Chapter 3

Illustrating Feedback and Control

There is no free lunch.

Milton Friedman[1]

3.1 Introduction and Motivation

When there is a chill in the air, we feel uncomfortable and we are likely to put on some extra clothes and our body automatically reacts with shivers to increase our internal heat generation. If our environment is too hot, we sweat to extract heat from the body. This is feedback.

Typically, useful systems are complex and they derive their overall functionality from a set of different subprocesses that interact in a non-trivial way. This is the case even when the whole system serves a unique purpose. In nature this is the norm, and more and more engineered systems exhibit a similar structure and complexity.

The analysis and design of any system demands the integration of the physical understanding of the components' behavior together with control principles to achieve the overall purpose of the desired system. In design, the constraints matter most. The basic ideas underpinning the systems and control engineering approach to system design will be described in the following chapters. Here, a few examples are introduced to put the nature of feedback design into focus.

A system requires design at every level, from the scale of its smallest sub-system to the global scale involving the entire integration of all subsystems. A corresponding hierarchy of control levels, from local sub-system control to supervisory control strategies has to be designed to work seamlessly together in such a way as to achieve the system's goals and to sustain these over an extended period of time (see Chap. 10 for more details). Control cannot be an afterthought it must be an integral part of system design. Its fundamental limitations are just as essential as the perhaps more obvious physical constraints in the system. Equally control design cannot be meaningfully progressed without taking notice of the constraints imposed by the physics.

In this chapter we will illustrate the role of feedback and control to deliver purposeful behavior. Our examples are derived both from the engineered as well as the natural world.

We start with a description of a factory producing ceramic tiles. It serves as the archetypical manufacturing process, where the overall goal is reached through the execution of a sequence of discrete subprocesses. The ideas generalize to many manufacturing processes, at least in the structure of the global plant, being split into subprocesses with interconnections and interdependencies.

[1] Milton Friedman, US, Nobel Prize winning economist, 1912–2006, well-known for his contributions to consumption analysis, monetary history and theory, and stabilization policy.

P. Albertos et al., *Feedback and Control for Everyone*

Most natural and human made systems are distributed over time and space, hence the need for local measurements and local actions and a hierarchy to coordinate a global outcome. The control of large scale irrigation systems provides a good example of such a system.

The benefit of control in achieving accuracy and high repeatability are illustrated using the control of antennae for radio-astronomy. Accuracy combined with speed is the holy grail of mass manufacturing, perhaps best appreciated in the automotive industry.

Not all the control systems are so complicated. In everyday life we see how a car washing plant operates in a sequential way to (hopefully) wash, wax, rinse and dry our car. You can find many simple systems like this around us.

There are many regulatory processes in our body: the homeostasis of body temperature, chemical balances in our cells, blood and organs … Normally we are oblivious to these processes, until something goes wrong.

Finally, feedback and control play an important role in social systems.

3.2 Manufacturing Ceramic Tiles

Process and manufacturing systems are easily split into subprocesses carrying out different logically ordered operations. Often the goal is to manufacture a particular product with its desired characteristics (quality), in the most economically viable manner. This objective translates into specific targets that have to be met at each stage of the process. The ideas presented here in the context of the manufacturing of ceramic tiles apply generically to manufacturing and chemical process systems.

In a ceramic tile factory the objective is to manufacture ceramic tiles that meet the expectations of the market in terms of quality, cost, durability and purpose. The production must of course be economically viable and the production process must meet all legal constraints.

In broad terms, the process lay-out is shown in Fig. 3.1.

The following subprocesses are identified:

- *Preprocessing* of raw materials. The different natural minerals (clay, lime, sand …) are stored, pre-ground and moistened.
- *Milling*. The raw materials are ground and homogenized and mixed in the appropriate proportions, and stored in a slip tank.
- *Spray drying, and storage*. Milled and mixed material is spray dried and stored. This provides a buffer in the process.
- *Pressing*. The material goes from the slip tank to the press, where the "biscuit" is formed. Here the tile is shaped.
- *Drying*. Typically pressing is followed by drying, to reduce moisture content. Dried tiles can be stored before processing continues.
- *Glazing*. The upper surface of the tile is appropriately treated. Glazed biscuits are either stored (another internal buffer) or moved to the kiln.
- *Kiln firing*. In the kiln, the glazed biscuits are "fired". The tiles obtain their required mechanical and aesthetic properties.

