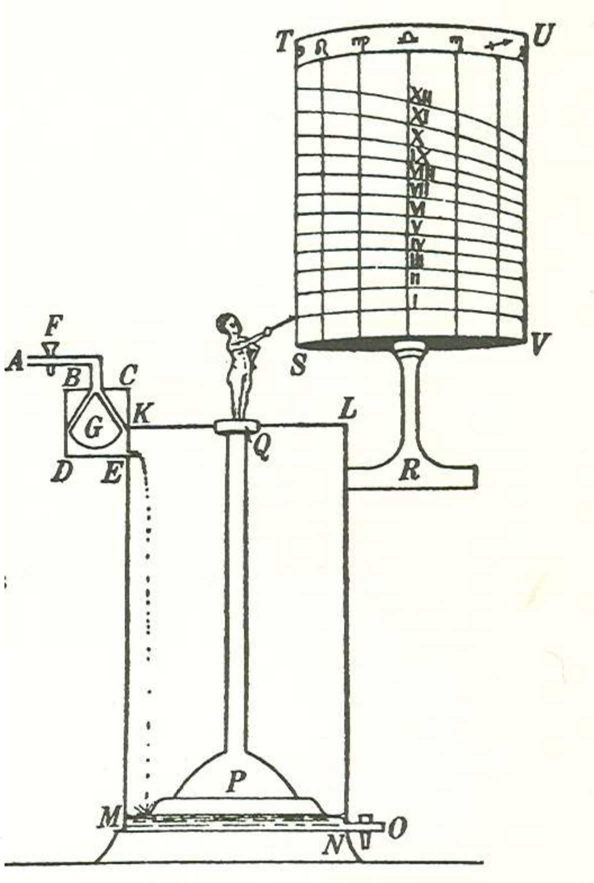
The essential role of Systems and Control in meeting critical societal challenges

Alberto Isidori

22 December 2020

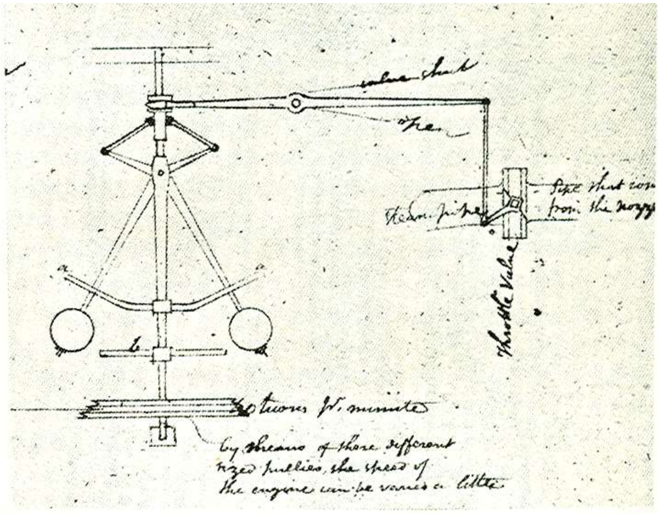
Feedback Systems

The core of any automatic control system is the idea of feedback, a simple principle governing any regulation process occurring in nature.
Humans have always copied nature in the design of their inventions: feedback is no exception.
The introduction of feedback in the design of man-made automation processes occurred as early as in the golden century of Hellenistic civilization, the third century b.C.
The scholar Ktesibios, who lived in Alexandria circa 240-280 b.C. and whose work has been handed to us only by the later roman architect Vitruvius, is credited for the invention of the first feedback device. He used feedback in the design of a water clock.



Feedback Systems

The idea of using feedback to moderate the velocity of rotating devices led to the design of the centrifugal governor in the 18th century.
In 1787, T. Mead patented such a device for the regulation of the rotary motion of a windmill.



In 1789, Boulton & Watt, used same principle to adjust the steam inlet valve of a steam engine.

With rising speed the weights swing outward and, through the pull of a rope, the canvas is rolled up, i.e. the sail area is reduced.

SAPIENZA
UNIVERSITÀ DI ROMA

Seeking the roots…

The roots of Systems and Control Theory are illustrious:
From the very beginning it was nurtured by the rigorous contributions of great mathematicians and physicists and
by the creativity of great engineers.
Among the great XIX century physicists, James C. Maxwell:

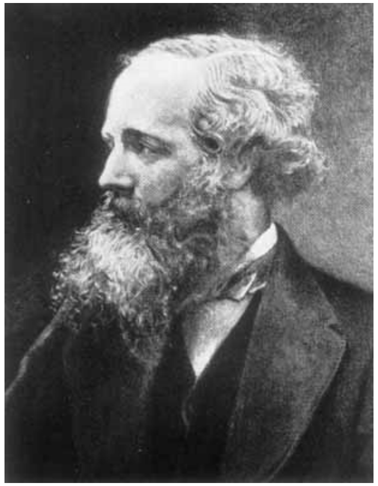
ON GOVERNORS

J.C. MAXWELL

From the Proceedings of the Royal Society, *No.100, 1868*.

A GOVERNOR is a part of a machine by means of which the velocity of the machine is kept nearly uniform, notwithstanding variations in the driving-power or the resistance.

Most governors depend on the centrifugal force of a piece connected with a shaft of the machine. When the velocity increases, this force increases, and either increases the pressure of the piece against a surface or moves the piece, and so acts on a break or a valve.



Seeking the roots...

This paper presents the first rigorous study of the stability of the Watt's governor and can be considered as the first contribution to the so-called Control Theory.

Putting $(dA/d\phi)\omega = K$, the equations become

$$A\frac{d^2\theta}{dt^2} + X\frac{d\theta}{dt} + K\frac{d\phi}{dt} + G\phi = L, \tag{25}$$

$$B\frac{d^2\phi}{dt^2} + Y\frac{d\phi}{dt} - K\frac{d\theta}{dt} = 0. \tag{26}$$

The condition of stability of the motion indicated by these equations is that all the possible roots, or parts of roots, of the cubic equation

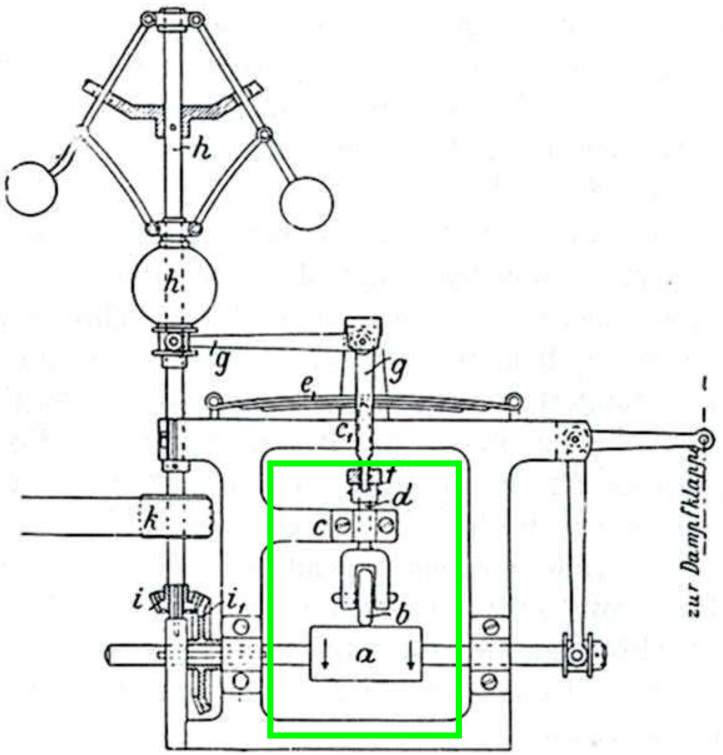
$$ABn^3 + (AY + BX)n^2 + (XY + K^2)n + GK = o \tag{27}$$

shall be negative; and this condition is

$$\left(\frac{X}{A} + \frac{Y}{B}\right)(XY + K^2) > GK. \tag{28}$$

Seeking the roots …

Among the great XIX century engineers, Werner von Siemens,
who in 1882 patents a centrifugal governor
in which the integral action is for the first time deliberately introduced, to the purpose of zeroing the steady-state error.
The collar movement is integrated by means of a mechanical integrator "wheel-and-cylinder".



Seeking the roots…

At the beginning of the 20th century, feedback was used in the design of automatic steering systems. In 1922 Nicholas Minorsky introduced PID control in the design of autopilots.

Minorsky's controller was successfully experimented on the USS *New Mexico*. However, the device was soon removed because "*the ship crew was strenously opposed to automatic steering*".

In 1947, the first fully unmanned flight of a C-53 over the Atlantic, including takeoff and landing.

DIRECTIONAL STABILITY OF AUTOMATICALLY STEERED BODIES.

BY N. MINORSKY.

I. INTRODUCTION.

The problem of directional stability of automatically steered ships is gradually becoming of increasingly greater importance for various reasons.

The possibility of obtaining more accurate steering by automatic means than can be accomplished by manual control with its inherent limitations due to the low sensitiveness of the human eye in detecting slow angular motions, fatigue, etc., becomes of greater importance with the increase in size of ships and cost of fuel.

For merchant ships an accurate and reliable automatic steering device becomes a real money saving proposition, largely justifying its use.

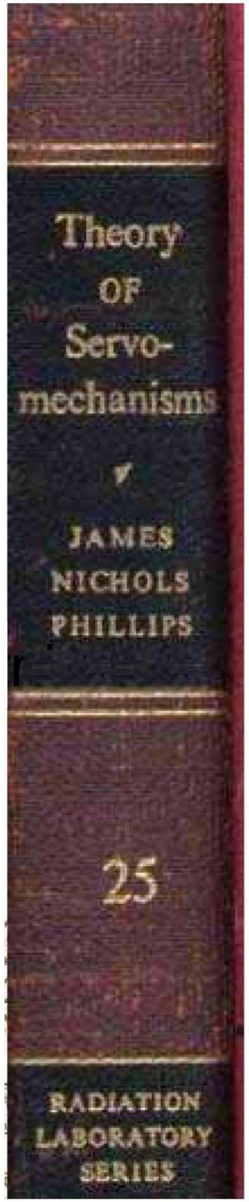
On battleships, by its use the absence or reduction of yawing in action means a better efficiency in gunfire, increased maneuvering speed and also a greater cruising radius.

In the case of airships, especially for long distance trips, directional stability is also of importance because the behavior of direction indicating instruments is then more satisfactory which leads to a still better stabilization, so that the certainty and safety of aeronavigation is thereby increased to an additionally greater degree.

A new discipline emerged …

The perception that feedback control and, in a wider domain, automation were taking the shape of an autonomous discipline occurred right after the second world war, where the application to radar and artillery had a dramatic impact.

By the early 1950s, the principles of this newborn discipline quickly became a core ingredient of most industrial engineering curricula, professional and academic societies were established, textbooks and handbooks become available.



The second phase (1960-2000)

At the beginning of the 60’s, two new thrusts cause an enormous leap forward:

The space race

The appearance of digital computers.

