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Control Systems as Used by the Ancient World

Lisa Ferguson
Embry-Riddle Aeronautical University, fergusl2@my.erau.edu

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AS USED BY THE ANCIENT WORLD

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by

Lisa M. Ferguson

FergusL2@my.erau.edu

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Embry-Riddle Aeronautical University
Prescott, Arizona

Abstract

For as long as humanity has had time to devote to thought, there have been engineers developing technology. In the ancient world, especially during the Hellenistic period, the engineers and philosophers devoted their time to developing control systems and bringing automation into the modern world. A control system is a device or process that regulates the behavior of another device or system. Ancient control systems used water almost exclusively as their method of control, mainly because of its availability and its versatility of states. From the rapid flow a river to the rising power of hot steam to the slow drip of water from a bucket, water was the harness of the natural world for control engineers. Without easy access to water, many of the control systems of the ancient world would not exist.

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1. Introduction

For as long as humanity has had time to devote to thought, there have been engineers developing technology. At their most basic definition, an engineer is anyone concerned with understanding and controlling the materials and forces of the natural world for the benefit of human kind. The very first engineers were the ones who decided that hollowing out pieces of wood into bowls would be easier for carrying and cooking than just bare hands. In the ancient world, especially during the Hellenistic period, the engineers and philosophers devoted their time to developing control systems and bringing automation into the modern world (Wilson, 2002).

1.1. Definition of Control Systems

A control system is a device or process that regulates the behavior of another device or system. The control engineer (responsible for designing control systems) is concerned with understanding and controlling segments of their environment to provide useful economic products for society (Lewis, 1992). These segments of their environment are often referred to as systems and were once derived from the natural world. Profit is not always a direct product of control systems, but the ability for a system to run semi-autonomously or a manual task to become easier allows for time to be committed to more profitable activities.

Control systems can classically be divided into two separate categories based on the feedback they receive: open loop and closed loop. Most forms of control systems that provide automation rely on the system feedback and are labeled as a closed loop system. System feedback can be defined by the reliance of the current action upon the results from the past or previous action or actions. Conversely to this, an open loop control system does not receive any feedback and will continue to run using only its starting conditions (Phillips & Parr, 2011). Open loop control systems are best described by single task automata. They have a preprogrammed task to complete and regardless of differing factors or changes in their environment, they will complete their task.

Because of the lack of feedback, open loop control systems do not adapt so the results are dependent upon their operating conditions.

1.2. Definition of Ancient Control Systems

In the ancient world, control systems and control engineers held the same definitions as their modern counterparts, however the definition of the natural world was taken much more literally. Today, the tools of a control engineers are often nothing more than a computer, software, and a device to empirically measure the output of the system. In the era of digital control systems, the control engineer is far removed from the system, doing most of the work from behind a keyboard (Phillips & Parr, 2011). An ancient control engineer worked directly with the forces of the natural world. Water, air, and fire were the forces used to both power the system and the controller.

Ancient control systems also fell into the categories of open loop and closed loop feedback types. Closed loop systems were much more difficult to design with the materials available at the time (Lepschy, 1992). Before the discovery of electricity and the majority of feedback being supplied by water, the closed loop control systems had must slower response times than their modern equivalents. Open loop feedback systems were much more common and were used for everything from manufacturing to entertainment to religious ceremonies. The control systems of the ancient world were often viewed by the general populous as magic or even the work of the gods and brought the control engineers almost mythical standing. The control engineers of the ancient world remain in the literature of today and their control systems are still a source of admiration and study.

2. Water: Source of Life, Source of Control

Humanity has been dependent on water as a source of life since the beginning of time. Ancient settlements grew around water sources. Water came to supply food, transportation, trade, and even control system. Whether the still waters of a lake or the swift flow of a river, the power of water was harnessed by ancient engineers to develop control systems that regulated the tasks and devices crucial to their daily lives.

2.1. Rivers

Like veins in the human body, rivers spread throughout the ancient world with civilizations and cultures sprouting along their banks. The constant source of water supplied by the river allowed life to thrive with plentiful agriculture and an easy mode of transportation and trade. Therefore, the civilizations that grew along the riverbanks were able to devote more time to philosophy and engineering. The river became more than just a source of agriculture, but also a source that could be harnessed by control engineers.

In control engineering terms a source is anything that supplies power to a system (Lepschy, 1992). Conversely, a sink is the output of a system after the controller has been applied. In the ancient world, a river became an excellent source for control systems. Because the flow of a river is constant and in a single, uniform direction, a river becomes a source of power for control systems. Depending on how the control system interacted with the river, different input functions could be created for difference systems (Phillips & Parr, 2011).