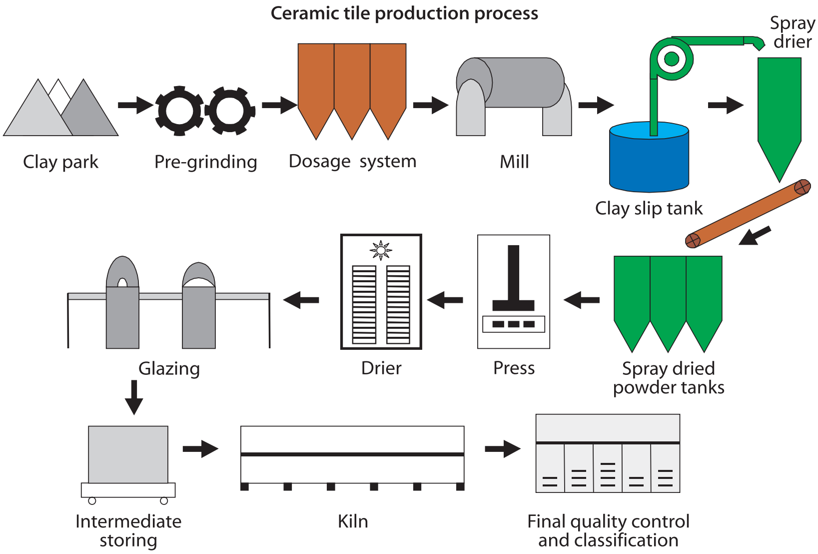

Fig. 3.1. Ceramic tile factory layout

- *Sorting and storing*. The final product, ready for delivery is stored. This is typically preceded by an inspection phase, in order to group tiles according to quality and consistency. Defective tiles are removed.

Production engineers maintain and tune the manufacturing process to get high production yields with consistent quality. The quality of the tiles depends on their dimensional accuracy, and general mechanical characteristics such as hardness and breakability, as well as their aesthetic appearance. The engineers tune the overall process to reduce costs and improve production flexibility at the same time. Cost reduction is mainly centered around saving energy, but also savings in raw materials play an important role, as well as improving the consistency. Other aspects of process tuning center around minimizing the environmental impact, reducing chemical and noise pollution.

Direct measurement of many of the important variables, like for example the mechanical properties of the tiles is difficult. Control objectives are as a consequence based on the more easily accessible process variables, which in turn affect the mechanical properties. Statistical quality control measures are used to try to minimize product variability.

Most of the final characteristics of the tiles depend on the firing process. The kiln is therefore the core of the whole production plant. The main control objective is to achieve a pre-defined temperature profile. In principle each tile should experience the same profile. This means that oven control is of critical importance. Also the conveyer belt speed determining the dwell time for the tiles in each oven section must be tightly controlled. Other variables that are maintained within specified ranges are airflow and air composition. The ventilation is of critical importance to ensure the surface finish of the tiles.

The Ceramic Kiln

A kiln is a long tunnel (can be 100 m or more) with a useable rectangular cross section of say 2 m by 0.5 m. The firing is a distributed process. The variables to be controlled are the air temperature and air pressure along the length of the tunnel. Both temperature and pressure must satisfy a specific profile to ensure tile quality. To simplify the modeling, but also remain in line with the limited freedom available in the control variables, the kiln is divided into particular sections. In some kiln sections combustion units will heat the air and the tiles. In other sections external air will be used to cool the tiles. Tiles are transported through the consecutive sections on a conveyer belt moving against the air flow. It is also important to distinguish between the upper and lower part of the oven cross section, above and below the tiles.