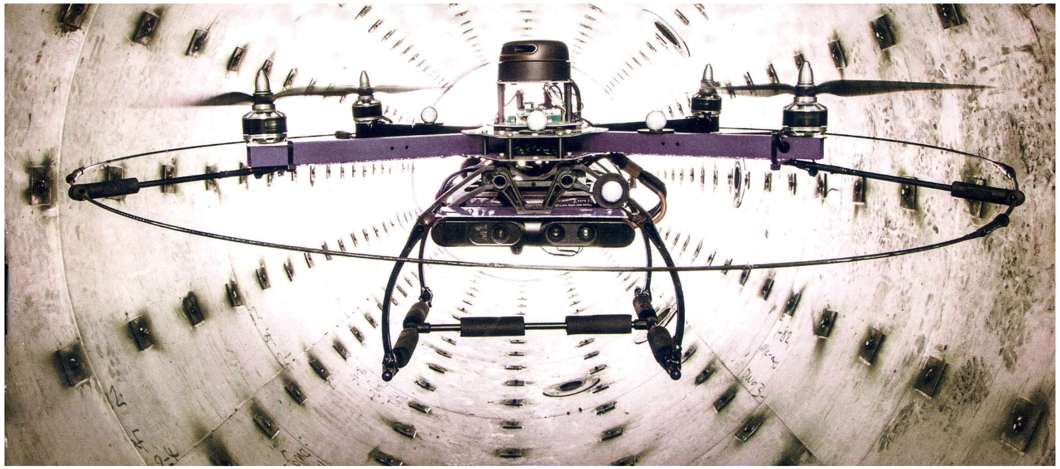
The principle of optimal control (Pontryagin the Soviet Union, Bellman in the United States) proves to be indispensable ingredient in the solution of the problems of smooth landing on the moon and in the implementation of manned space flights.

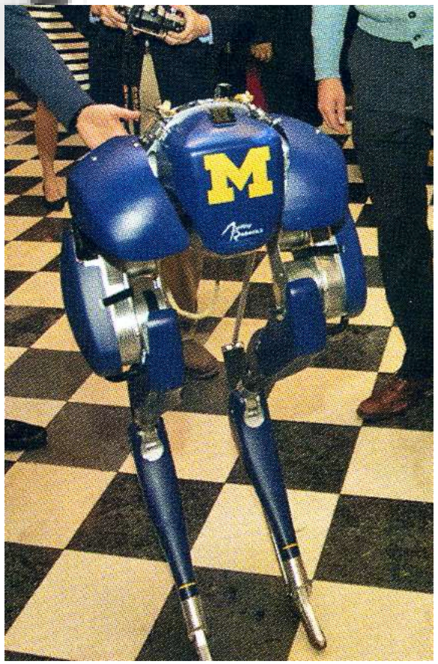
Integrated computer control, introduced in 1959 by Texaco in a refinery, for regulation and coordination of set points, soon became the standard technique for automatic control of industrial processes.

Nowadays control is everywhere…

SAPIENZA
UNIVERSITÀ DI ROMA

Nowadays control is everywhere…





Nowadays control is everywhere …

Some thoughts:

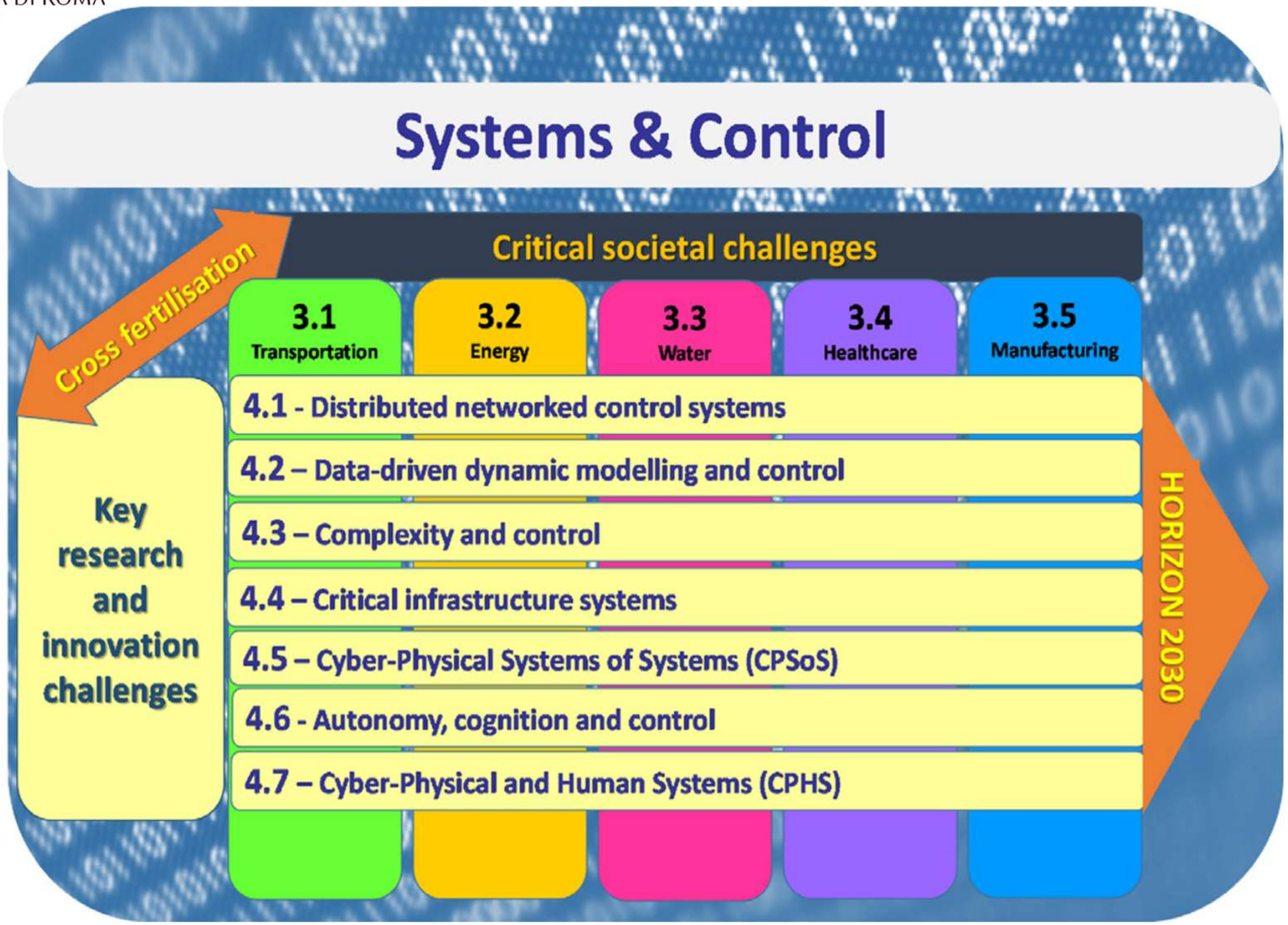
Principles and techniques of Automatic Control are pervasive,
effective and most often indispensable
in the development of most technologies.
However, Automatic Control is unknown to the general public,
when not confused with other disciplines.
Exemplar in this respect is the misuse of the prefix «cyber», now used essentially to mean «internet-connected», while originally introduced by N.Wiener (1948) to mean «government», form the Greek word «κυβερνώ», i.e. «govern» or «control».

Automatic control is a Hidden Technology.
As such, easily dismissed as … irrelevant.

Why ?

It is much easier to describe apparatuses, rather than ideas.

Control and contemporary challenges

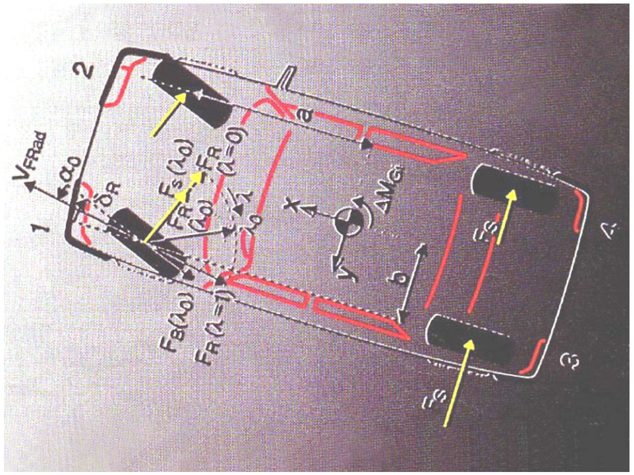


This and part of the following material are borrowed from the recent Vision Paper: «*Systems and Control for the future of humanity, research agenda: current and future roles, impact and grand challenges*», Annual Reviews in Control, Vol. 43, pp. 1-64, 2017.

Transportation

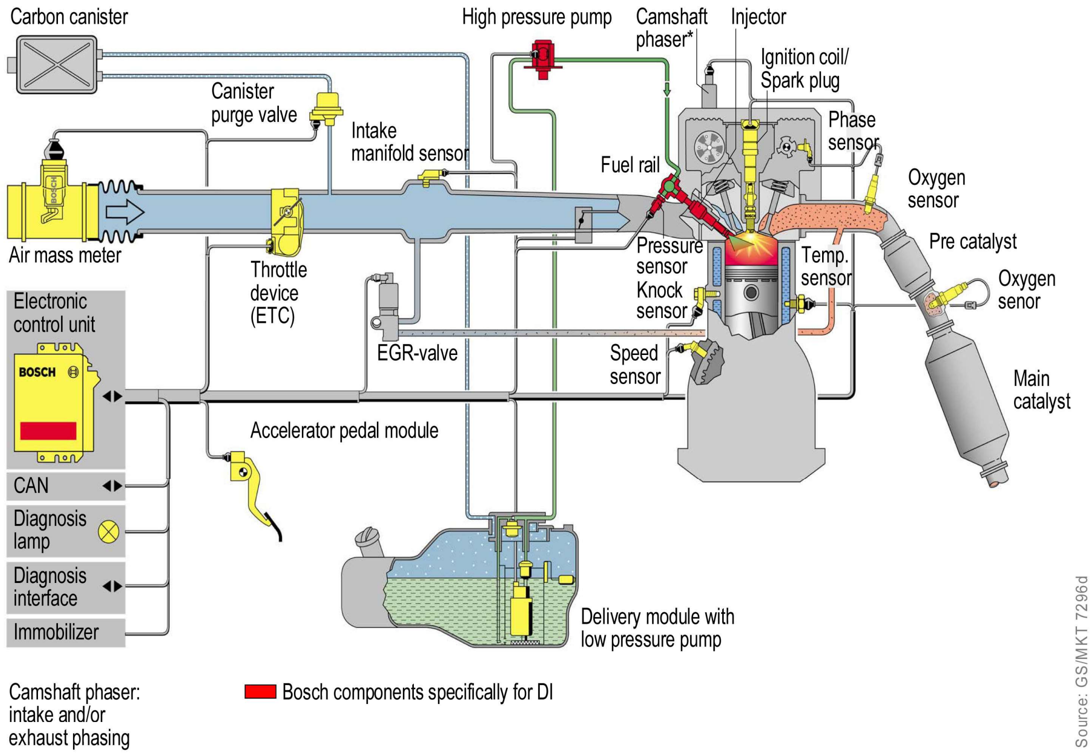
According to the 2013 European accident and safety report, approximately 1.2 million individuals worldwide perish in traffic accidents every year, with over 90% of accidents caused by human error.
These figures could be significantly reduced if the human driver is helped by a control system which is free from inherent human biological limitations like drowsiness, fatigue and inability to focus on a task for prolonged periods of time.
Maximum safety and minimum energy expense with comfort characterizes the definition of ideal human mobility.

Advanced Driving Assistance Systems (ADAS) is associated with driver/passenger comfort and safety enhancement
Its main purpose is to support simultaneous lateral and longitudinal autonomous control.



