Introduction to Control Systems

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1.0 Control as an Enabling Science

Most human activities involve the exertion of actions to actualize a pre-determined outcome. There are two situations: either the actions that are immediately released by the human operator are enough to actualize the outcome, or they are not enough to do the job (figure-1).

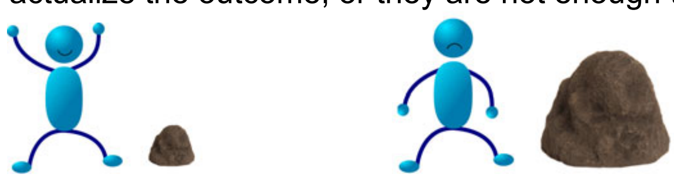


Figure-1: Failure of self-capabilities in carrying-out a task

When the immediate actions fail to do the job, some humans figured-out a way to indirectly actualize the desired outcome (figure-2). The scheme involves the following steps:

1- The human operator searches for a device or a process that is capable of actualizing the outcome.
2- The operator sends an order or a message to the device to execute the task
3- The device executes the task and the outcome materializes.

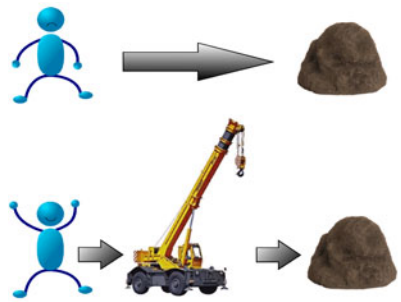


Figure-2: Shortcoming of self-capabilities can be compensated for by using a middle process to execute a task.

This device or process serves the operator by enabling him to indirectly perform a task. The suffix servo is usually used with a device or process (servo-device, servo-process) to indicate the ability of this device to perform the task and its willingness to yield to the commands of the operator (figure-3)

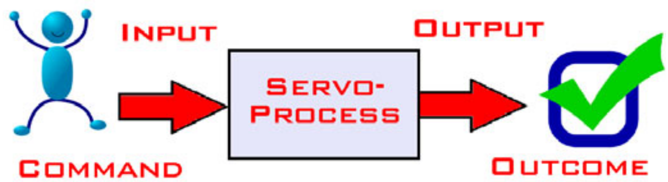


Figure-3: A middle process that works as an enabler is called a servo process

2.0 Servo-Processes

For a device or a process to be able to serve an operator, it must have three components:

1- It must have the means (variables) that enables it to affect the environmental aspects of interest to the operator. This set of environmental aspects is refereed to as the output. It is depicted by an arrow leaving the process
2- It must grant the operator the means (variables) to command it to affect the environment variables of interest. These variables are called the input and are depicted by an arrow entering the process
3- It must have the ability to link, couple or transfer the input variables to the output variables.

As can be seen not any device or process can be considered as a servo-process (figure-4). If the device can perform the desired task but refuses to accept the commands of the operator, it is not a servo-device. If a device does accept the commands from the operator, but it is unable to perform the task, it is not a servo device.

Consider the following example to illustrate the above. A person wants to move at a speed of 60 Km/h. This is beyond the capabilities of a human. Therefore, this person needs a servo process to help him achieve the task. This person could ride a turtle. This animal is yielding, i.e. it allows him to ride it (input exist). However, it cannot deliver the desired speed (output does not exist). Therefore a turtle is not a servo process. Assume the choice is a lion! A lion can move fast (i.e. output exist). However, most probably it will not allow someone to ride it (input does not exist). In other words, as far as the person is concerned, a lion is not a servo process. Now let's assume that one selects a monkey to do the job. Since an unskilled monkey is neither able nor willing to do the job (i.e. both input and output do not exist), it is not a servo-process. Therefore The obvious choice is to ride a good horse. A horse is fast (i.e. output exist) and does allow a subject to ride him (input exist). The horse is a servo process.

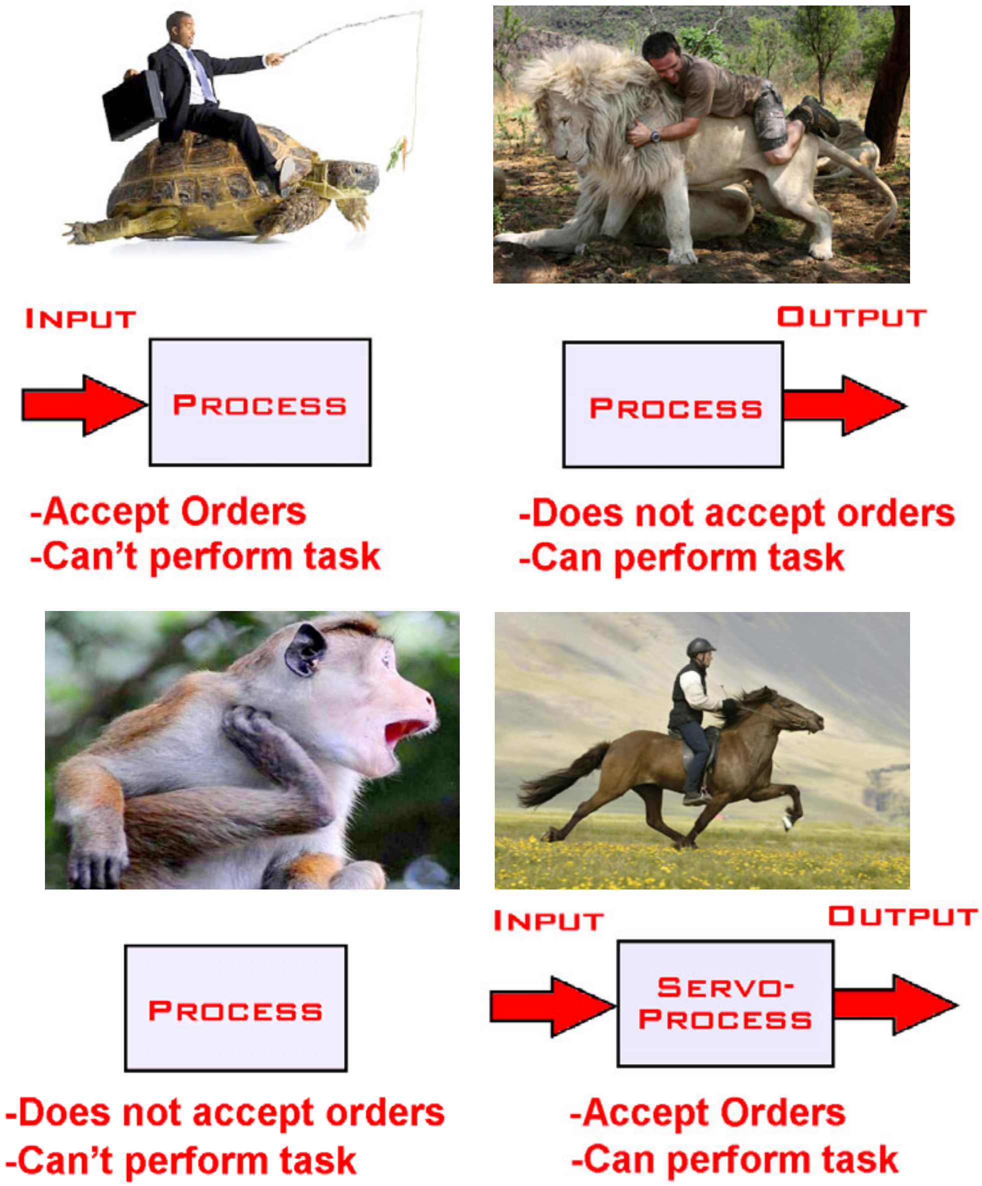


Figure-4: Not all processes may be classified as servo-processes

A servo-device or process can assume any form as long as it can perform a function, which a human operator needs and cannot do. Example of servo-processes (figure-5) may be

1- Since one cannot make his voice reach another city, he has to use a phone to transmit his voice for a long distance
2- Since one cannot generate enough heat to boil a cup of tea, he has to use an oven to do that
3- Since one cannot see in a dark room, he needs to use a lighting system to allow him to see
4- Since one cannot fly by flapping his hands, he has to use to a plane to enable him to fly
5- Since one cannot move electronics and micro particles by hand, he has to use a nano machine to allow him to do that
6- Since one cannot move at 200 KPH, he has to use a good car to be able to do so

Figure-5: Examples of servo-processes

2.1 Physical Form and System Form of a Servo-Process

What the operator sees is known as the physical form of the servo-process. What helps the operator in executing a task is known as the system form of the servo-process. The first step in using a servo-process is to obtain its system form. Constructing a system representation of a servo-process requires identifying three things

1- What variables may be considered as an output of a system (not as easy as it sounds)
2- What variables may be directly manipulated by the operator to affect the outcome (also requires some work)
3- The causality or transfer relation between the input and the output.

Loosely speaking, obtaining the above three items may be referred to as modeling the servo-process. Equivalently, this maybe called: converting the physical form into the system form. Lets explain this using the lighting servo-process example (figure-8).