The kiln sections are functionally grouped in zones: pre-kiln, pre-heating, firing, forced rapid cooling, normal slow cooling and final cooling zone. The organization is presented in Fig. 3.2. The construction of the kiln, the number of sections, the distribution of the burners and fans, as well as the refractive material of the oven walls and the mechanical properties (rollers, drive speed) constrain the production possibilities, as well as the final product quality. The control goal in each zone is to maintain a temperature profile. The temperature profile is a function of the material that moves through the kiln. This is depicted in the upper part of Fig. 3.2. The control algorithm manipulates

- *the burners*, the flame temperature is controlled through fuel and air flow valves;
- *the fans* that adjust the airflow in the section, and determine the pressure and temperature in the section; and
- *the roller speed* to control the movement of the biscuits.

The control objective is to achieve the best possible tiles at the least cost within the physical limitations of the plant. Sensors[2] keep track of throughput, air temperature,

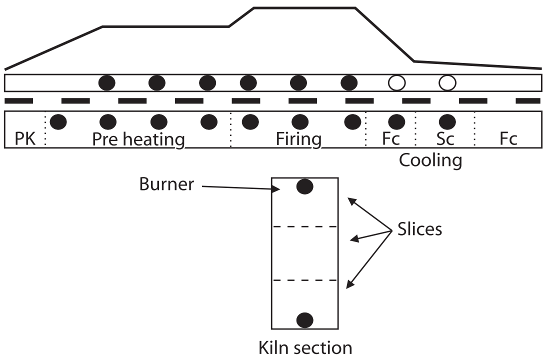

Fig. 3.2. Schematic view of a continuous kiln used to bake ceramic tiles

[2] See Sect. 9.2 about sensors and data acquisition systems.

fuel flow and airflow. The physical construction of the oven enables the control, and in order to be really effective, the construction and control design are to be coordinated.

In order to optimize the quality of the tiles at the kiln output, two kinds of control are used. A local control loop keeps the temperature profile along the kiln based on temperature sensors in the walls of the kiln. A supervisory control, rule-based, modifies the desired temperature and pressure profiles to counteract quality defects that are measured at the kiln output (Bondía et al. 1997).

The common sensing devices are thermocouples for temperature, and pressure and speed sensors. The actuators are the motors that manipulate the rollers and fan speed, and the valves that modify the flow of fuel and air.

On exiting the kiln some tile properties can be measured like dimensions, shape (flatness) and color. Mechanical strength can only be measured off-line. Typically this involves a great time delay and a destructive test, therefore this is not suitable for on-line control of the production process. A large number of variables are measured for ongoing monitoring purposes.

Kiln Control

The control goals for the kiln are to guarantee the quality of the tiles, to speed up production and minimize costs (energy, waste). To achieve these (competing) goals, the following controls are available:

- roller speed,
- temperature profile,
- pressure and ventilation profiles,
- transition between biscuit batches and
- batch packing density.

Most of these can be set for normal operational modes, and local control ensures then that the *set points* are maintained within acceptable tolerance margins. It is more difficult to create the entire collection of appropriate operational conditions. For example, some defects in the tiles may actually be traced back to the pre-processing (mill, press, dryer) and some of these can be corrected, perhaps partially, by appropriate action in the kiln. In order to minimize waste it pays to continue the production and indeed modify the operation of the kiln to compensate for the defects in as much as possible. When the kiln is operated manually, experienced operators know intuitively how to change the temperature profile or ventilation profile to drive the kiln to a new steady state to take these appropriate corrective actions. In automatic mode, however, these type of corrections are particularly difficult to carry out, and normally one has to resort to rule-based control actions, whereby the actions of *experienced* operators are *mimicked*.

The following hierarchical control structure is usually implemented

- Over the life span of the kiln the supervisory level of control continuously monitors the main variables, logs and acts on alarms, stores process data for off-line analysis and further improvement of the exploitation of the facility and an appropriate man-machine interface. Economic analysis of the product in the market place is linked

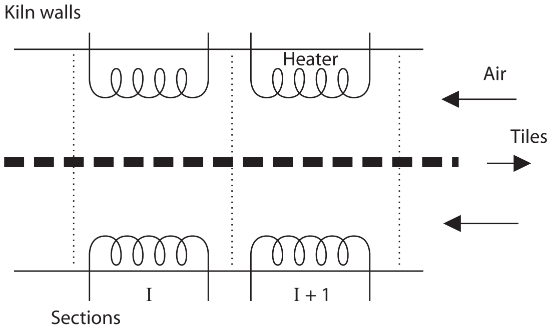

Fig. 3.3. Schematic view of the kiln: tiles move to the right and air flows to the left

with design and production, to provide the economic drivers for further investment in the production facility.