Transportation

The purpose of Powertrain or Energy Management Systems (PMS or EMS) is to minimize energy consumption
and, in the case of combustion engines, minimize CO2 emissions and carbon footprint



Engine control system: 15 – 25 sensors, 8 -12 control inputs,

Transportation

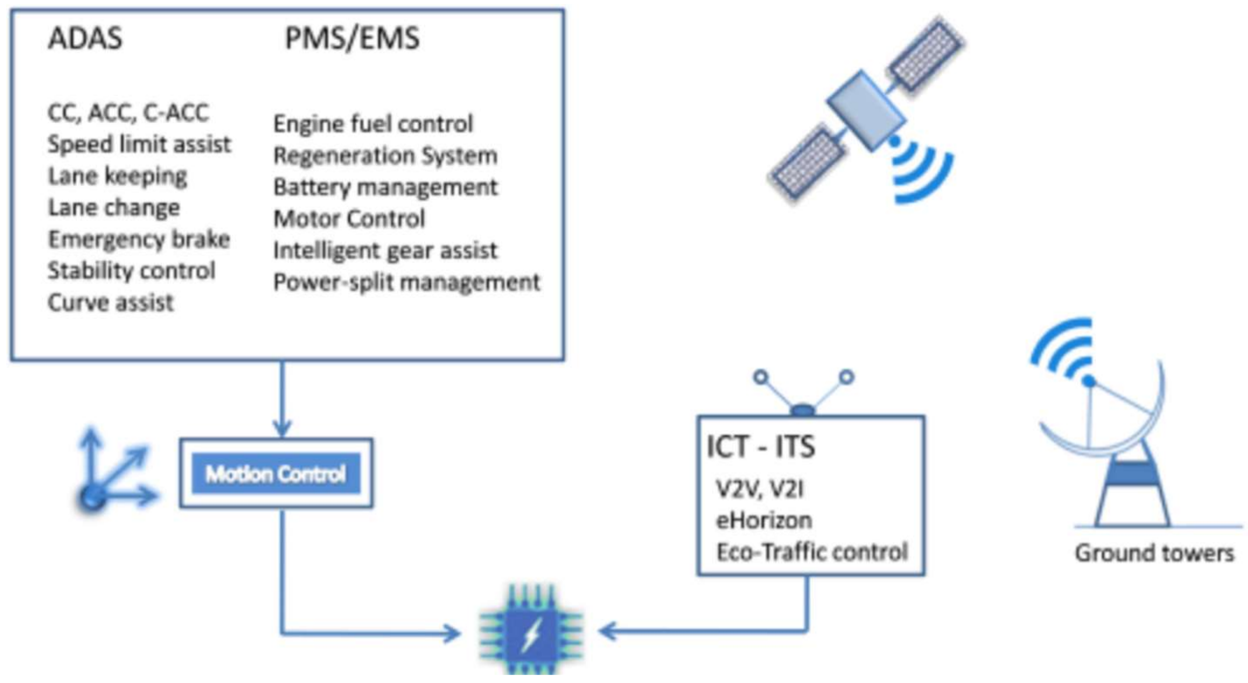
As of today, the automobile “as a machine” is on the verge of reinventing itself, and its conversion to a fully automated mobile robot may happen sooner than projected.

In an Autonomously Driving Vehicle (ADV), the active safety systems must cooperate with the powertrain control systems.
In fact, the concept of ADV, where the driver himself is replaced, renders the original definition of driving assistance obsolete.

In parallel, there has been high-level penetration of ICT in the automotive field
resulting in development of automotive-specific data exchange platforms like Vehicle to Vehicle (V2V) and Vehicle to Infrastructure (V2I).
It enables electronic mapping and navigational guidance, through the e-Horizon and traffic control algorithms.
This has resulted into advancement of a new approach towards transportation management: Intelligent Transportation Systems (ITS).

Transportation

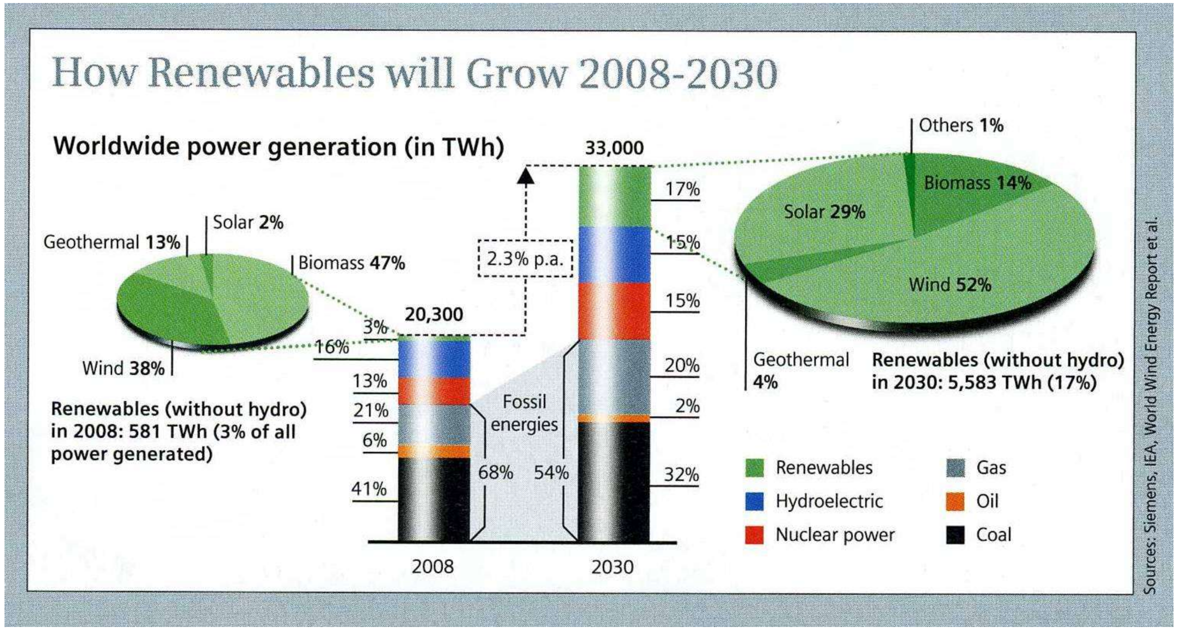
ITS supplies relevant information to the vehicle motion control system so that decisions regarding safety (*trajectory planning, safe headway, lane keeping, etc.*) and efficiency (*eco-driving, energy saving, etc.*) can be taked and implemented in real-time.



ICT : Information Communication Technology
ITS : Intelligent Transportation Systems

Energy

Wind flow and solar radiation are main sources of energy offered by nature to human beings.
In the 21st century, their employment in industrial power systems has become more and more realistic, with a non-negligible share of total produced power.



Energy

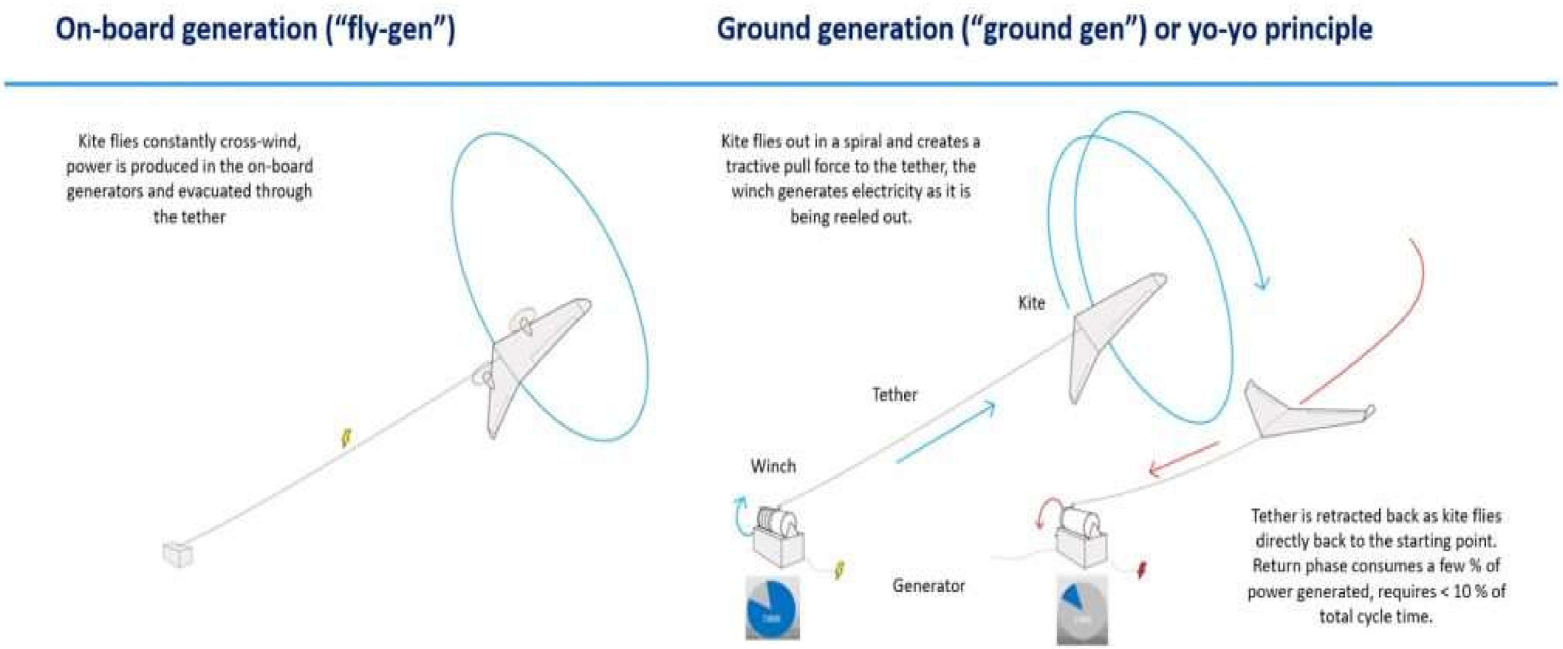
SAPIENZA
UNIVERSITÀ DI ROMA

Modern wind power production has been driven towards the scale of multi-megawatt (MW) turbines operating in large wind farms.

Wind farm-level controllers need to be developed, maximizing energy capture and minimizing operation and maintenance costs.
Control focus has moved from individual machines to arrays of turbines, where whole-farm modelling is required that describes the loads and the time-dependent interaction between turbines imposed by the wakes and the overlying wind flow.