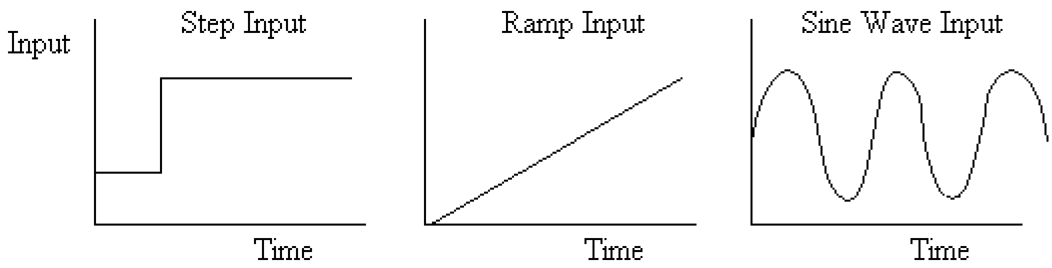


Figure 1: Control System Inputs[1]

A step function could be created by simply inserting and removing the driving element of the control system from the river. By slowly inserting the driving element into the faster flowing portions of the river, a ramp function can be created. Using the waves or swell in the river, even a sinusoidal input function can be created, although not often utilized.

The constant flow of a river becomes not only a source of life for the ancient world, but also a source for ancient control systems.

2.2. Steam Power

When water is heated past boiling, it changes state and becomes a vapor called steam. Unlike liquid water and due to the boiling process, steam is superheated and rises quickly. The transformation from liquid water to steam can be made to happen rapidly with the simple application of heat. The invention of the steam engine is hailed as the birth of the Industrial Revolution and the dawn of the modern era. With the advent of the steam engine, automation was no longer tied to a source of moving water and power could be created with nothing more than water and heat. The steam engine was the predecessor to the gasoline motor and the electric motor, both crucial elements of modern life.

While the steam engine was not invented officially until it was patented in 1606 by the Spanish inventor Jeronimo de Ayanz Beumont, it was not unknown to the ancient world (Wilson, 2002). Steam was well known to ancient control engineers and was harnessed

[1] http://eleceng.dit.ie/gavin/Instrument/Dynamic/Dynamic%20Notes_files/image001.gif

in a variety of control systems. Oddly enough, most of these devices were for entertainment purposes and were not really used for power sources. The control systems that harnessed steam were used from the theaters of ancient Alexandria to the temples of the ancient gods. Open loop control systems powered by steam imitated birds, automated stage props, and even acted as the voices of gods for stunned worshippers. Steam was easy to create, easy to harness and its natural tendency to travel upward and condense back into liquid water made it ideal for control systems.

2.3. Tracking Time

The modern world is run on a strict schedule. From the time one wakes in the morning to the time one returns back to bed, the pace of life is maintained by a clock. There are 60 seconds in a minute, 60 minutes in an hour, 24 hours in a day, and 365 days in a year, these are the modern divisions of the time the Sun is in the sky and the Earth's path around the Sun. Tracking the passage of time is crucial to every aspect of time. From determining the winner of a photo finish as the Olympics to accurately marking a birth certificate with the correct birthday, measuring time is critical.

For control systems, time is the metric used to determine the response of a system. The settling time and the time to system response peak are both parts of a control system that can be made as either design specifications or desired system outputs. The settling time determines how long the system takes to reach its final output and can be tuned by varying the control system. If the settling time is too long or too short, the overall effect of the control system may not be the outcome desired. Similarly, the time to system response peak is the amount of time it takes for the system to reach its maximum value and can be used to trigger an action or actually be the desired outcome of a control system.

In the ancient world, time was measured simply by the rising and setting of the sun. The months could be loosely tracked by the moon and the year passed with the seasons, but the day to day passing of time was not tracked to the accuracy of the modern era. Time was used more in the capacity of a stopwatch timing a certain event, rather than a clock used to perpetually track the passing of a day. Once again, the value of water in control systems becomes apparent.