- On the production planning horizon, batch planning involves determining the kiln profiles, the packing density and scheduling of the kiln to ensure minimal transients between different production profiles. The planning provides set points for the burners (fuel flow, air flow), roller speed, and ventilation.
- Over the duration of a single production batch, quality control-based on measurements at the exit of the kiln is used to fine-tune the temperature and ventilation profiles. These changes are decided using heuristics or table look up methods.
- Over the duration of a particular batch the desired temperature profile, ventilation profile and speed profile are maintained using local controllers, which act in each of the separate kiln sections (see Fig. 3.3). The control actions are coordinated in such a manner as to maintain the section at the right set point whilst minimizing interactions with neighboring sections.
- For each actuator, a local controller provides the desired command based on their sensory input and the reference signal. The reference signals are provided from the quality control supervisory algorithm and the coordination control layer.

Producing Good Tiles

To produce quality tiles you need

- quality raw materials,
- excellent tile design,
- excellent processing units (mills, presses, kilns, …)
- skilled operators,

but you also need

- precise control units and control algorithms,
- integrated factory information,
- quality control,
- automatic process management.

3.3 Gravity-Fed Irrigation Systems

Most utilities, like electrical power generation and distribution, water harvesting, bulk transmission and distribution and gas distribution are large scale engineering systems requiring careful control in order to match supply with demand, when and where it is needed. Similar control issues arise in the control of transport networks and even the internet or telecommunication networks more generally. The challenging issues here are the geographic scale and the variety of time scales on which dynamics are important. In such applications control is invariably organized to be distributed over space as well as hierarchical to cope with the many different time scales. The example we discuss relates to the control of irrigation networks, where the implementation of distributed control schemes is a recent phenomenon. The discussion will emphasize the spatially distributed nature of the control on the fastest time scale. The issues of supervisory control responsible for scheduling, long term exploitation and (preventive) maintenance as well as alarm handling are equally challenging and important but not that different from any process control application, like the ceramic tile factory.

In Australia irrigation accounts for 70% of all fresh water usage (UNESCO 2006; The Australian Academy of Technology Science and Engineering 2002). The main civil infrastructure for irrigation consists of reservoirs for harvesting and storing water and open canals for water distribution. The distribution of water is controlled through regulating structures that can restrict the flow in the canal between virtually no flow and a maximum flow which depends on the geometry of the canal (slope, and cross section) and the available water head (potential energy) at the reservoir feeding the canal. Here we look at how large scale distribution of water powered purely by gravity can be automated with great advantage above typical manual canal operations.

When water is in ample supply, and hence a cheap commodity, there is no economic pressure to be efficient in water distribution, and one way to operate the canal infrastructure is to ensure maximum flow, which guarantees the best water availability to the users. Water distribution is then a mere scheduling problem, and there is no need for closed loop control. Scheduling, which is a form of supervisory control, is unavoidable as typically the combined flow capacity of all water outlets onto farms is about ten times the flow capacity at the top-end of the canal system. Scheduling ensures that demand is averaged out to stay below the flow capacity of the canal system and such that the water is distributed to all users in an equitable manner. When there is an over-supply of water, this water simply returns back to the natural river systems or ground water storage, and is no longer available for irrigation (in that same season). Although present manual operations are certainly not operating on this maximum flow principle, which would be maximally wasteful, present canal exploitation reportedly achieves at best between 55% to 70% water efficiency and in many places around the world no better than 50%. Moreover a four day in advance water ordering policy is enforced in most irrigation districts, which does not favor efficient irrigation on farms, as farmers have to minimize the effect of uncertain irrigation timing. About 10% to 15% of the water is wasted through seepage and evaporation (no amount of control can change anything about that of course) and about 20% to 30% is lost through outfalls or is unaccounted for (The Australian Academy of Technology Science and Engineering 2002).