Energy

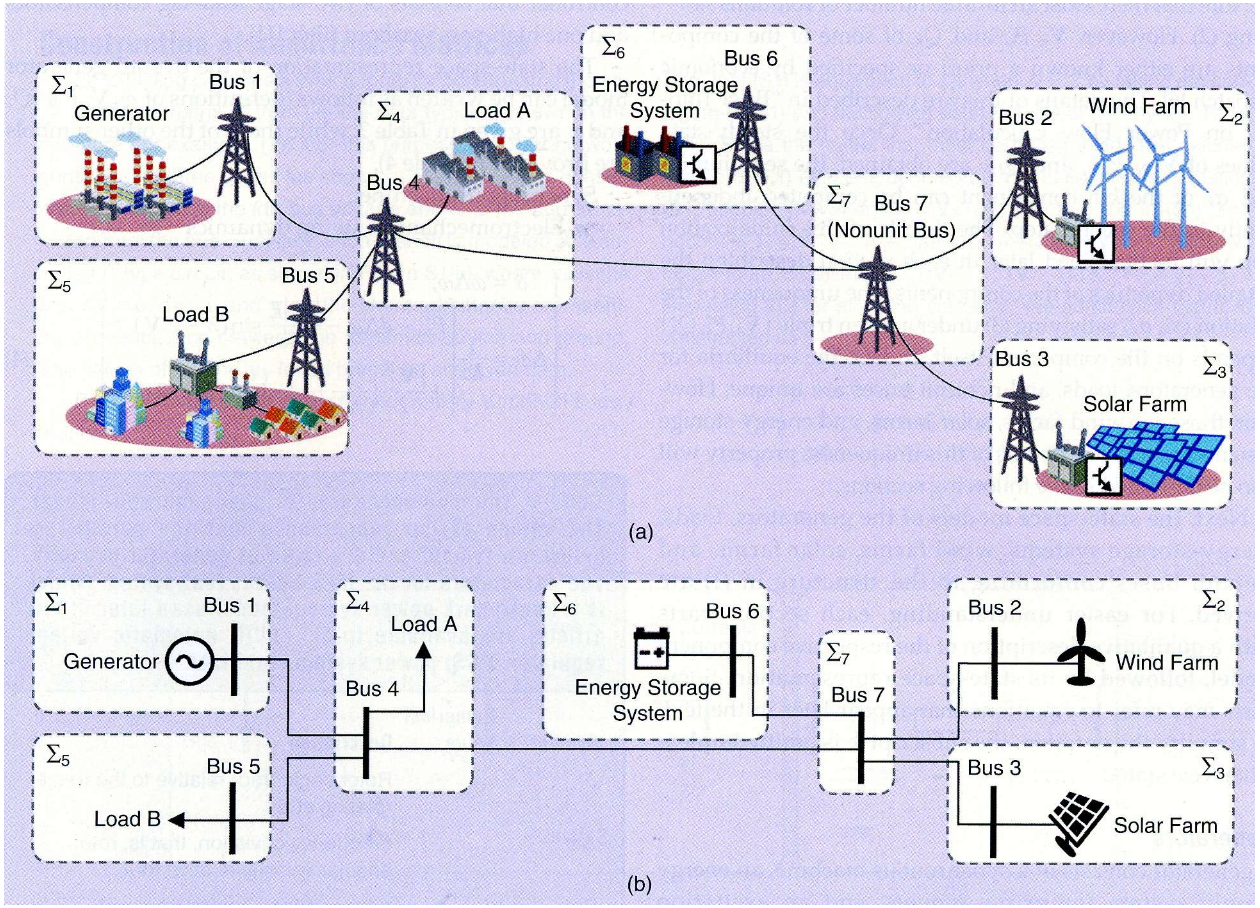
New and better WTs are developed, by exploiting the benefits of variable stiffness materials for aeroelastic tailoring, for which servo-aeroelastic —rather than just aeroelastic —principles are exploited.
Airborne wind energy (AWE) systems is another design concept that seeks to attain operating altitudes (200 m –1000 m) where there is a greater and more stable wind resource .



Energy

Electric power networks are among the largest and most complex man-made systems. They connect hundreds of millions of producers and consumers.

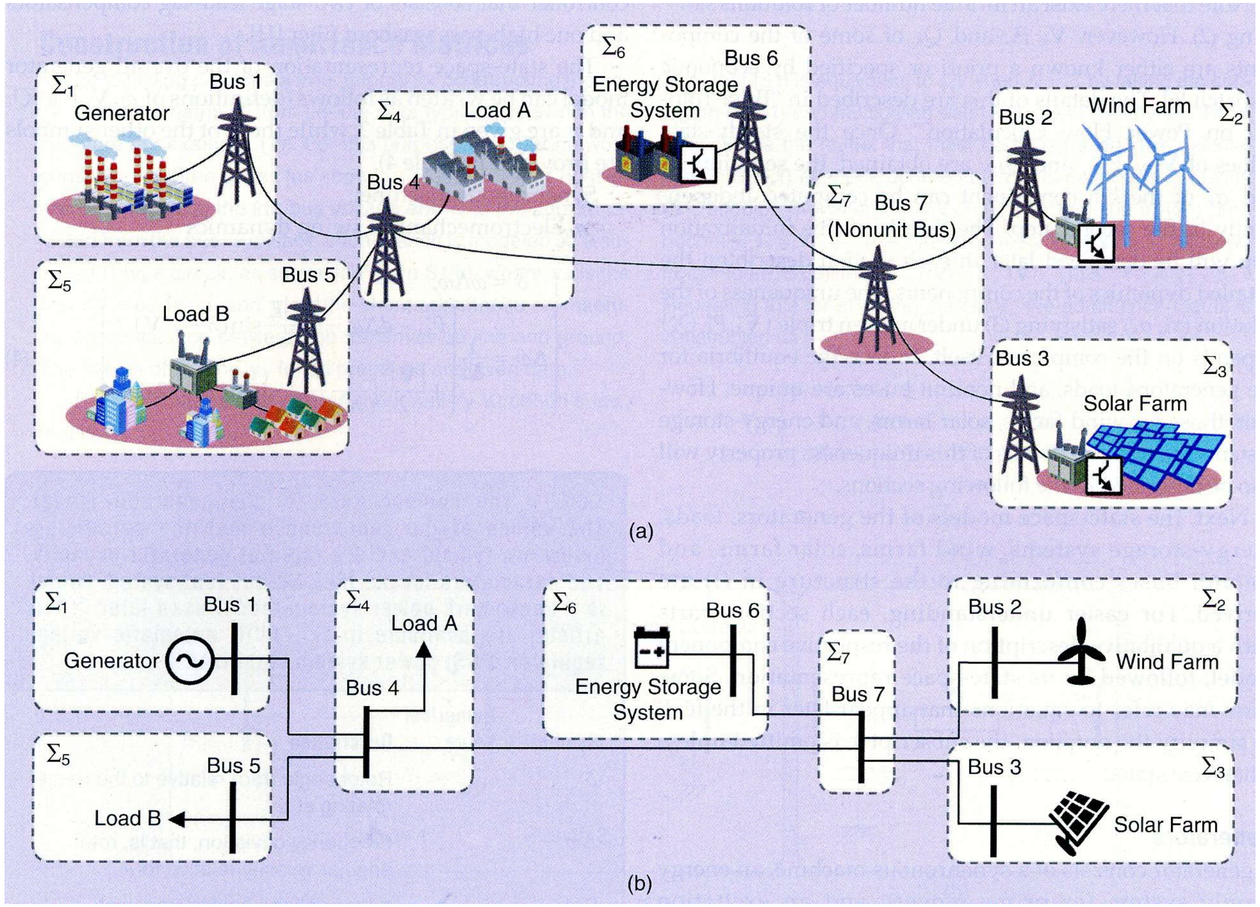
Currently, major changes to the networks structures are being implemented, to support the large-scale introduction of renewable energy sources



Energy

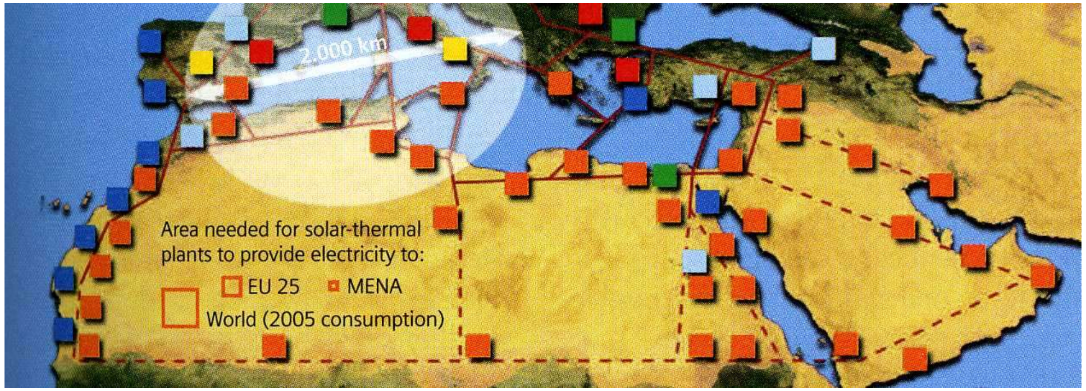
Most renewable sources are small generating units, dispersed over a wide geographical area; and their primary energies (wind, sun, tides) are by nature not controllable and fluctuate over time.

Integration of these highly intermittent, randomly variable and spatially distributed resources calls for new approaches to power system operation and control.



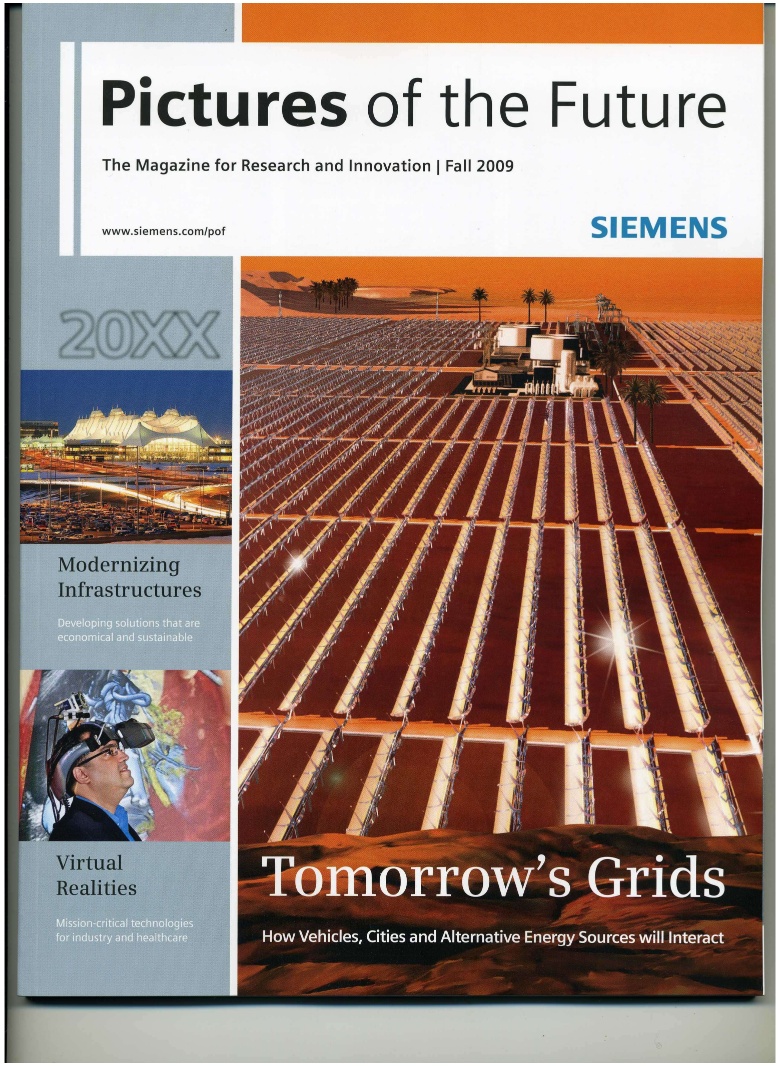
Energy

One possibility for the massive integration of renewables is the use of Direct Current Networks (known as Multi Terminal High Voltage Direct Current MT-HVDC), in support of the present AC (Alternative Current) grids.
DC allows much longer lines, and such grids will be better fit to integrate the wide geographical dispersion of renewables.
Future power networks, already called SuperGrids, will be mixed AC/DC grids.
These SuperGrids will connect offshore renewables to the main AC grid, as well as reinforce these main grids.