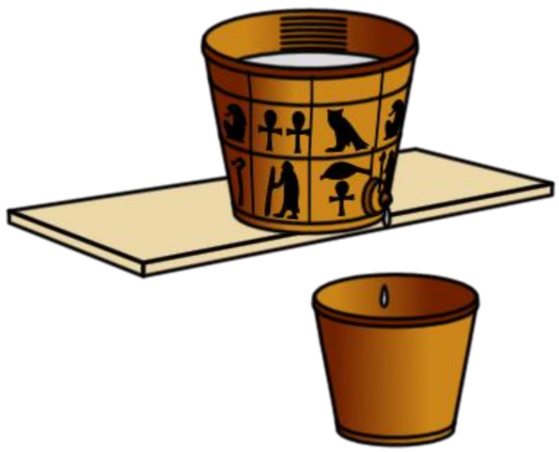


Figure 2: Ancient Egyptian Open Loop Water Clock[2]

The earliest clocks were nothing more than two clay pots, one with a hole near the base marked with a scale and a second pot to catch the falling water (Lepschy, 1992). The first pot would have the hole stopped with wax while it was filled with water and the second pot was placed below. When time was needed to be measured, the wax would be removed and a stream of water would flow into the second pot and start to fill it. The length of the event was then measured by the amount of marks that had been exposed by the water level in the first pot. The system had no feedback and was an open loop system because after every time measurement the system was reset manually and if the second pot was moved, the first pot was not aware and would continue to provide a flow of water.

2 http://exchangedownloads.smarttech.com/public/content/7a/7ab8ee15-dfcb-45ee-882f-c4898115b5d0/previews/medium/0001.png

3. Application of Ancient Control Systems

Ancient control systems used water almost exclusively as their method of control, mainly because of its availability and its versatility of states. From the rapid flow a river to the rising power of hot steam to the slow drip of water from a bucket, water was the harness of the natural world for control engineers. Without easy access to water, many of the control systems of the ancient world would not exist.

3.1. Water Wheels

A water wheel is a large wheel with a set of paddles extending from the outer edge of the wheel that are extended into a source of moving water to produce a rotational motion (Wikander). Water wheels have many applications in the ancient world, from agriculture to industry. Using the source of rapid moving water available in rivers, water wheels quickly became the ancient equivalent of the DC motor.

By changing the shape of the water wheel paddles from flat planks to curved buckets, the water wheel could now be used to move water up and into a reservoir. The water wheel could now be used for both a source of rotational power and a means of moving water. In agriculture, water wheels were attached to mills that ground cultivated grains into flours and meals. Water wheels can also be attached to trip or helve hammers that can then be used to pound grain into its polished form, wrought molten iron into bars, and release ore locked in stone. Harnessing the power of moving water, the water wheel becomes an important source of control in the ancient world.

Some of the earliest water wheels were referenced by Antipater of Thessalonica in his poems sometime between 20BC and 10 AD (Wikander). The water wheel referenced is referred to as an overshot water mill because the source of water is supplied to the top of the wheel from a waterfall or aqueduct.

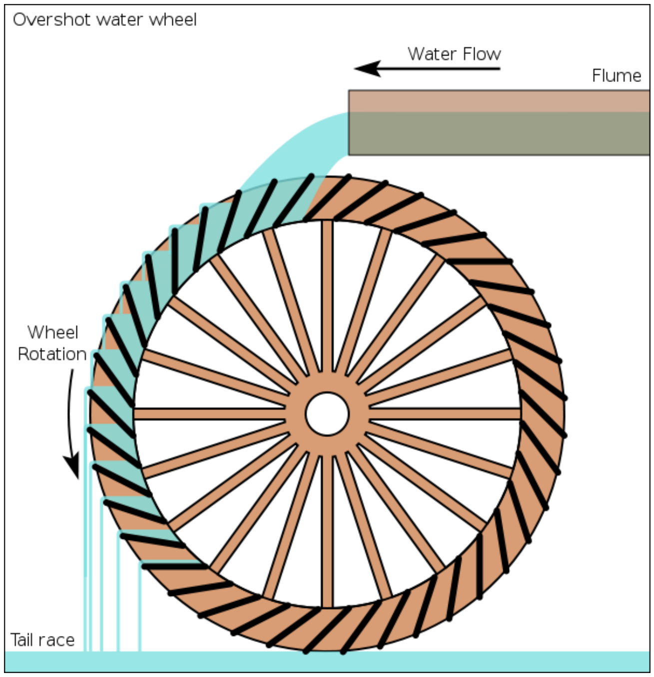


Figure 3: Overshot Water Wheel[3]

The water wheel is an ancient representation of an open loop control system that could be used as a source of rotational motion. The system is considered open loop because the system that the water wheel drives does not provide any feedback to the water wheel. As long as the wheel is in the water, it continues to turn and the system operates. If the wheel stops turning, the system stops working and if the system stops, there is no feedback to stop the water wheel from turning.

A water wheel can provide various types of inputs based on how the water wheel interacts with the water. If the wheel can be inserted and removed from the water, a step input can be created. If the wheel can be moved into swifter moving water, a ramp function can be simulated. A step input is often referred to as a bang-bang system because it exists in a binary state; it is either on or off. A ramp function can be described as an increase of speed over time. The faster the water moves, the faster the water wheel turns and the faster the system operates.