Start by determining what the output of the process is. Remember that output is what the human user is interested in. If one examines the emissions from a lighting system (figure-8), he may notice the followings (figure-6):

- Heat
- Audible sound
- Visible radiation (light)
- Magnetic field
- And other things

Since the operator is only interested in lighting a room, then the output should be selected as visible radiation which is known as luminance (Ω) (the unit to measure luminance is candle).

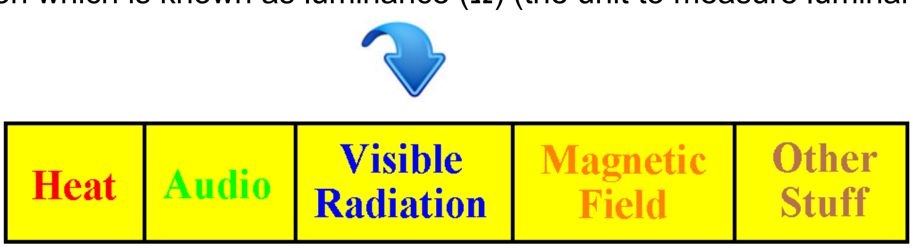


Figure-6: Emissions from a light bulb are not all considered as servo-process output

Let us now turn our attention towards the input of the process (figure-7). Should we select the input as the electrical voltage that feeds the lighting system? To answer this question remember that in a city the voltage comes from a power generation station that feeds all the city. Turning Off and On that generation station is not an action that an operator can perform. However, the mechanical switch movement Is an action that the operator can directly perform to affect the output. Therefore, the mechanical signal from the switch should be selected as an input to the lighting system.

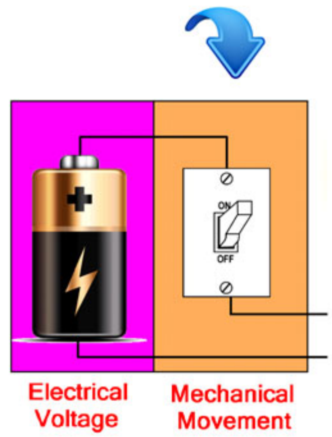


Figure-7: Input is what an operator can directly influence.

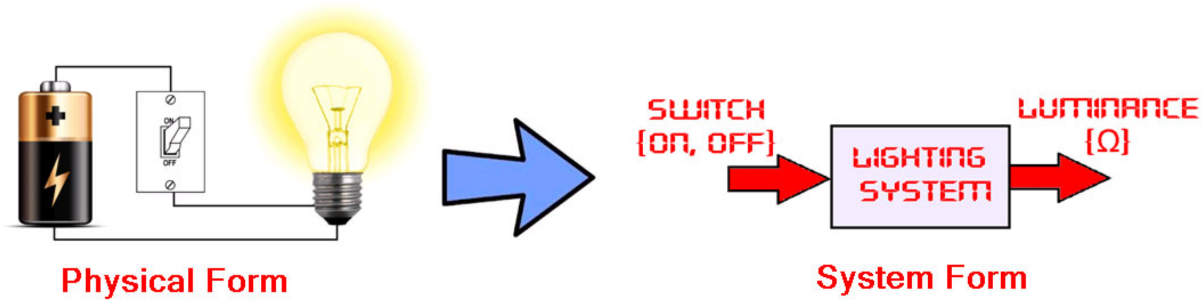


Figure-8: Physical form and system form of a lighting process

To complete the system description we need to determine the causality relation tying the input variables (the position of the switch) to the output variables (the amount of luminance). This is needed so the user will know what future results his present actions will yield. This causality relation is known as a model. For this simple case it can be easily obtained by experimenting with the input and recording what output is generated (figure-9).

SWITCH	LUMINANCE
ON	HIGH
OFF	LOW

Figure-9: Input-output relations are needed to derive useful action from a servo-process

NOTE: THERE IS NO PHYSICAL RELATION BETWEEN THE INPUT AND THE OUTPUT OF A SERVO-PROCESS (SWITCH IS MECHANICAL, LUMINANCE IS ELECTROMAGNETIC RADIATION). THE REALTION IS ONLY CAUSALITY, i.e. THE INPUT CAUSES THE OUTPUT.

3.0 Modeling of Servo-Processes

The predictive ability of models is very important for allowing an operator to utilize a servo-process. If one doesn't know what is the future output of the process his action (present input) is going to generate he cannot obtain a useful effort from the process (figure-10). On the contrary, his actions could be seriously counterproductive.

Figure-10: Lack of Knowledge of future outcomes generated by present actions can be counter productive.

Therefore, all areas of human endeavor attempt to build models of the processes that are of interest to it. Models exist everywhere in engineering, economy, politics, medicine, physics, chemistry, sociology, astronomy and many other areas. They assume many different forms and can be expressed in many different ways let that be graphical, mathematical, using charts or any other means of expression (figure-11).

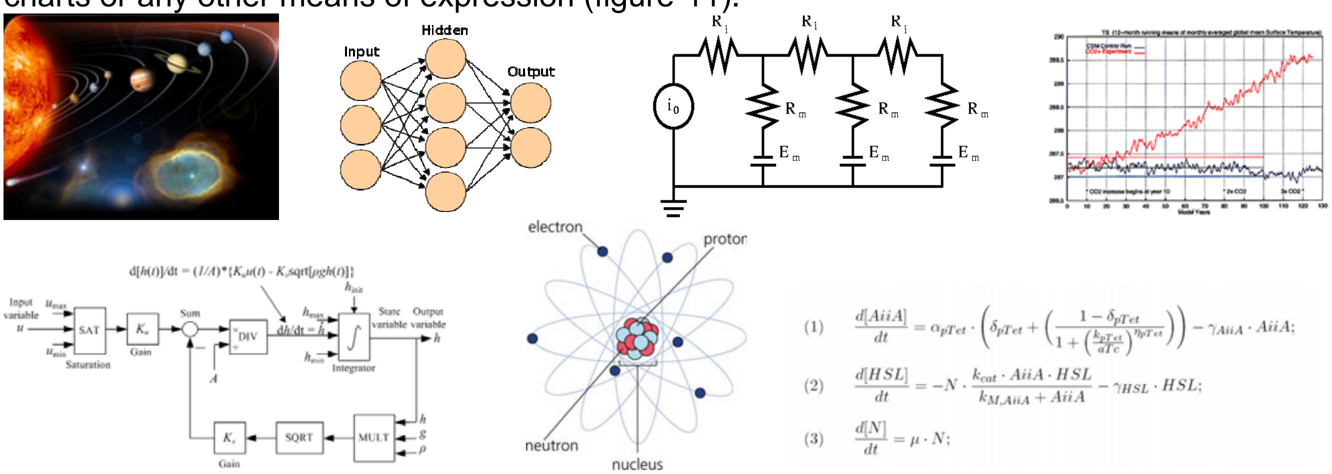


Figure-11: A model may assume any form as long as it can tell an operator what will happen if an input is applied to servo-process.

IT DOES NOT MATTER WHAT THE FORM OF THE MODEL IS. WHAT MATTERS IS ITS PREDICTIVE ABILITY. IT SHOULD ACCURATELY TELL THE OPERATOR WHAT FUTURE OUTCOME WOULD MATERIALIZE IF AN ACTION IN THE PRESENT WERE APPLIED TO THE SERVO-PROCESS.

Think of a model as the modern crystal ball (figure-12) which physicist and engineer use to tell the future.

Figure-12: A model is a device which an engineer or a physicist uses to guess the future

3.1 How Models are Constructed

How are models constructed? The straight forward way is to experiment with the process subjecting it to all possible values of the input variables. The resulting output is observed and the causality relation is captured using a suitable form. In other words, a model of the process is construed. Experimentation is not always possible to use in constructing models (figure-13). An outcome that could result in an irreversible damage will not only prevent the gathering of the information needed to construct a model, it will also destroy the process itself that the operator wants to utilize. Another, non-experiment based, approach should be used for constructing models.

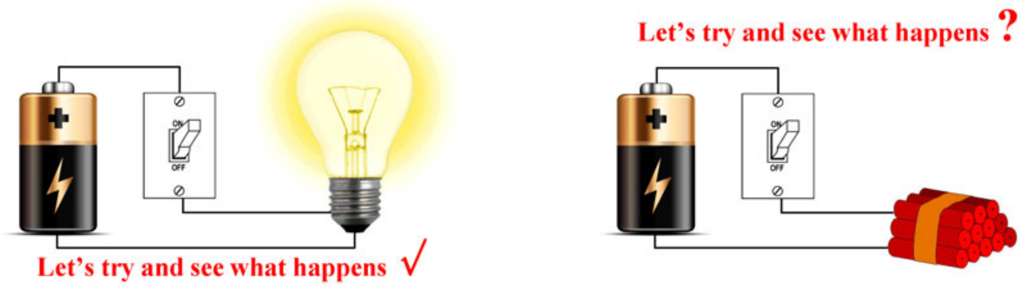


Figure-13: Constructing models cannot always be done using experiments

An alternative to experimentation is:

1- Study the physical behavior of the components making-up the servo-system.
2- Study how these sub-components interact with each-other.
3- Derive mathematical (or other) relations that capture the self-behavior of the components and the interaction among them,
4- Select a method to solve the equations to find the causality relation the process has as a whole. This relation is what links the present input to the future output.