Energy

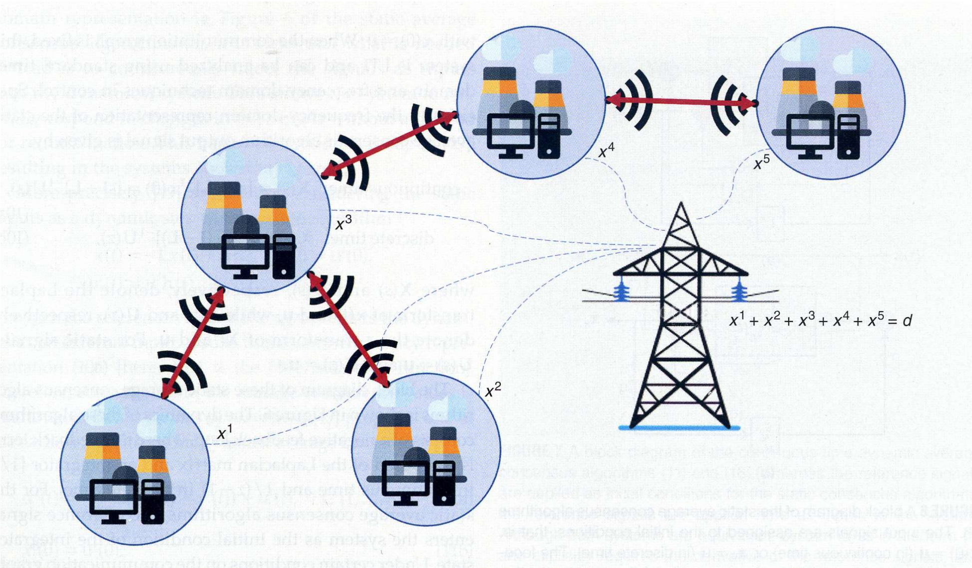
One of obstacles in adoption of DC grids is the lack a global variable such as the frequency, as in the case of AC,
to help in estimating locally the required power to balance the system.
DC grids' dynamics may be much faster than AC ones.
AC grids are mainly composed of very large rotating masses with very large inertia, which mitigates the effects of the disturbances.
DC grids have no inertia at all. As a consequence, stabilization of DC grids is much more delicate.



Energy

New power electronics and other ICT (Information and Communication Technology) devices open new possibilities for control and will ultimately be the tools for stabilizing these new smart grids.
While today's grid model is based on unidirectional power and information flow, the future grid will have bi-directional flow of both power and information with new generation and new loads.

Establishing a cyber-physical infrastructure with information flow among the distributed controllers
that provides ubiquitous sensing and actuation
will be vital to achieving the responsiveness needed for future grid operations.



Water

The World Water Group 2030 report indicates that the world is headed towards significant economic water scarcity unless fresh-water resources are better managed.

Water for food, or irrigation water, represents 70% of the world's fresh-water usage.

Given the size of irrigation water distribution networks, some non-trivial control engineering problems emerge.

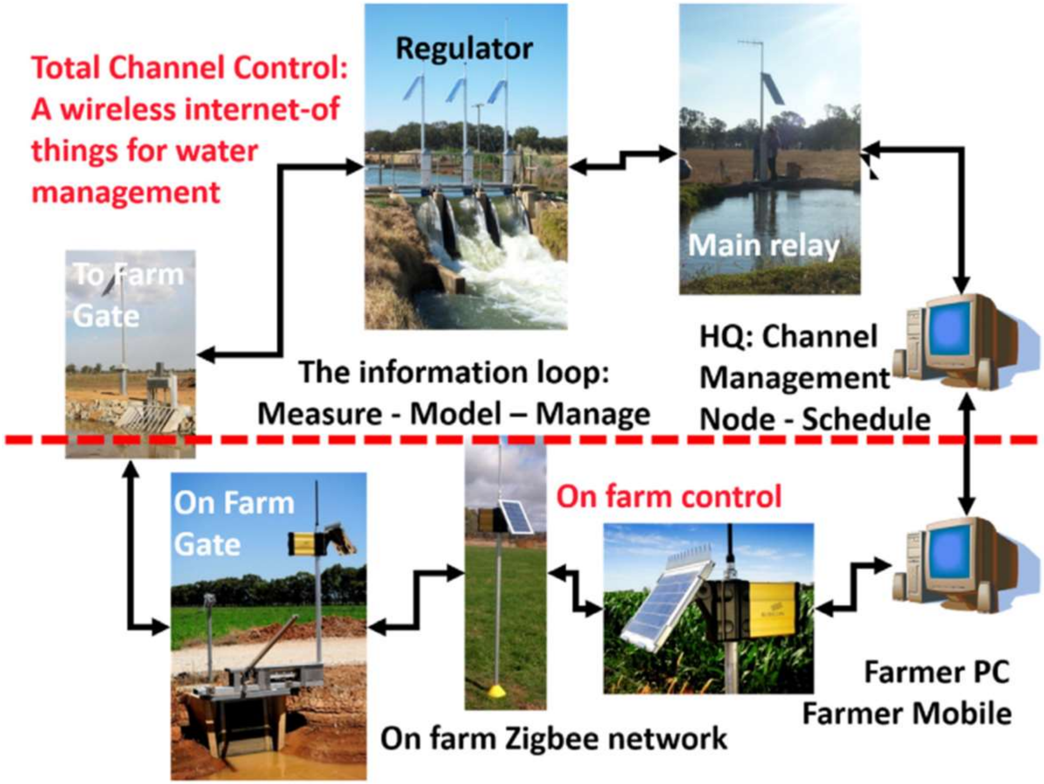
Periodic sampling of actuators and sensors may not work. Most of the time there is not enough dynamic variation to warrant this, and when things change, sampling has to be relatively fast to capture the essence of the transients, e.g. to route flood waters and avoid flood damage.

Equally, because of area and distances involved, a fully centralised controller that schedules an entire water distribution system is not advisable. The required communication infrastructure and bandwidth becomes prohibitively expensive.

The amplification of disturbance-induced responses must also be addressed. This requires limiting the gain from a disturbance to (a distant) control action.

Water

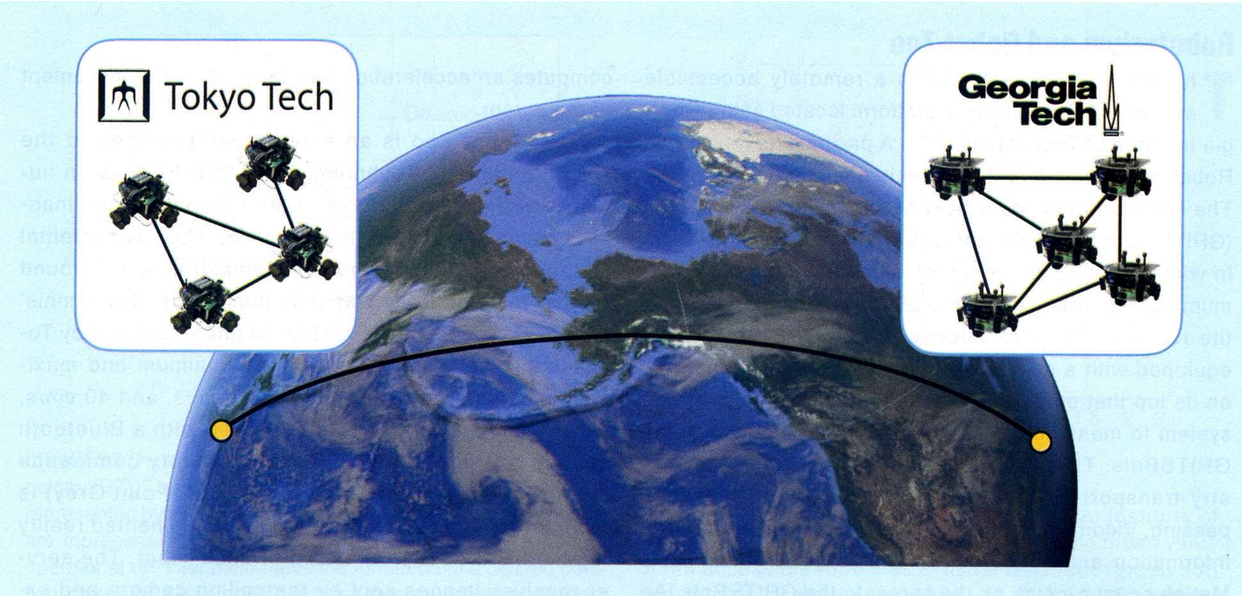
Commercial fully automated irrigation districts report overall conveyance efficiencies near 90% and on-farm water productivity gains of close to 100% (double the harvest with the same amount of water, largely due to precision timing in response to crop needs).



Water

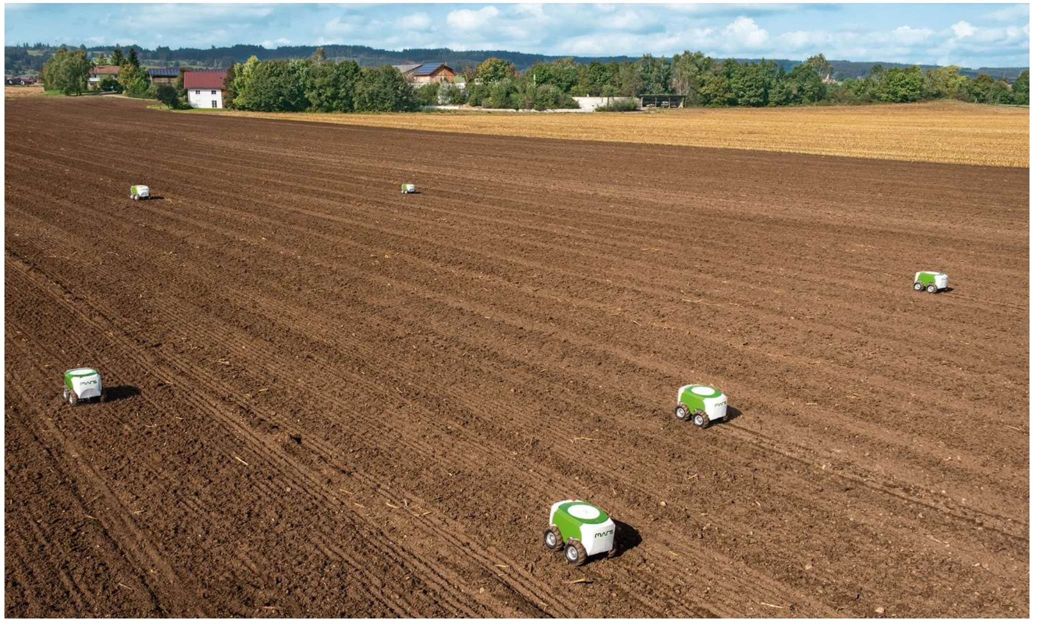
Also, cybersecurity is important because water networks are critical infrastructures.
This is more difficult when the control is performed over wireless communication networks.

A recent experiment in control over communication networks.
Delays play a role of paramount relevance in the control.



Agriculture

Water management is not the only aspect of Control in Agriculture
Modeling, identification and control methodologies are sought at the process level (*photosynthesis of crops, soil-water-plant-atmosphere cycle and metabolism of farm animals*),
as well as at the systems level (*control of greenhouses, warehouses, animal houses, plant factories and controlled ecological life support systems*)
Robotics and mechatronics are essential in agricultural automation



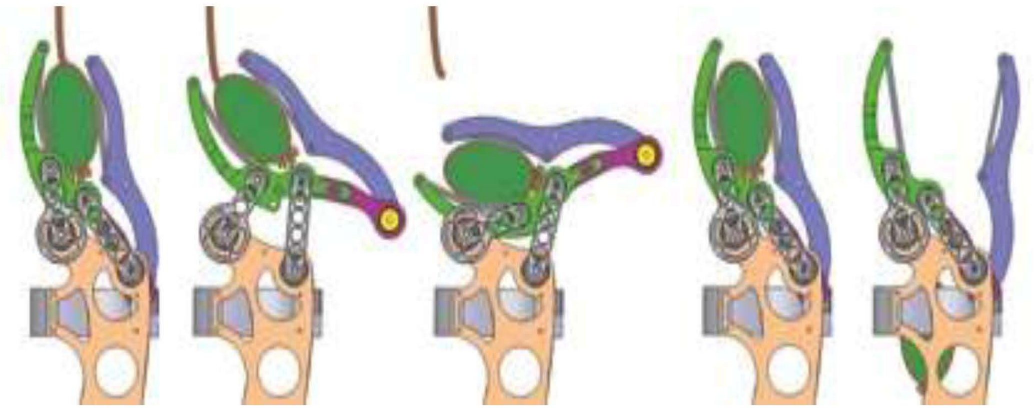
SAPIENZA
UNIVERSITÀ DI ROMA

Agriculture

Post-harvest operations such as grading, drying, storage of crops of fruits and vegetables, also food processing (quality and safety)
Precision farming, cultivation processes and harvesting. It includes computer networks, image analysis and sensors and artificial intelligence applications.
Ergonomics, including man-machine systems and man-machine interfaces in agriculture for human and animal comfort and welfare.