[3] http://commons.wikimedia.org/wiki/File:Overshot_water_wheel_schematic.svg#/media/File:Overshot_water_wheel_schematic.svg

Water wheels were in use well into the Industrial Revolution to power everything from saw mills to sewing machines and helped usher in an era of mass production. In the ancient world a water wheel was a source rotational power that was harnessed for industry and agriculture.

3.2. Heron's Aeolipile

Heron of Alexandria (10 – 70 AD) was a Greek mathematician and controls engineer from Alexandria in Egypt (Shuttleworth, 2008). Heron was an expert control engineer and was responsible for many of the control systems that were used to mystify the populous of Alexandria. Some of his inventions included a system for automatic temple doors that opened with an offering to the gods, the first coin operated vending machine that dispensed holy water, and an entire play that was automated with nothing more than counterweights and pulleys (Ralph, 2013). He was also an expert mathematician and discovered Heron's Formula, which determines the area of a triangle based on its side lengths.

Heron's most famous invention and control system is known as Heron's Aeolipile and is the first known steam engine. While the engine did not actually produce any harness-able output and was viewed a nothing more than a curiosity at the time, the aeolipile harnessed the power of water and steam to create a circular motion. Heron's Aeolipile was another ancient form of a DC motor and could have been a source of rotational power.

Figure 4: Heron's Aeolipile[4]

Heron’s Aeolipile was a sealed spherical container with two exhaust pipes pointing in opposite directions (Shuttleworth, 2008). The container was suspended so that it could rotate freely by two sets of hollow pipes that fed into a sealed basin. To power the engine, the lower basin was filled with water and a fire was lit below the basin. As the water in the basin boiled, steam traveled up the pipes and out of the two exhausts, causing the container to spin. As long as there was water in the lower basin to be evaporated, the aeolipile would spin.

The aeolipile was an open loop control system that could produce rotational movement until its supply of water had evaporated away. Again, there is no feedback from the spinning container to the water basin and the container does not know if the basin is about to run dry. There was also no way to control the rotational speed of the engine so there is no feedback from the container either.

As an open loop control system, Heron’s Aeolipile was one of the first sources of rotational energy that was portable in the sense it was no longer tied to the flow of a river. Had the rotational energy of the aeolipile been harnessed, it has been postulated that the Industrial Revolution could have started almost 2,000 years earlier. Instead, the

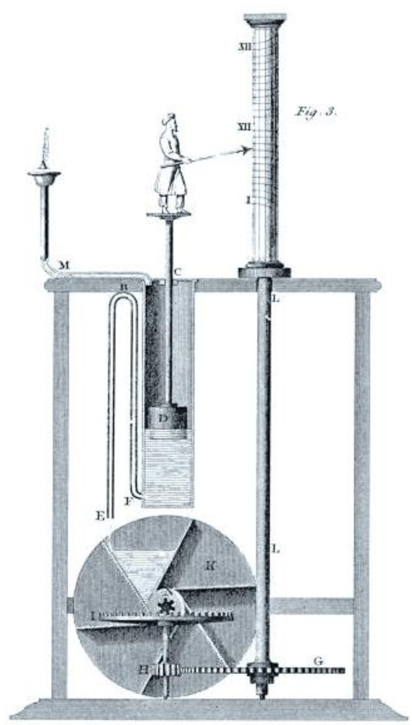
[4] http://commons.wikimedia.org/wiki/File:Aeolipile_illustration.png#/media/File:Aeolipile_illustration.png

upper classes of ancient Alexandria were entertained by Heron's spinning aeolipile, but the control system was never put to any productive use.

3.3. Ctesibius's Water Clock

Ctesibius of Alexandria (270 BC) was an inventor and controls engineer from Alexandria, Egypt (The Editors of Encyclopedia Britannica, 2009). While most of his work was based on using compressed air as a control substance and he is known as the Father of Pneumatics, his most famous control system was the feedback he added to the already existing water clocks of the day.

In ancient Greece, water clocks were referred to as clepsydra or water thief because the water used by the clocks was seemingly stolen with no feedback to the user. Ctesibius's water clock changed this with the addition of a moving pointer to the current time and even, in some cases, alarms and moving figures to signal time events.



