and highly efficient fuel control for a cleaner environment.

Control systems are decision-making systems where the decisions are based on predictions of future behavior derived via models of the systems to be controlled, and on sensor-obtained observations of the actual behavior that are fed back. Control decisions are translated into control actions using control actuators. Developments in sensor and actuator technology influence control methodology, which is also influenced by the availability of low cost computational resources.

Put Control in Your Future

The area of controls is challenging and rewarding as our world faces increasingly complex control problems that need to be solved. Immediate needs include control of emissions for a cleaner environment, automation in factories, unmanned space and underwater exploration, and control of communication networks. Control is challenging since it takes strong foundations in engineering and mathematics, uses extensively computer software and hardware and requires the ability to address and solve new problems in a variety of disciplines, ranging from aeronautical to electrical and chemical engineering, to chemistry, biology and economics.

Brief History of Control
From Ancient Water Clocks to Autonomous Space Vehicles

Automatic control Systems were first developed over two thousand years ago. The first feedback control device on record is thought to be the ancient water clock of Ktesibios in Alexandria Egypt around the third century B.C. It kept time by regulating the water level in a vessel and, therefore, the water flow from that vessel. This certainly was a successful device as water clocks of similar design were still being made in Baghdad when the Mongols captured the city in 1258 A.D. A variety of automatic devices have been used over the centuries to accomplish useful tasks or simply to just entertain. The latter includes the automata, popular in Europe in the 17th and 18th centuries, featuring dancing figures that would repeat the same task over and over again; these automata are examples of open-loop control. Milestones among feedback, or "closed-loop" automatic control devices, include the temperature regulator of a furnace attributed to Drebbel, circa 1620, and the centrifugal flyball governor used for regulating the speed of steam engines by James Watt in 1788. In his 1868 paper "On Governors", J. C. Maxwell (who discovered the Maxwell electromagnetic field equations) was able to explain instabilities exhibited by the flyball governor using differential equations to describe the control system. This demonstrated the importance and usefulness of mathematical models and methods in understanding complex phenomena, and signaled the beginning of mathematical control and systems theory. Elements of control theory had appeared earlier but not as dramatically and convincingly as in Maxwell's analysis.

Control theory made significant strides in the next 100 years. New mathematical techniques made it possible to control, more accurately, significantly more complex dynamical systems than the original flyball governor. These techniques include developments in optimal control in the 1950's and 1960's, followed by progress in stochastic, robust, adaptive and optimal control methods in the 1970's and 1980's. Applications of control methodology have helped make possible space travel and communication satellites, safer and more efficient aircraft, cleaner auto engines, cleaner and more efficient chemical processes, to mention but a few.