Policy makers in Australia have recognized that it is important to reconsider present water practices in view of long term environmental and sustainability issues. They are providing clear economic incentives to be water efficient, both in canal exploitation and on-farm water usage. Climate change, population and industrial growth pressures compound the sustainability problem.

Irrigation efficiency, whilst maintaining the other objectives of water level regulation (which is the potential energy available for irrigating farm land) and meeting water demand is an ideal objective for closed loop control. The conflicting requirements between meeting demand and achieving water efficiency make for an interesting challenge.

In order to realize closed loop control the existing civil infrastructure has to be upgraded with an information technology infrastructure of sensors and actuators linked through a Supervisory Control And Data Acquisition (SCADA) communication network. The approach to efficient water distribution is in three stages: building the information infrastructure, extracting the data to build models for control and finally closing the loop. This infrastructure enables automated decisions to set the regulating structures such as to deliver the water, and only this water that has been requested by the farmers. A project of this kind has been ongoing in Australia from about 1998, and it has achieved pleasing outcomes with canal operations running at around 85% efficiency, achieving a high level of on-demand water delivery (more than 90% of water orders are not rescheduled) and maintaining excellent water level regulation. In addition, because the system is now more responsive, farmers have adopted irrigation schedules that are much better suited to the crop needs with additional and significant water efficiency improvements and better economic returns on-farm.

The information infrastructure underpins the entire control approach, and can support decision making on all time scales ranging from hours to years:

- On the longest time scale the main issue is sustainability: how to best use the limited renewable water resource. This involves the development of appropriate infrastructure, policy and pricing mechanisms.
- On a yearly and seasonal basis the allocation of water volumes and crop plantings/treatments are decided according to the specific economic and also environmental requirements. The existing infrastructure is maintained and upgraded.
- On a weekly basis irrigation is planned to meet needs (on this time scale the local weather forecast plays an important role), and bulk distribution is scheduled at this point.
- On a daily time scale water is scheduled into the down-stream end of the canal system.
- On an hourly time scale individual canal sections under control react.
- On a minute time scale, water levels and flow regime are regulated and hardware and variables of interest are monitored to enable preventive maintenance and to ensure a graceful degradation in performance when sensors, actuators, or the radio network develop failures.

Figure 3.4 provides a picture of the information infrastructure hardware put in place in Victoria, Australia in juxtaposition with the old mainly manually operated technology that it is replacing. At regulation points, water levels are measured and water flow

Fig. 3.4. Radio networked actuator/sensors for irrigation, developed in Australia by Rubicon Systems Australia, in collaboration with the University of Melbourne (**c**) replacing the old manually operated infrastructure (**a–b**)

is inferred. Through communication with their peers over the entire network, a real time water balance can be deduced. Besides these main variables, a host of other variables is measured for maintenance and operational purposes (like battery levels, solar radiation, sensor calibration, etc). A schematic of the radio network, which allows for peer-to-peer and broadcasting, is represented in Fig. 3.6. Any regulator, with its associated actuators, and sensors has an internet address and can communicate via the radio network with any other regulator in the network. Most communications are based on an exception protocol, a communication is initiated only when something interesting happens. Regular polling is also performed to interrogate (parts of) the entire system to establish health checks. Broadcasts are performed to facility software upgrades, coordination and general management of the networked resources.

Data derived from the sensors and actuators is used with appropriate model parameter estimation and system identification techniques (Weyer 2001; Eurén and Weyer 2007) to develop simple models that relate control actions (at up and down stream regulators) to water level (and flows) on the basis of a single pool, that is a stretch of canal between two regulating structures. The emphasis is on simplicity, as irrigation systems are large scale and hence the models must be able to grow with the system. To get an appreciation of size consider the Goulburn Murray Water district, with more than 6 000 km of irrigation canal, more than 20 000 customers and 5 000 regulating structures spread over an area of 68 000 km^2. (There are much larger irrigation systems.)