Let's illustrate the above procedure using the following example. Consider an operator who wants to throw an object a far distance. He does not have the ability to do that himself. Therefore, he has to utilize the servo-process that is called a projectile system to accomplish the task (figure-14). Since the operator is interested in the horizontal distance traveled at $y=0$ (i.e. the range X), X is the output of the system. Assuming that the operator can directly influence the process by only changing the firing angle, θ is the input (figure-15).

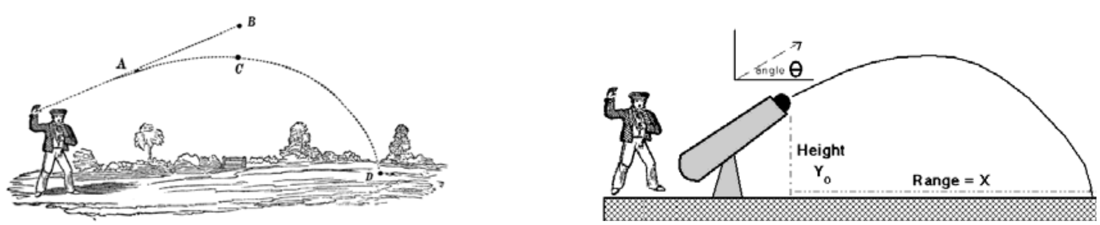


Figure-14: A projectile servo-process

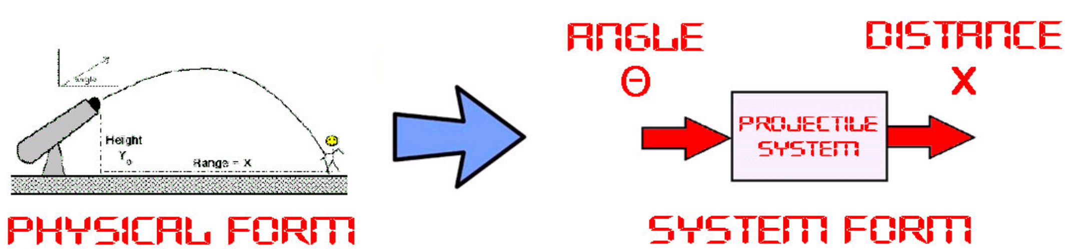


Figure-15: System form and physical form of a projectile servo-process

In this case experimentation may be used to obtain the causality relation tying θ to X. The model comes in the form of a table showing the values of x that correspond to the values of θ (figure-16). A compact alternative to constructing a model for the projectile process is to use the physics of projectiles to derive a mathematical formula that encodes the relation between the input and the output.

Angle	Net Vertical Displacement	Horizontal Displacement
20		
30		
40		
50		
60		

$$X = \frac{v^2}{g}\sin(2\theta)$$

Figure-16: Models can be a look-up table or mathematical relations.

The complete system form of the projectile servo-process is shown in figure-17 below.

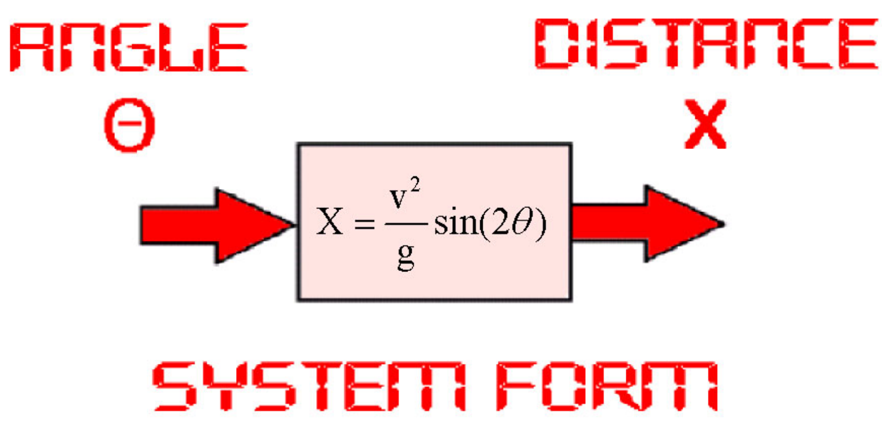


Figure-17: Complete system form of a projectile containing, input, output and transfer relation

Engineers use mainly differential equations to derive models (figure-18). By studying the physics of the process an engineer can write the differential equation that specify the relation between the input variable and the output variable. For example

- An electrical engineer uses Kirchoff and Ohms law to model an electric circuit
- A chemical engineer uses mass balance law to model a liquid tank
- A mechanical engineer uses Newton’s law to model a mechanical system

The differential equation modeling a process has to be solved in order to explicitly know the output that will materialize when an input is applied to the system. There are two ways for obtaining the solution:

- The analytical approach which utilizes mathematics
- The numerical approach which utilizes computer algorithms

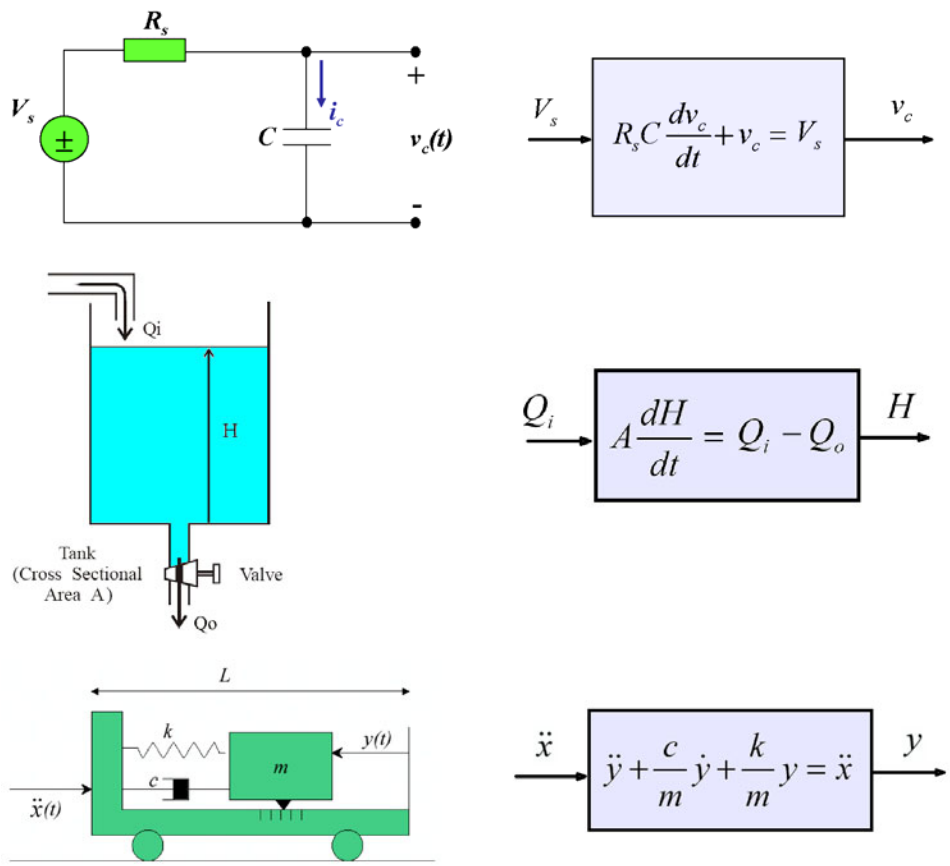


Figure-18: Differential equations are commonly used to model physical systems

Remember: A CONTROL LINK IS THE SEQUENCE OF OPERATIONS THAT MAKES IT POSSIBLE FOR THE COMMAND OF AN OPERATOR TO BECOME A REALITY (i.e. get executed).

4.0 Controllers

Here is an important question: Is the existence of a process that is willing and able to do the job (i.e. a servo-process) enough to realize the operator's command. To answer this question consider the following example. Assume there is a task that someone (let's call him an operator) wants to do but can't. There is another person who does not speak the same language as the operator. This person can do the task and is willing to accept the instructions from the operator (let's call this person the servo-process). If the operator sends a command signal to the servo-process will the job get done (figure-19)? The obvious answer is no. This means that no control link can be established. To fix the problem and establish a control link, a middle process, a translator, must change the command signal from a format that is understood by the operator into a format that is understood by the servo-process. Let's refer to the translated signal as the control signal. In control terminology, the translator is known as the controller. It is highly unlikely in nature to find a servo-process that would directly accept the commands of an operator without a controller in the middle being present.