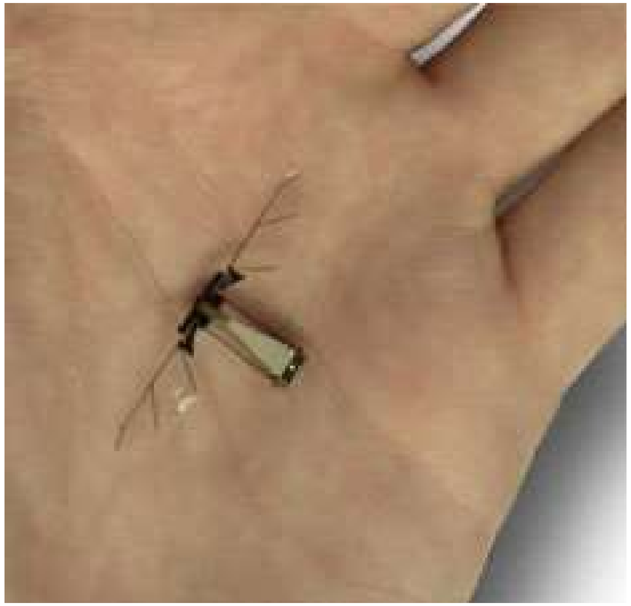
Agriculture

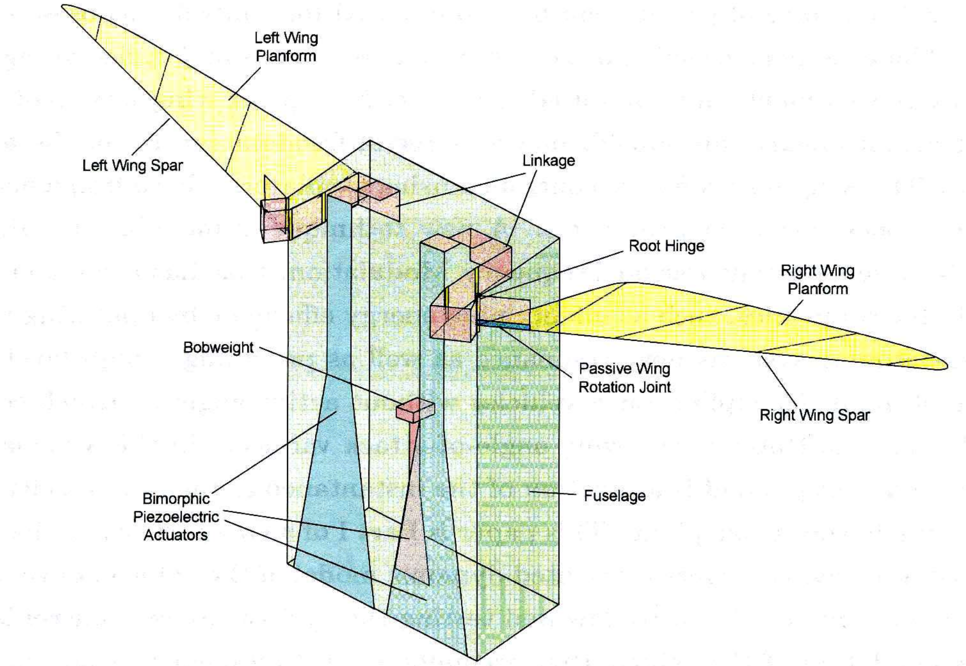
Fully integrated automated fruit picking:
Flexibility: all terrain, all weather, all task
Multiple tasks include: pick, prune, pollinate, fruit count
Navigation, to and within the orchard
Appropriate design of robot arm and end effector
Computer vision: target detection and recognition
Only pick fruit of the correct size and shape
Inspect and discard defective fruit



Agriculture

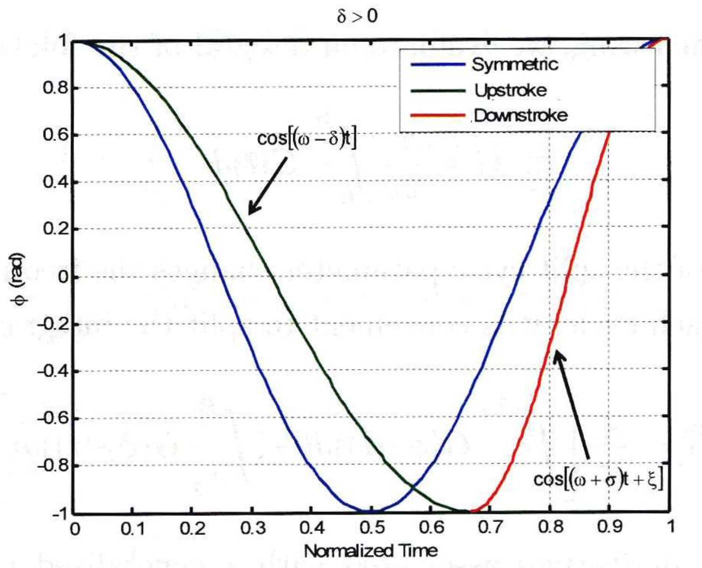
Pollination could be handled via Roboflies.
These are devices that fly by beating wings.
Leonardo's dream has come true.





Agriculture

Robofly is actuated by a pair of piezoelectric actuators, that control the angle of the wing support with respect to the body.
The angle of attach is a function of the rotation speed of the wing support.

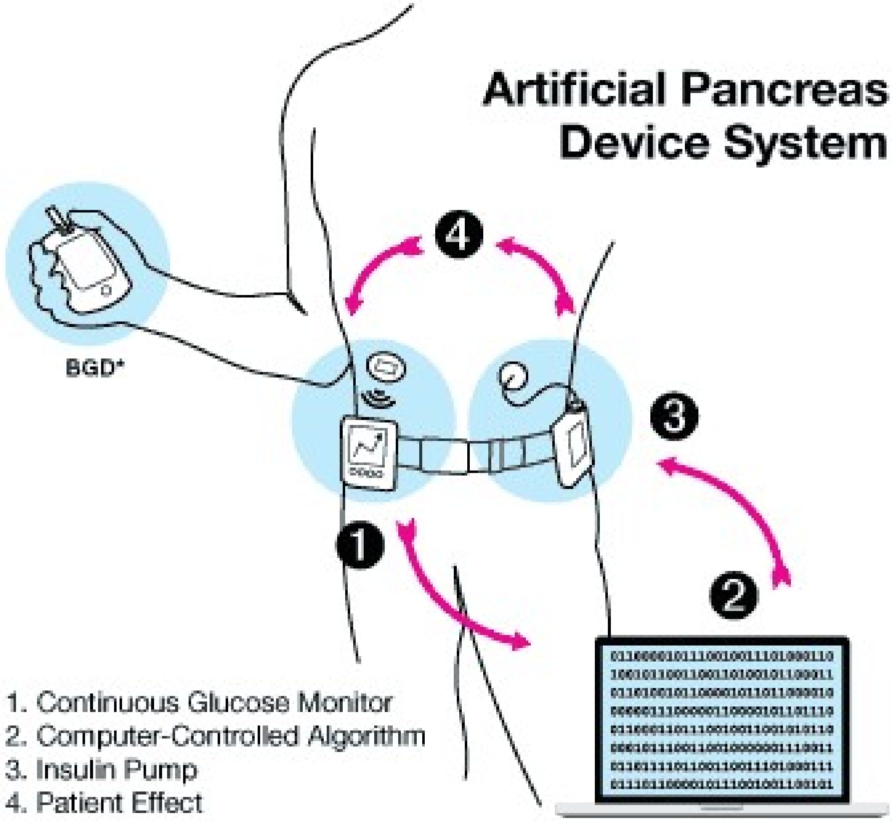


The control challenge: shape the waveform of the angles of support so as to obtain 6 DOF as in a helicopter or in a quadrotor.

Healthcare

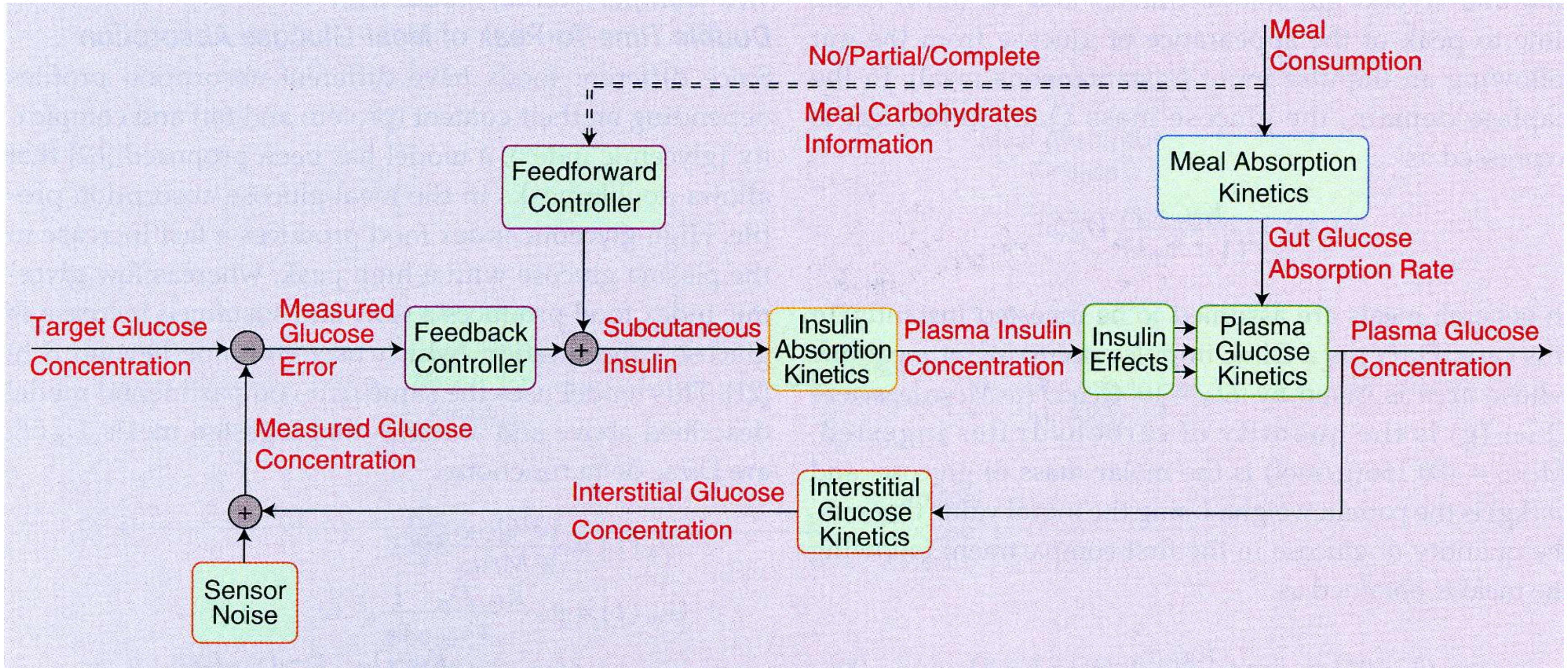
Prosthetics is one of the most appealing fields of application of automatic control in healthcare.
The Artificial Pancreas (AP) for diabetis patients is a reality..