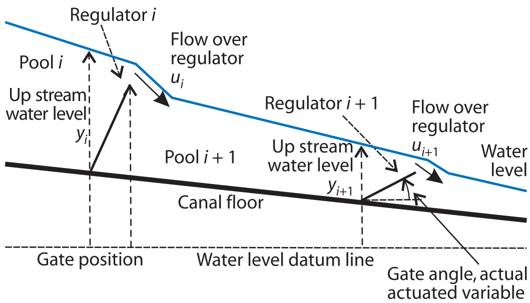

Fig. 3.5. In-line canal system, a series of regulators and pools (sections of canal between regulators)

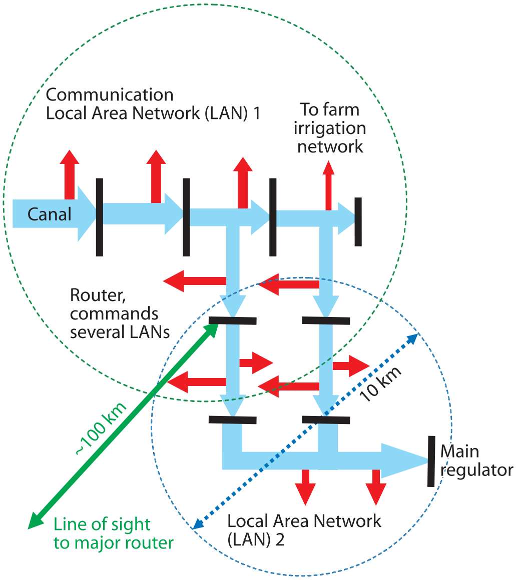

Fig. 3.6. Diagram of information infrastructure and radio network for an irrigation canal

To focus the ideas, we consider the smallest time scales and consider a simple canal, with a number of consecutive pools like in Fig. 3.5. A very simple model could be:

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Change in pool volume = (in flow - out flow) X time_interval
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It only captures water storage. This is a little too simple, and see for example Weyer (2001) and Eurén and Weyer (2007) for more comprehensive models and discussion. Nevertheless, it is enough to get some appreciation for the problem. The canal model is then the collection of all the pool models combined with the models for the regulators, all of which are derived from the measurements, and maintained in a central data base.

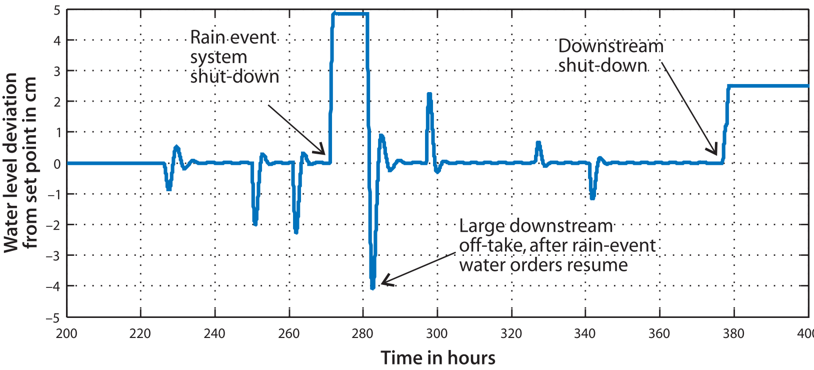

Fig. 3.7. Control response to a significant rain event

The control objective is to ensure that the water levels are regulated at the desired levels whilst the control inputs are constrained to be within their physical capacity limits (between open and close). All of this despite significant disturbances in the form of water off-takes, evaporation and seepage. Moreover it is important that the demand placed on the radio communication is limited and that the irrigation network copes with inevitable communication errors, as well as hardware failures in sensors and/or actuators.

The control objective (no losses, water level regulation, meeting demand) is achieved using a two staged approach. When a water order is placed (e.g. through the internet), the central node verifies against a global model of the system if this water order can be delivered as requested within the system capacity. It also checks prices, and water allocation rights, but that is irrelevant for the control process. Here the use of demand forecast including a weather forecast can be used to advantage to manage the irrigation district. If the water order can be delivered then the central node informs the canal regulators and the on-farm off-take gate of the requested water order. The flow is then implemented and the local controllers ensure that the water level is maintained, despite the imposed flow changes.