A FULL CONTROL LINK IS MORE THAN A SERVO-PROCESS

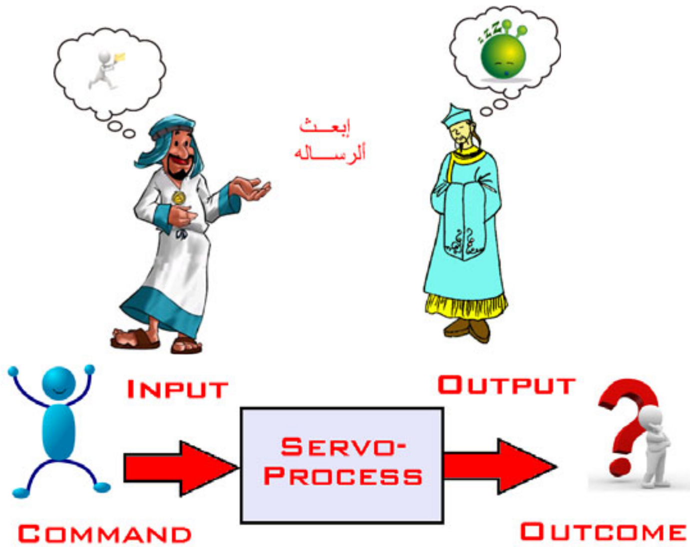


Figure-19: Mismatch between the format of a command signal and format of the signal a servo-process responds to can disrupt the control link.

The controller (figure-20) is needed in most control links to change the format of the command signal from one that suits the operator into one that suits the servo-process while maintaining the same informational content in the command signal (lossless conversion). If a controller dos its job correctly, then the outcome should be the same as the command.

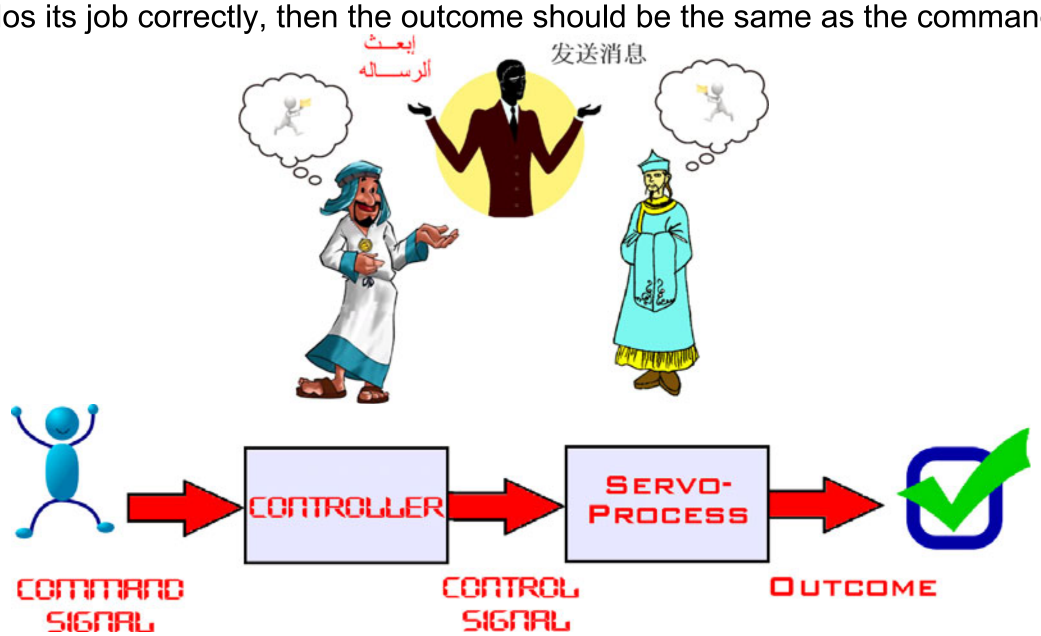


Figure-20: Controllers are usually needed to match an operator to a servo-process and establish a causality pathway between a command and an outcome.

4.1 Feed-Forward Control Systems

Let's take the projectile system as an example of the above control link. What the operator cares about is throwing an object at a specific distance Xr. This is the command that he will issue to projectile servo-process. However, the output of the projectile process can only be controlled by the angle θ. Therefore a middle process (i.e. a controller) is needed to convert the linear distance (Xr) which the operator understands into an equivalent angular distance (θ) which the servo-process can understand and act upon (figure-21). The controller is constructed based of the knowledge of the physics of how the projectile system works.

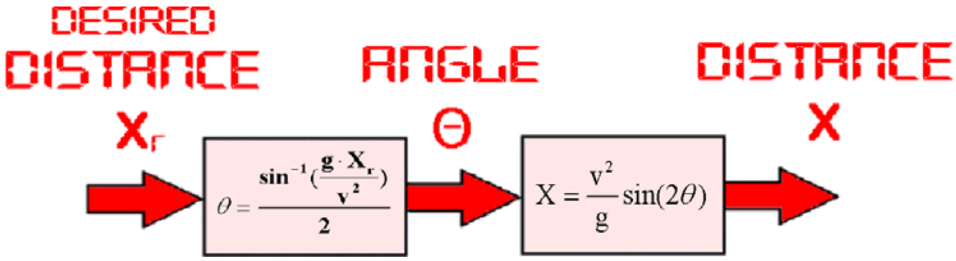


Figure-21: Full control link of a projectile system with servo-process and controller.

Consider the command of the operator as the beginning of the control link and the output of the servo-process as the end. The command signal causes the control signal to happen and the control signal causes the output of the servo-process to happen. As can be seen the causality flows in one direction from the input to the output. Therefore the above type of control links (figure-21) is called a FEED FORWARD control link. Feed forward control links are information based. In other words, they require full knowledge of how the servo-process works in order to actualize the command. The following example shows that this could be a source of problems.

4.2 Feedback Control Systems

Assume one takes a projectile system to the filed. The firing angle needed to send a projectile a distance Xr is computed. The experiment is performed in the field. Most probably one will observe that it was not possible to achieve the objective (figure-22). For the same angle the projectile fell at a location different from Xr each time it was fired.

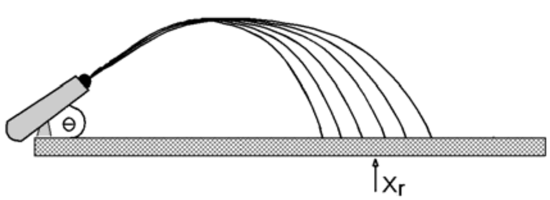


Figure-22: Lack of information can impede the execution of a task by the control link.

The reason for this is that the information about the servo-process is lacking. The servo-process is composed of the chain of causality (i.e. motion altering forces) starting from the operator-initiated action and ending with the outcome. Usually a lot of information is missing. The most obvious in the projectile example (figure-23) is the effect of wind on the trajectory of the projectile (believe it or not, earth's rotation is also a factor in the process).

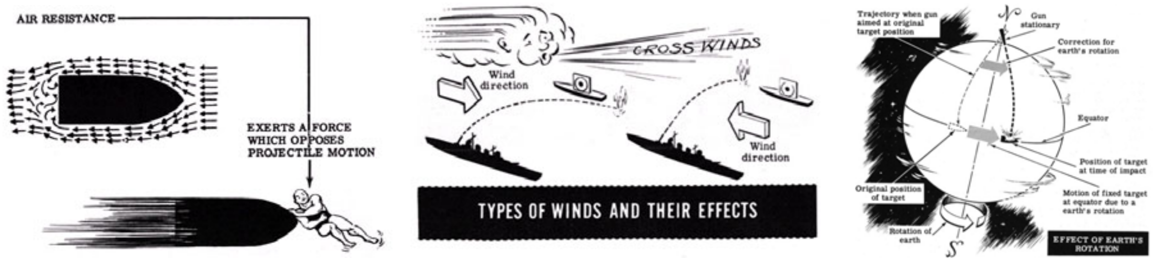


Figure-23: Information absent from the model of a projectile servo-system

The error caused by the lack of information prevented the command of the operator from being actualized. Information about a process can never be complete. This means that feed-forward control links are highly unlikely to be able to actualize the operator's commands.

An alternative to using information for control exist. The approach, most of the time, requires little or no knowledge. It works in the following way (Figure-24)

1- continuous sensing of the actual output of the process is utilized
2- this sensory data is made available to the operator (i.e. is feedback to the operator)
3- the actual output is compared with the desired output
4- a correction force is initiated to reduce the error

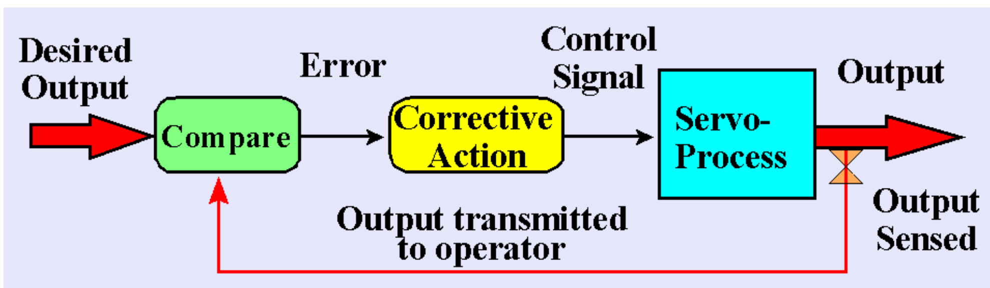


Figure-24: Feedback control link uses sensory data to execute tasks instead of information

Controlling a projectile servo-system in a feedback mode (figure-25) would require targets to be continuously monitored. A signal representing the location of projectile relative to the target must be made available to the operator. A crew need to continuously use this signal to correct the firing angle until the error becomes zero (i.e. output becomes equal to desired output).