The feedback control system monitors the level of glucose and releases and releases insuline.
The implants are minimally invasive.

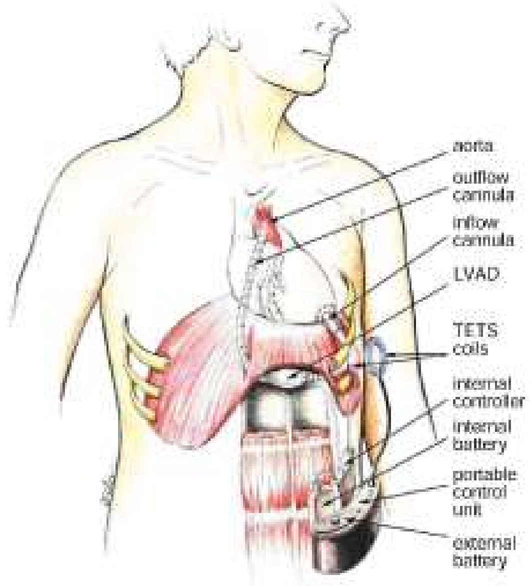


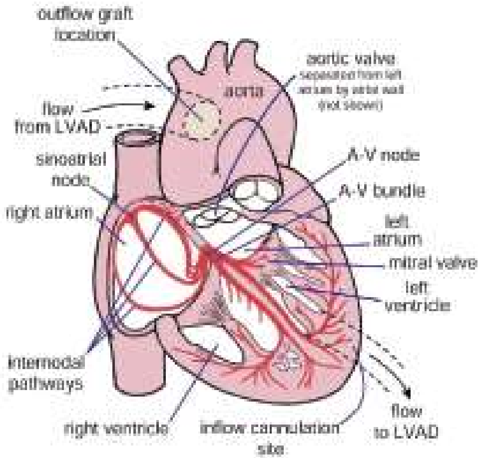
Healthcare

Prosthetics is one of the most appealing fields of application of automatic control in healthcare.
The Artificial Pancreas for diabetis patients is a reality..



Healthcare

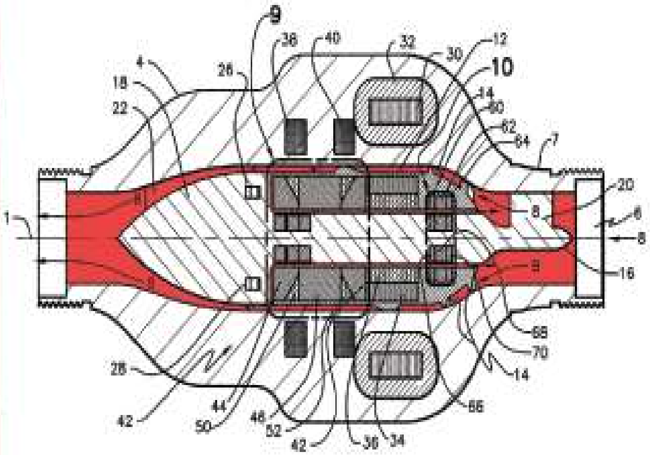




Left Ventricular Assist Devices (LVAD) cooperate with natural heart in pumping blood

Feedback controlled magnetically levitated rotary pumps

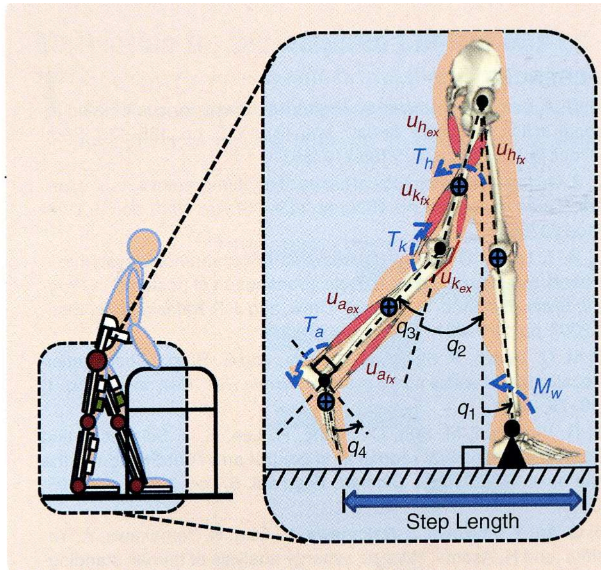
35.000 implants/year
(250000 pacemakers/year)



Healthcare

Rehabilitation technologies to restore standing and walking functions.

Hybrid neuroprostheses include powered exoskeleton (PES) and functional electrical stimulation (FES), which consists in artificially activating motor neurons to elicit muscle contractions



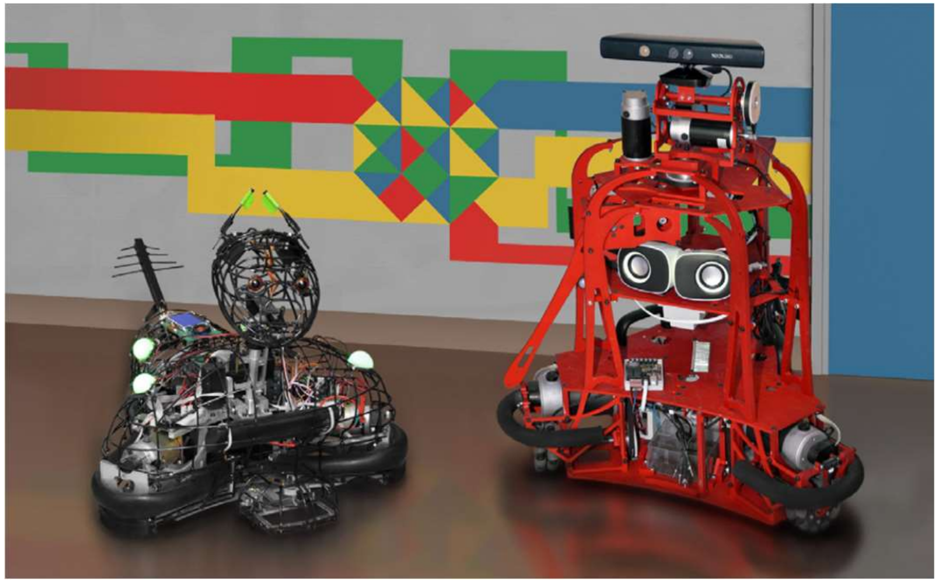
A four-link gait model based on a subject wearing a hybrid neuroprosthesis and using a walker for trunk stabilization.

The model has nine inputs that include stimulation inputs to evoke response from six muscles (hip, knee, ankle) and three electric motors acting on each joint of swing leg.

Healthcare

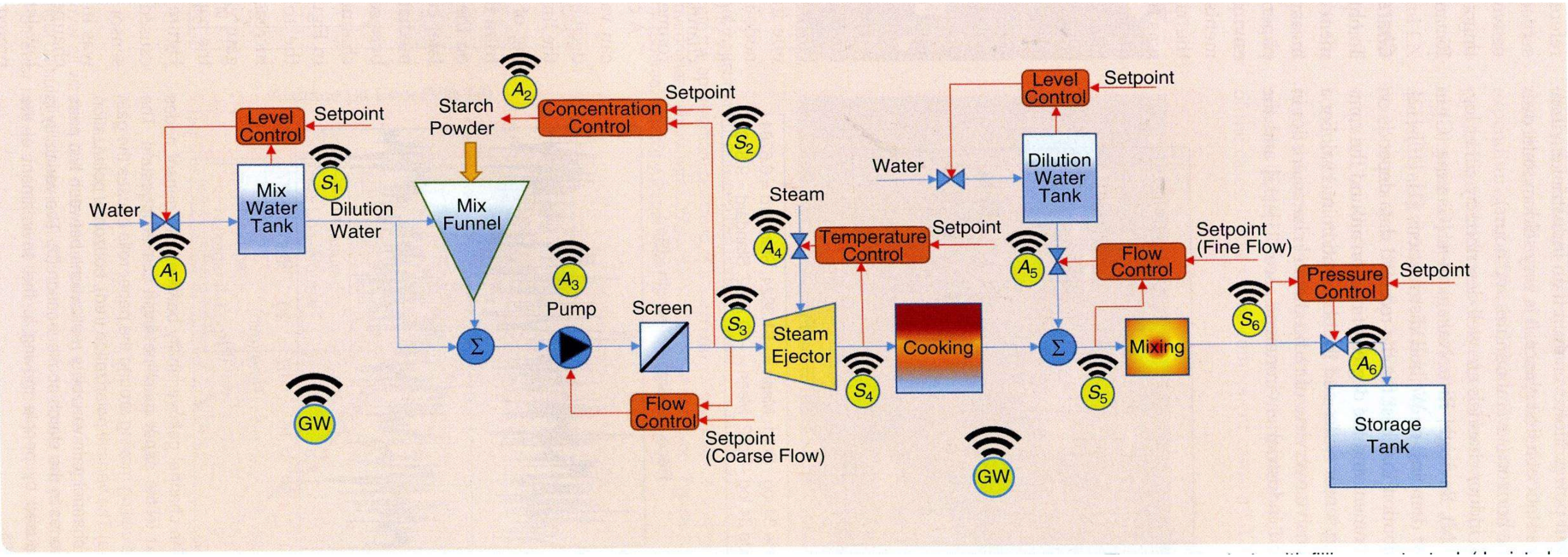
Most assistive robots were designed with human-like attributes in mind. However, there is no reason why robots should be built on the pre-concept of being either human or animal-like.
Their embodiment and behavior should rather be derived from the functional demand. Ethorobotics is a new emerging interdisciplinary field which aims at bringing together engineers who build robots and biologists who study behavioral disciplines (Ethologists).

Robot's autonomous behavior and interaction with other robots or humans is becoming a reality.
Ethologist are needed both for studying human-robot interaction but also for cooperating in the design and modelling of robot behavior.