(Lepschy, 1992)

Figure 5: Illustration of Ctesibus's Water Clock[5]

[5] http://upload.wikimedia.org/wikipedia/commons/7/7b/Clepsydra-Diagram-Fancy.jpeg

Ctesibius's water clock was a more elaborate version of the older water clocks that provided no feedback to the user. Unlike the version of the clocks that was reliant upon two pots and the flow of water aided only by gravity, Ctesibius's water clock used a system of gears and a water wheel to track the passage of time and report the time using an arrow on a scale that signaled to the user the current time. Water was fed into the top from the clock by an external source and filled a reservoir. In the reservoir floated a figure holding an arrow that would point at the time scale. At the base of the reservoir was a pipe whose U-shaped upper bend forced the water level in the reservoir to maintain at a constant level (The Editors of Encyclopedia Britannica, 2009). Water from the pipe then drops onto a water wheel, as the water wheel sections fill slowly; the wheel turns and causes a set of gears to move the time scale accordingly.

Ctesibius's water clock was also elaborated upon by other inventors of the time and noise makers were added to create an ancient alarm clock. The clocks also had decorations and automatons added and ancient cuckoo clocks were created as well. These clocks had the ability to track long periods of time or be used as stop watches. The length of time the clock runs was only limited by the external source of water. With the addition of alarms and the time scale, the Ctesibius water clock provided feedback to the user and became one of the first control systems of the ancient world to do so. With the advent of feedback control system, the era of automation could begin.

4. Modern Adaptations of Ancient Controls

Most of the control systems used today can trace their heritage back to ancient control systems. Where ancient control systems used water, modern systems use electricity but their control abilities maintain relatively unchanged throughout the ages. Even the digital control systems can trace the modals of their software back to the control systems of the ancient world.

4.1. DC Motor

The water wheels of the ancient world became the DC (Direct Current) motors the modern control systems. The only difference between the two systems is the source of power for the rotational energy. In the ancient water wheels rivers supplied the current needed to turn the paddle wheel and turn the output shaft. In modern DC motors, a steady, unidirectional flow of electrical current turns the motor and the output shaft.

Harnessing the rotational motion of a water wheel became a crucial for the advancements that lead to the discoveries of the Industrial Revolution which lead to the modern production techniques of today (Lewis, 1992). From lumber yards to grain mills, water wheels and then DC motors became the source of automated power to replace the repetitive up and down motion required by the user. By harnessing the natural force of water current, the ancient control system of the water wheel gave way to the modern DC motor.

4.2. The Engine

The Heron Aeolipile was the first steam engine created, but the rotational power of the steam engine waited 2,000 years to be harnessed. However, this does not deaden the importance of the power of steam and power of the engine. Today engines use explosive fuel to turn cranks to produce the rotational energy used in automobiles and power generators; however the use of a fuel to produce rotational energy can trace its roots back to the steam engines.

Using water as fuel and fire as the heat source to transform the fuel from liquid to vapor, the ancient steam engine functioned quite similarly to the combustion engines used today. Instead of water an explosive fuel is used and instead of a fire as the source of the state change, sudden compression of vaporized fuel is used. Although technically more advanced than the ancient steam engine, the process of converting a fuel to rotational energy remains the same.

In control systems, rotational energy was a crucial step in helping automate the monotonous repetitive tasks that are now almost entirely done by machines. Unlike the rotational energy created by the water wheel, the steam engine was not tied to a water source for power and could operate anywhere fuel was provided. By removing the restraint of working near a waterway, control systems that harnessed rotational energy could now be spread across land.

4.3. Timers

The water clock improved upon by Ctesibius was the birth of modern time keeping and of control systems that could be monitored and measured by time steps. With direct feedback provided to the user by the time scale and indicator, the output of the clock could now be used to determine what inputs were needed for the system (Phillips & Parr, 2011). The use of water clocks became the basis for both short term and long term time tracking and helped usher in the modern age of time-reliant mechanisms and control systems.

In modern control systems, timers are now implemented digitally by using the oscillation of a crystal to create the time steps that govern the passage of time. In ancient times these time steps were first simple lines on a pot dripping water and then a marker on a scale that moved according to a gear ratio. The concept of tracking time has not changed since ancient times and where water was once used as the control substance, electric current now powers the modern clocks. Without the ability to monitor and track time, control systems could not operate in the precise manner demanded by the modern era.

5. Conclusion

The control systems of the ancient world were based around the harnessing of the natural forces to regulate the processes and devices of everyday life. While the control engineers of the day were revered in an almost mythical sense, their control systems harnessed the water that was so prevalent in the ancient world to automate and measure their environment. From the earliest known steam engine that was used to entertain to the elaborate water clocks that lead the way to the modern measurement of time, the ancient control systems had a profound impact on the control systems of the modern world.

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