Figuer-25: A projectile servo-system using a feedback control link

Processes & servo-processes that employ feedback are ubiquitous. The concept of feedback allows, most of the time, an operator who does not know exactly how something works to derive useful outcome from that process far exceeding in quantity and quality his input to the process (figure-26).

Figure-26: Feedback systems amplifies the effort of the operator without the need of having knowledge of how the process works.

Feedback does not have to be artificially created. It does occur naturally in most systems, even simple ones that are frequently used (figure-27).

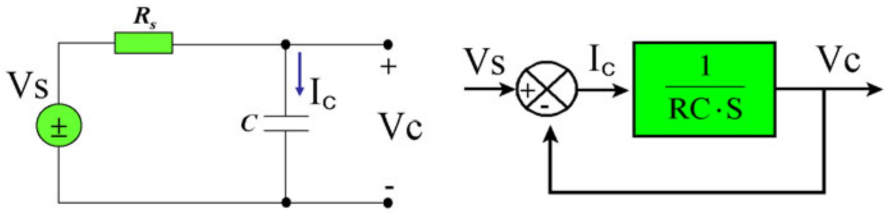


Figure-27: Feedback loops exist even in very simple systems

5.0 Control System Specifications

If a model of the control link is available, one may use mathematics or computer simulation to know what the outcome a given input will generate. However, sometimes the exact value of the output given an input is not important. What matters are only the properties of the solution.

Take for example the trip from home to work. In this case the servo process you may be using is a car. Most people don't really care about the exact path that the car takes. They only care about the path's properties, i.e. a reasonably short path, does not contain many turns, smooth ride, low gas consumption, fastest path etc. (Figure-28).

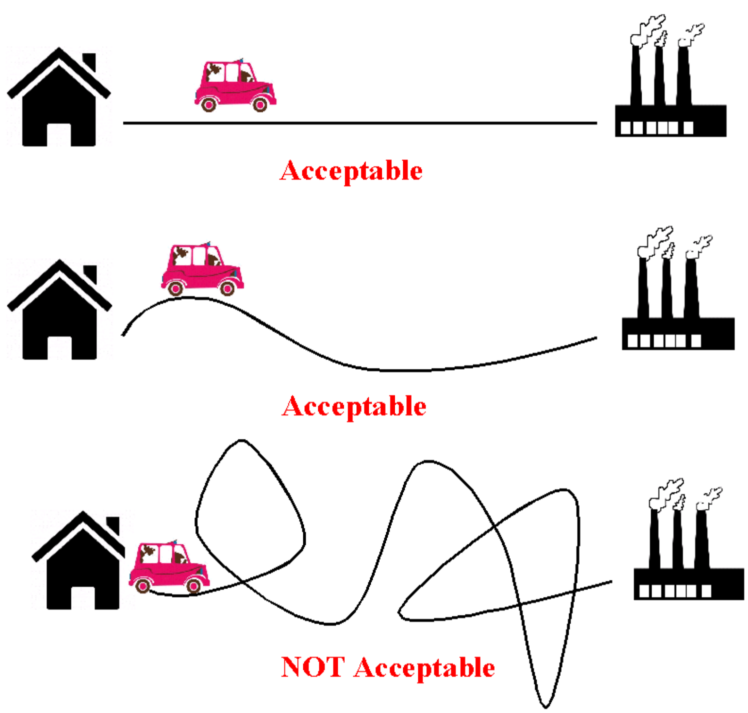


Figure-28: Exact knowledge of the outcome is not needed. Only its properties need to be known in advance.

Most of the studies concerning control links focus on the properties of the outcome not the exact value of the outcome. The properties are derived from the two phases an outcome can be in. The first phase is called the transient phase and the other is called the steady state (Figure-29). A Transient phase is characterized by the followings

- the system gets ready to executing the command of the operator
- no useful outcome is being produced

If the transient phase ends and the system is ready to produce useful outcome, the steady state phase starts. In the steady state phase

- the system starts producing useful outcome

Figure-29: Any output from a control link is divided into a transient phase and a steady state phase

The properties used to assess the control link are:

- The transient phase has to end. Loosely speaking, this property is called stability
- The duration of the transient period has to end as soon as possible. The duration of the transients are measured using three time periods, the rise time (T_r), the delay time (T_d) and the settling time (T_s)
- The maximum deviation of the outcome during the transient phase from its value during steady state (maximum overshoot) has to be small
- The error between the desired outcome and the resulting outcome during the steady state phase should be zero or an acceptable small value.

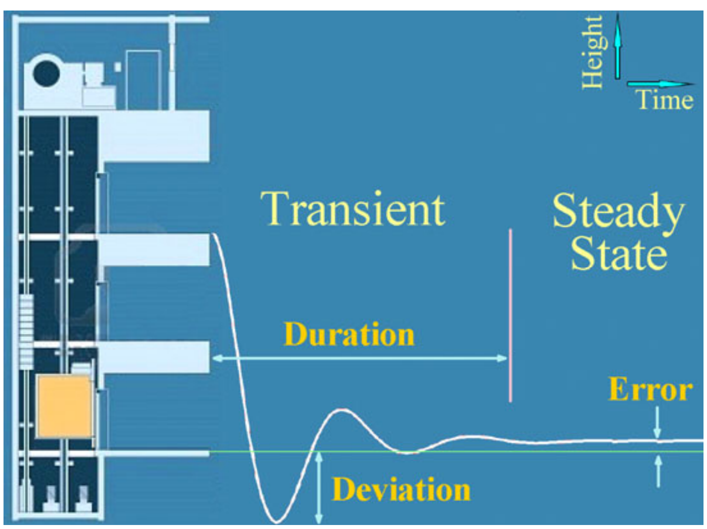


Figure-30: Different properties of servo-process output

Consider as an example of the above the response of the servo process that is called an elevator (figure-30). To deliver the service of moving someone from one floor to another, the process has to pass through a transient phase. It is required that this transient period has the shortest duration possible. Also, motion through this phase is expected to be well-behaved with little or no oscillations. If, for some reason, the transient phase does not end (i.e. the system is unstable), the service cannot be delivered (neither do anyone want to be in the elevator). When the transient period is over and the elevator arrives at the destination floor (i.e. steady state is reached) one wants the elevator floor to be exactly located at the destination floor level (i.e. steady state error is zero or tolerable).

The performance specifications needed to assess the usefulness of the servo-process may be obtained in different ways:

- Experimentally
- By computer simulations
- Mathematically if possible

6.0 Examples of Control Systems

The following briefly present examples of new and old control systems

6.1 Pneumatic Door Opener Servo-system

Control systems are not modern constructs. They were known and used thousands of years ago. An ancient example is the temple door opener. A sacrificial fire is lit so that the doors of the temple are opened and the faithfuls are herded-in. When the fire is extinguished, the doors close back.

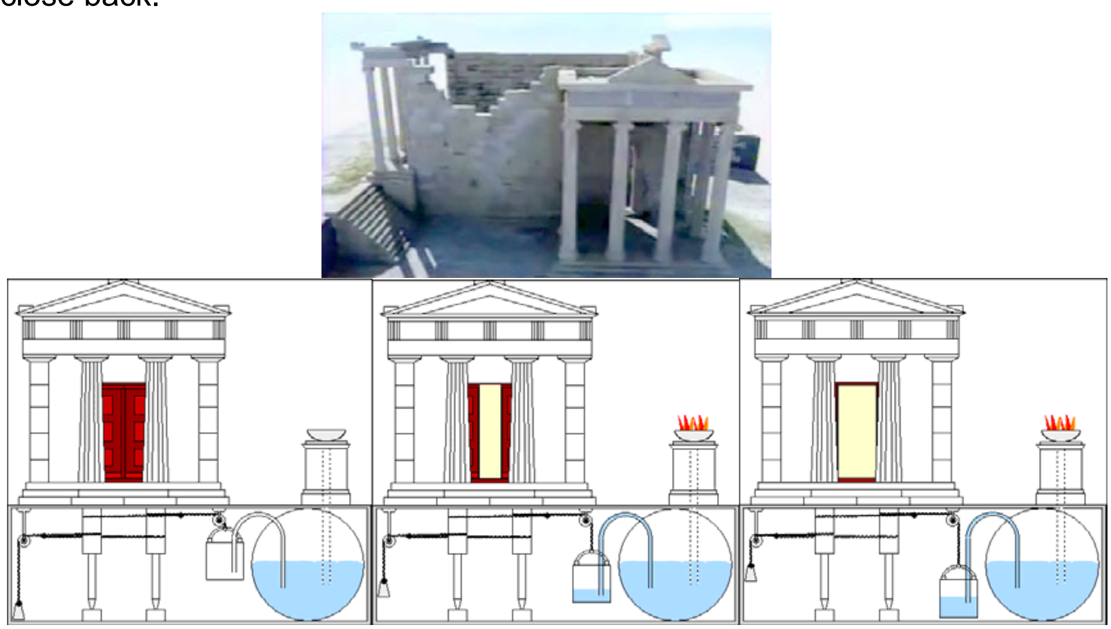


Figure-31: The temple door opener servo-process

The control system used is referred to using modern terminology as a feed-forward control system. Its input is heat from the fire and its output is the mechanical motion of the door (figure-32). The control link works as follows: fire heats water stored in a water vessel creating pressurized steam. Pressurized steam pushes water from the vessel to a receptacle. The increasing weight of the receptacle drives an actuation mechanism that opens the door. When fire is extinguished, the water is sucked back by the water vessel. The weight of the receptacle drops. The door actuators operates in the reverse direction closing the door back.