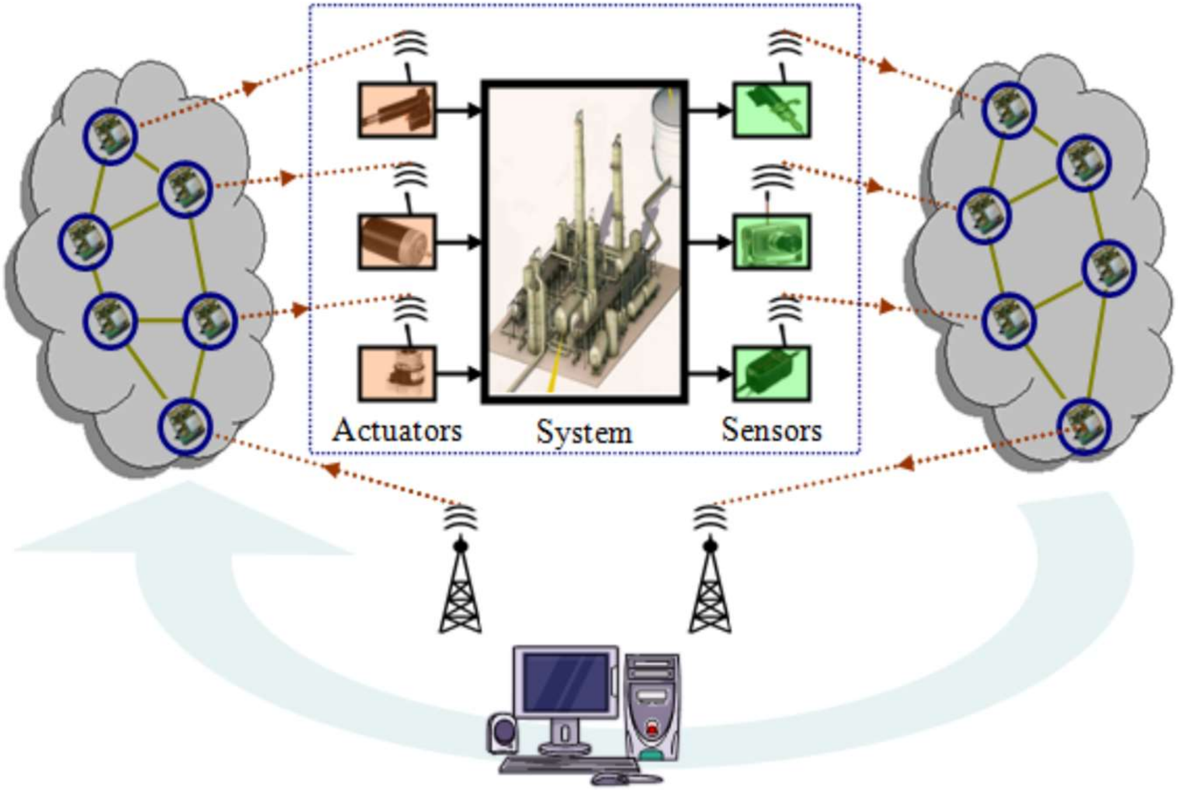
Manufacturing

Wireless sensors and networks are now used in control loops in the process industry.
The following is an example of an existing paper mill



Manufacturing

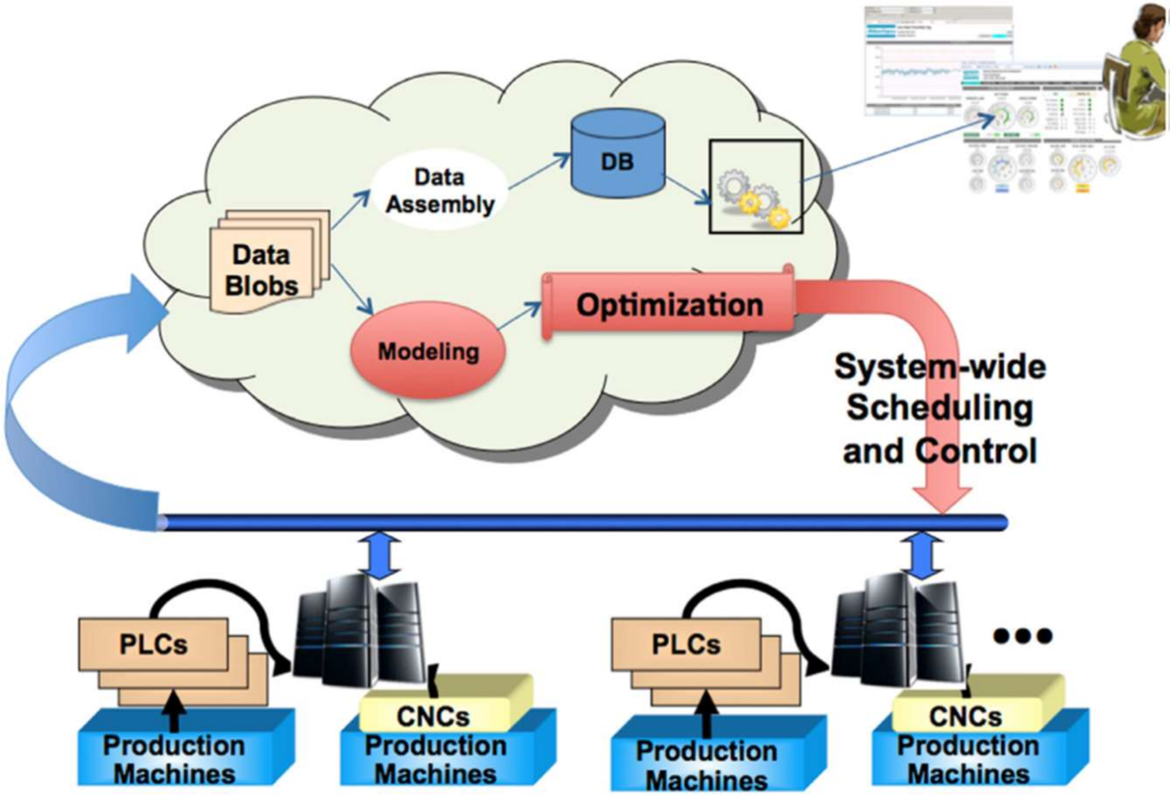
Along with the development of wireless technology, industrial control by means of wireless communications has received much attention in both academia and industry.



Wireless control is studied in the context of networked control theory, which, in general, focuses on control problems under network-induced constraints—delay, packet dropout, and channel capacity limitation

Manufacturing

Rapid developments in embedded and high-performance computing, wireless communication, and cloud technology, induce drastic changes in the architecture and operation of industrial automation systems.



SAPIENZA
UNIVERSITÀ DI ROMA

Conclusions: ICCT

Back to history, with a partisan conclusion

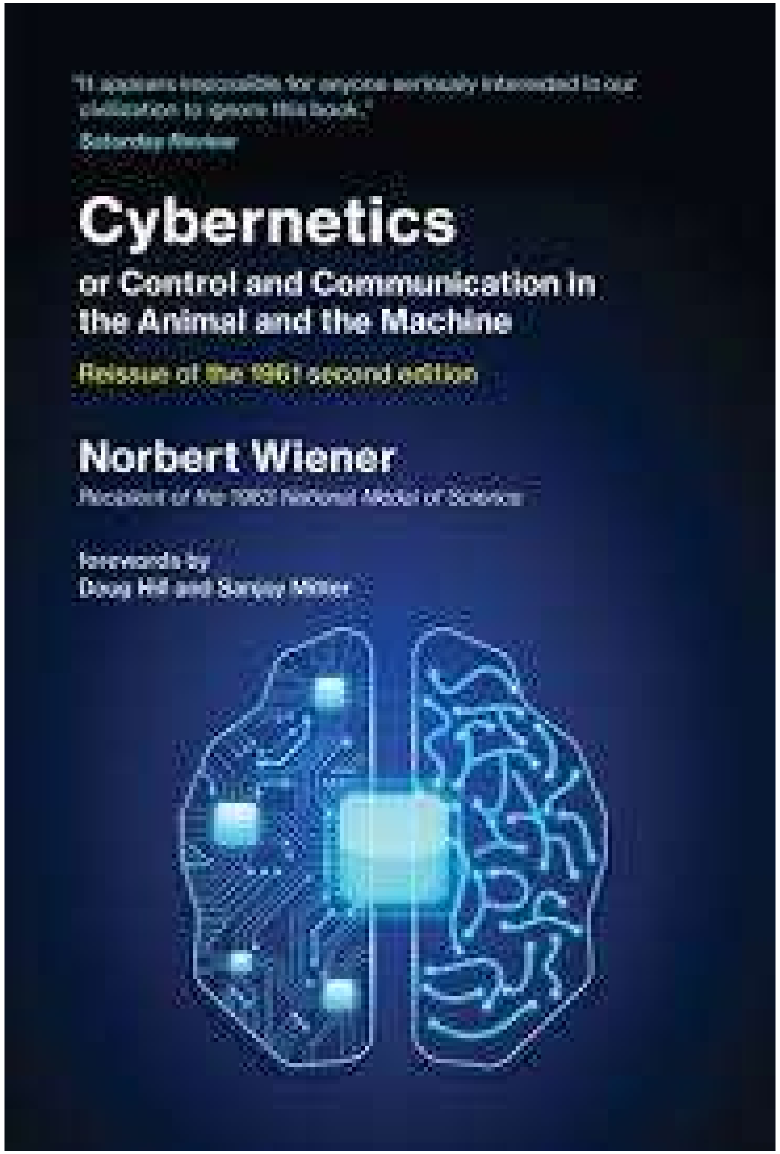
1948: CC = Control & Communication

1946-1955: The ENIAC

1950s: CCC= Computer, Control & Communication

1980s: ICT: Information & Communication Technology

Bang ! Control is wiped out !



SAPIENZA
UNIVERSITÀ DI ROMA

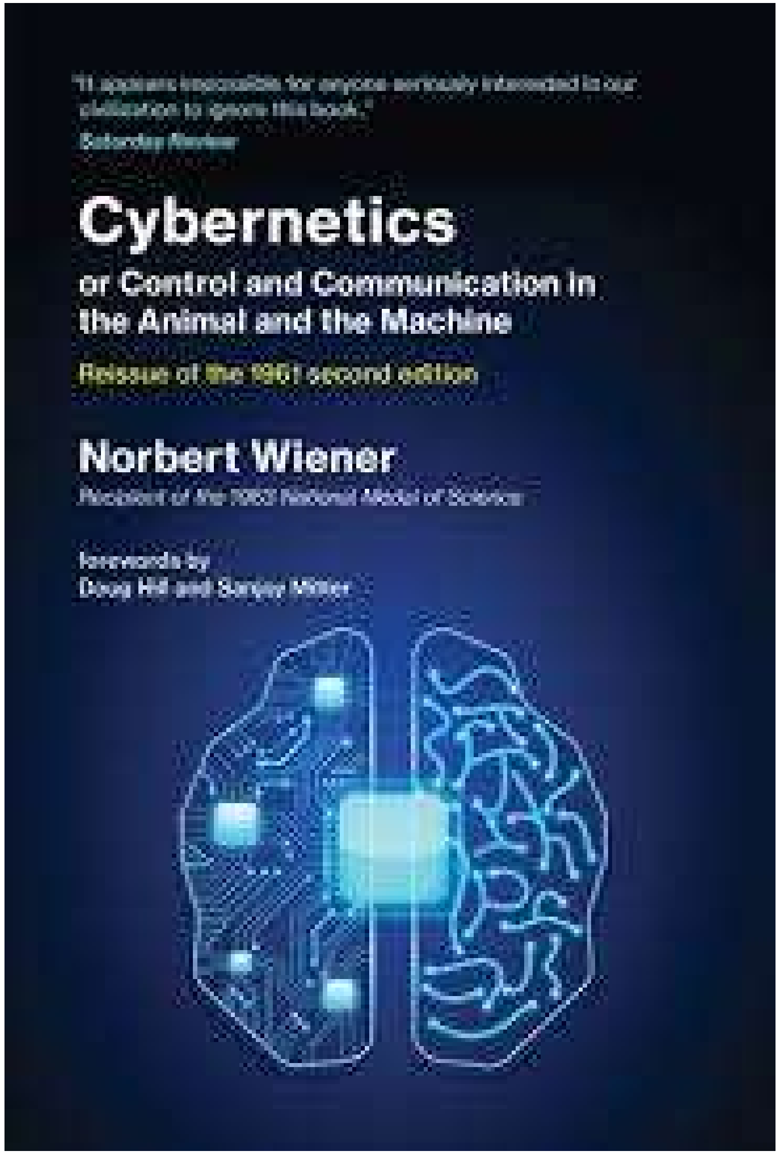
Conclusions: ICCT

Back to history, with a partisan conclusion

2020: We have seen form the previous quick survey that there are dozens of good reasons that motivate the essential role of control in meeting societal challenges.
You can find more of such reasons in the cited reference.

Time has come for the adoption of a more appropriate acronym

ICCT



Conclusions: ICCT

THANK YOU
FOR YOUR ATTENTION