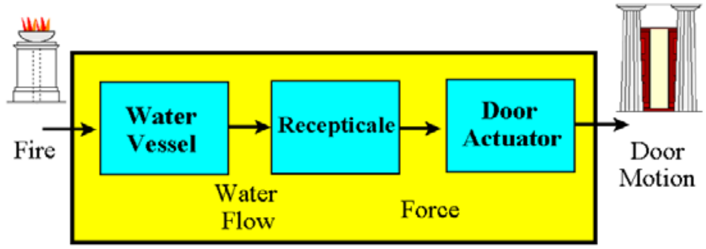


Figure-32: A system representation of the temple door opener

6.2 Water Level Regulators & Timing Machines

Another old control system that is still being used to this day, is the water level regulator that uses a float (figure-33). This system belongs to the family of feedback control systems. It automatically monitors the water level in a tank without the need for a person to manually attend to this task. Almost every water storage tank currently in use has a system similar to it.

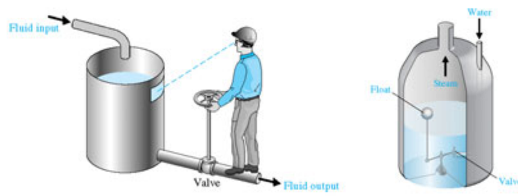


Figure-33: Water level regulation using a float-based servo-process

Regulating the water level in a tank has important historical applications. It allowed the construction of water-based, time measurement devices known as water clocks (figure-34). The constant water level allowed water to drip at a constant rate hence enabling the measurement of time.

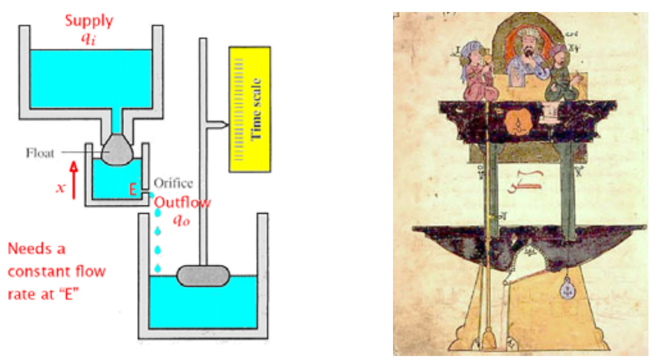


Figure-34: Water level regulation enabled the construction water clocks for measuring time.

The control system of a water-level regulator is shown in (figure-35). A water supply tank feeds another tank with a pinhole orifice at the bottom. The water level pushes a float to cut the water supply if the water reaches the desired level. This keep the water level in the float chamber at the desired level and maintain the constant rate dripping from the orifice.

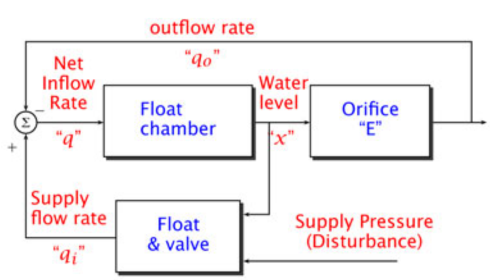


Figure-35: System representation of a float water level regulator used with water clocks.

6.3 Water Mixers and Temperature Regulators

A sophisticated, feedback, control system that is being used by almost everyone is: taking a shower. This process involves regulating the temperature of water so it is kept around a comfortable value. Mechanisms new and old were built for such a purpose (figure-36).

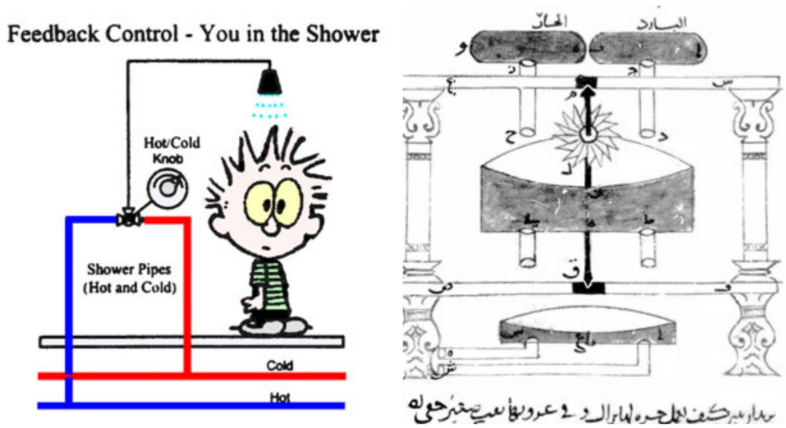


Figure-36: Showering is a complex servo-process that utilizes a feedback control link

Each person has a comfortable temperature (Td) which he likes. When the water from the shower hits the skin of the subject, the nerves in the skin senses the temperature. This sensory signal is sent to the nervous system and compared to the desired temperature. The nervous system of the subject controls his hand to adjust the mixer valve so that a better water temperature is obtained. This process continues until the comfortable temperature is reached (figure-37).

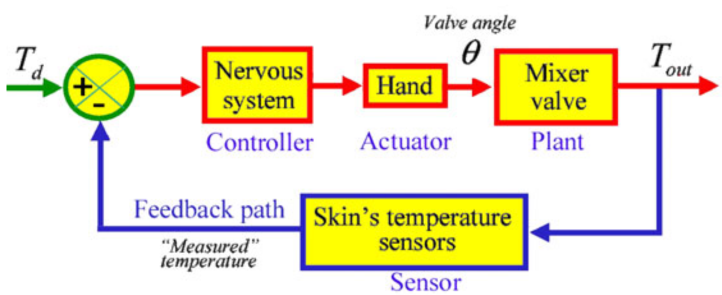


Figure-37: The system representation of a showering process

6.4 Oscillators

The creation of oscillatory motion of constant period is of great importance to many applications. Aside from time keeping, multiplexing of resources (e.g. water) is an important procedure that requires accurate implementation. Old devices were built for accurately carrying-out this task. The device shown in figure-38 utilizes the water signal in an inverted feedback configuration that is similar to the modern flipflop device.

A supply pours water into a pipe that could channel water into two opposite directions. Each direction has an auxiliary pipe that feeds a water bucket designed to create an antagonist, inhibiting action after reaching a certain threshold. As long as water is being poured into the device, water in each channel will oscillate between two states (ON, OFF) creating what is currently known as an astable multivibrator. A simplified system diagram is shown in figure-39.

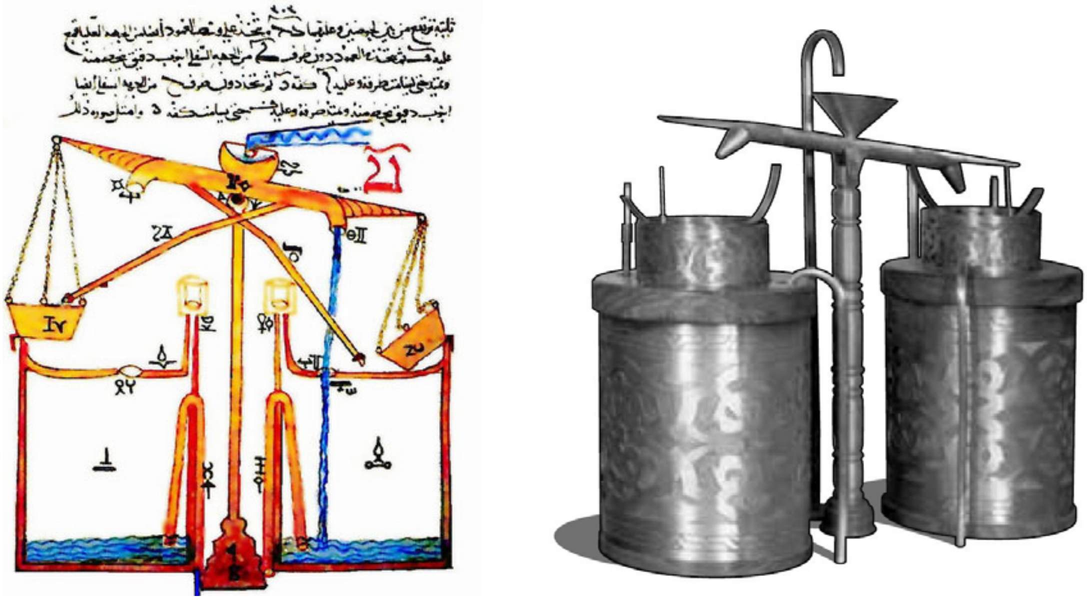


Figure-38: An old mechanical, constant period oscillator

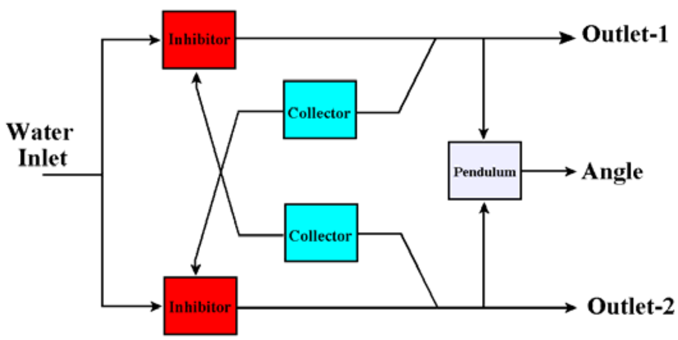


Figure-39: The system representation of the oscillator in figure-38

6.5 The Speed Governor

The Watt speed governor is a landmark in control system history and one of the enablers of the first industrial revolution. It functioned to maintain the speed of a steam engine (figure-40) to a constant value when connected to a load.

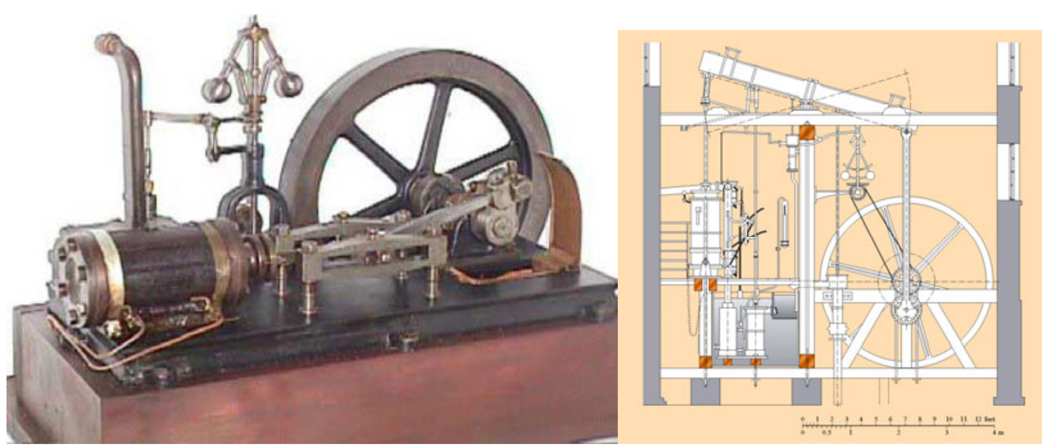


Figure-40: Steam engine with a Watt speed governor

The idea is simple. Two heavy metallic balls (fly balls) are connected to the rotating shaft of the machine (figure-41). When the speed drops, the balls also drop opening the steam valve wider and letting more steam into the engine. As a result the engine rotates faster resulting in the balls reducing the inlet steam hence regulating the speed of the engine.

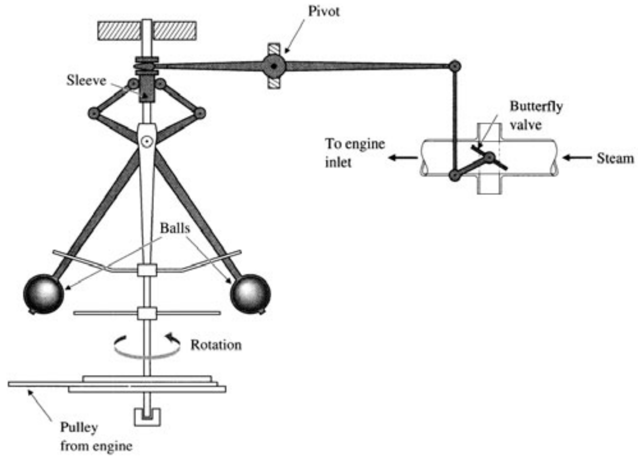


Figure-41: The watt speed governor

The complex feedback control action is shown in the system diagram in figure-42.

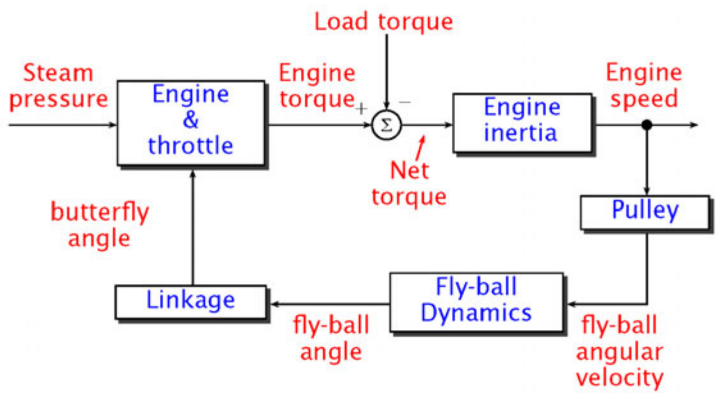


Figure-42: System representation of the steam engine with the speed governor.

6.6 The Feedback Amplifier

Modern control systems of the 20th century had their start in the communication area with the invention of the feedback amplifier (figure-43) at AT&T laboratories in the 1920's. This invention allowed the construction of amplifiers with high gains to send signals for a long distance. It also opened a wide door for the development of control system theory through the work of Nyquist on stability theory.

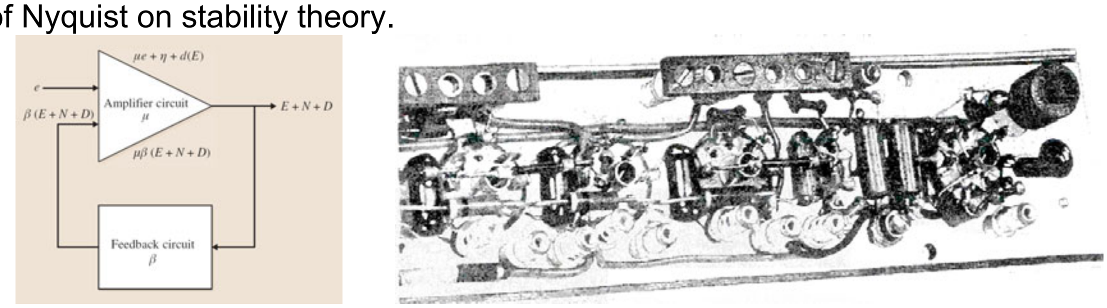


Figure-43: The first negative feedback amplifier built by Harold Black at AT&T

6.7: Modern Control Systems

Almost all modern devices need an embedded control system in order for them to function. These systems cannot be seen. Their presence can only be identified by their effect on the process. A car (figure-44) has many embedded control systems (e.g. cruise control) to provide a driver with a stable and good performance.

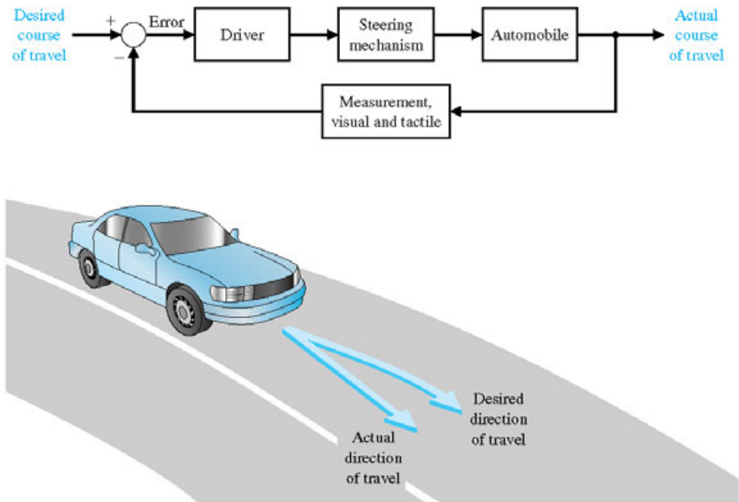


Figure-44: feedback servo control link are used in controlling car motion

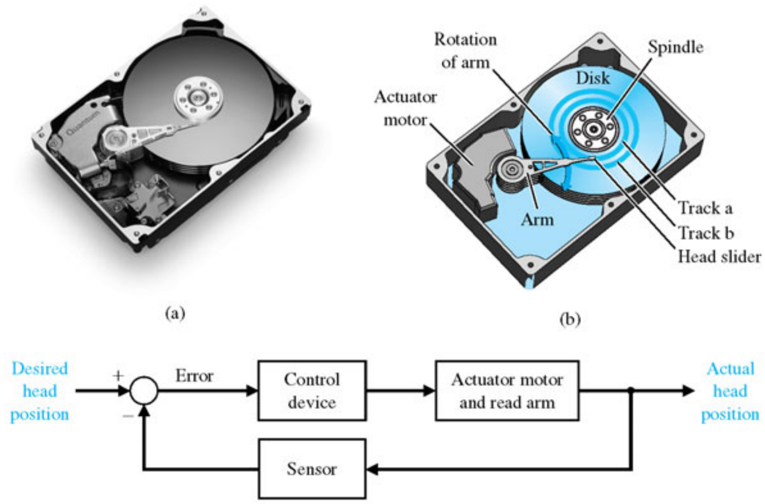


Figure-45: Control systems enable a computer had disk to function

A hard disk in a computer has several control systems embedded in it. One of these control systems converts the address of a piece of information into a mechanical motion that would move the arm holding the reader to the physical location on the magnetic disc on which the information is stored (figure-45).

Control systems could be as small as a thermostat (figure-46) which exists in almost every household. They could be as massive as distributed control systems (DCS) needed to control the activities of large scale industrial plants (figure-47).

Figure-46: A thermostat is an integrated, miniature control system

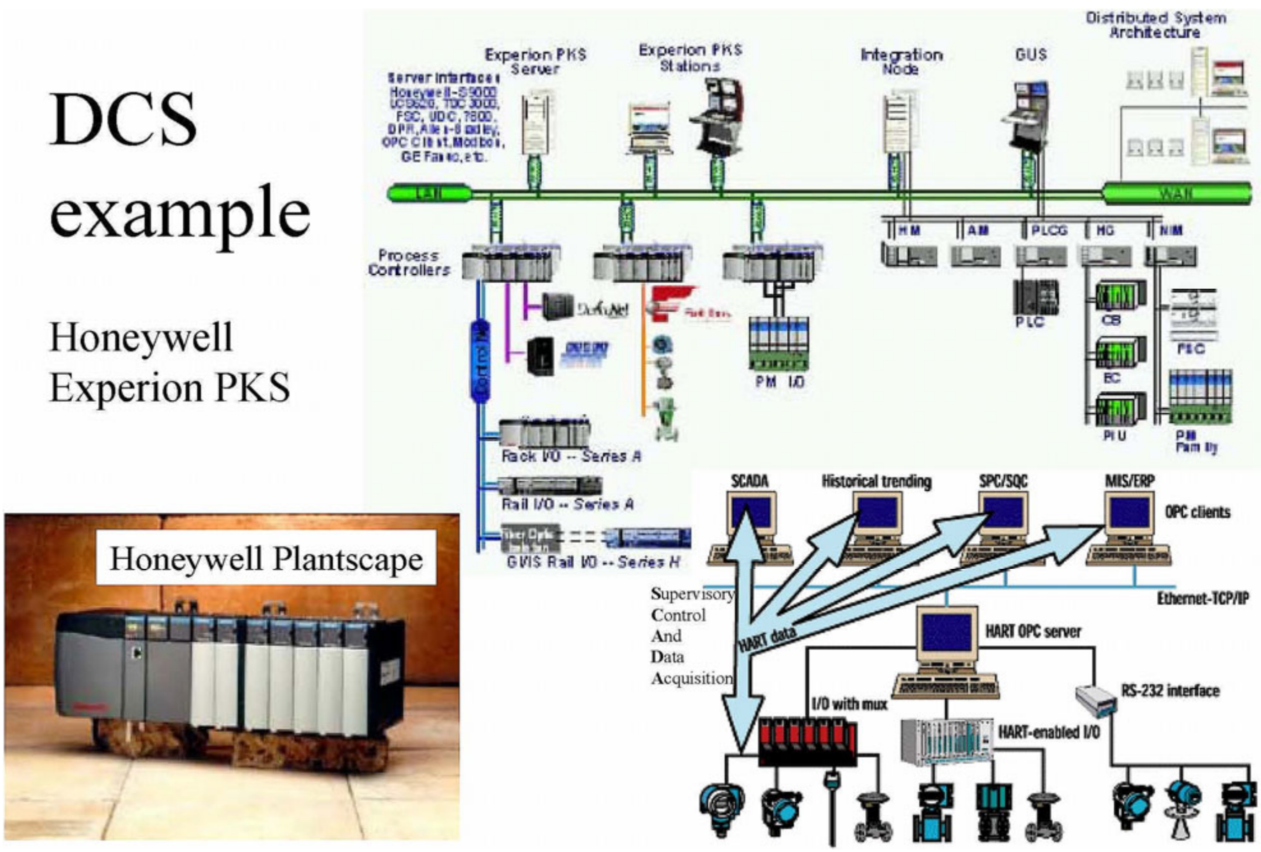


Figure-47: Distributed control systems used in industrial plants.

Control system exist in the macro world. An example air traffic control (ATC) systems (figure-48). ATCs are responsible for making the air transportation system work. They deconflict the use of airspace and advocate safe and cost-effective routing to target destinations.

Figure-48: Complex, feedback control systems keeps air traffic running

Control systems do also exist in the micro world at the cellular level (figure-49). Focused and intense research is being carried-out to understand the control mechanisms used to regulate activities inside living cells. Knowledge of how these mechanisms work has a promising future in the treatment of dangerous diseases such as cancer.

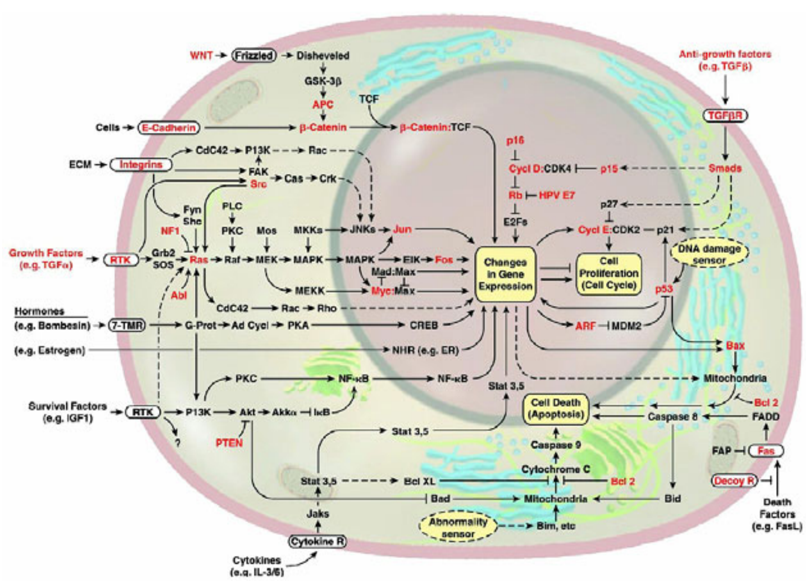


Figure-49: Control system theory is used to understand the behavior of human cells

Control systems are essential for the generation and distribution of electric power (figure-50). This importance significantly increased with addition of alternative energy sources to the power grid (figure-51).

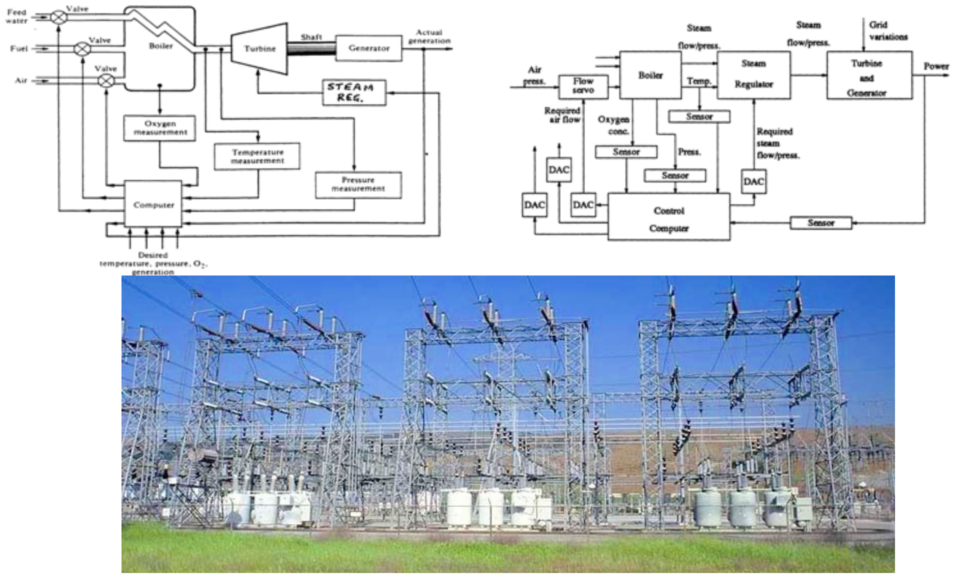
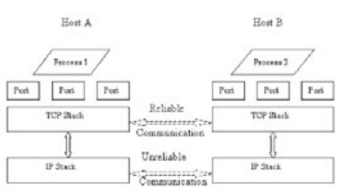


Figure-50: Power generation is highly dependent on control systems

Figure-51: Alternative energy sources require advanced control systems to operate and integrate in existing power grid.

Control is also an integral part of any communication system.

1974 - TCP/IP



- TCP/IP - Cerf/Kahn, 1974
- Berkeley-LLNL network crash, 1984
- Congestion control -Van Jacobson, 1986

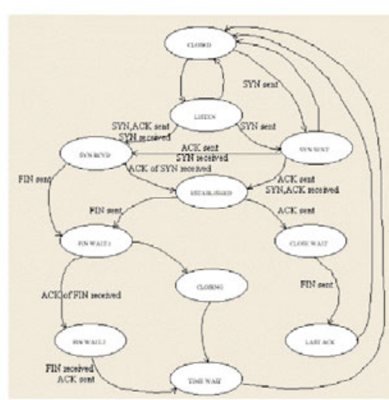


Figure-51: Data transmission control is needed to enable communication networks to function.