A typical response of the controlled system, in a week of operations on a particular pool, is presented in Fig. 3.7. The figure shows the quality of the set point regulation (deviation measured in cm). Under manual operation, the deviation from the desired level was considered adequate if the water level was within 25 cm of the desired level. The rain event, a serious disturbance, causes a shut down of the system as all irrigators on the channel stop irrigating. After the short rain event major water orders are resumed. At the end the effect of saturation can be seen, as the gates close in view of no down-stream demand.

Similarly in Fig. 3.8, a single day of operations is displayed, and both flow and level responses are presented. Notice the enormous flow variation over the one day period. This demonstrates the flexibility of the automated system.

Field trials over a number of seasons have demonstrated that the automated system, called Total Channel Control^{TM}, is very effective (Cantoni et al. 2007; Mareels

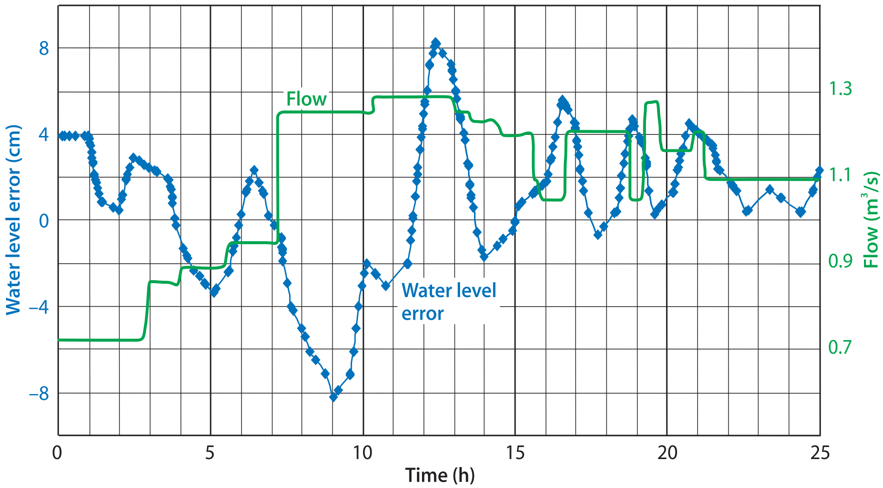

Fig. 3.8. Control response to large flow variations

et al. 2005). The automated system brings a number of side benefits that are not to be underestimated:

- more precise accounting of water flows and water volumes (order of magnitude improvement in flow metering accuracy),
- leak detection (water balances can be maintained per pool, pools requiring maintenance are easily identified),
- redundancy in data and sensor hardware can be used to reconfigure control action in case of hardware failures, ensuring a very graceful degradation of system performance under hardware failures.
- water ordering flexibility, which leads to better on-farm water efficiency.

Further developments include

- integration of weather forecast into the feedforward in order to improve the reaction to rain events, and manage system wide storage and flow conditions,
- flood mitigation (this is essentially reservoir control, using the canal system to disperse excess water),
- integration with river control, optimizing the use of the water resource.

The final goal being the real-time closed-loop management of water resources on the scale of an entire water catchment area (Mareels et al. 2005). This appears entirely feasible, and would go a long way towards the management challenge raised in the UNESCO World Water Report 2003, repeated in the 2006 and 2009 editions of the report (UNESCO 2006; 2009), all of which talk about a water management crisis in the world.

Best Use of Water

Water is a limited renewable resource, in need of (better) management that requires

- accurate information about resource availability,
- clear management policies, appropriately prioritized,
- substantial civil infrastructure (reservoirs, canals, pipes, valves),

but also

- real time water (level and flow) measurements,
- demand measurement and/or forecasts, and short term weather forecasts,
- wireless communication network,
- process models, these can be derived from the measurements,
- control design enabling in conjunction with policy, optimal exploitation of available resources within physical constraints.

3.4 Servo Design for Antennae for Radio Astronomy

Antennae are everywhere: they capture particular radio waves, that have been encoded to carry information. Often radio waves are directional and antennae orientation relative to radio wave is critical for a good reception, and subsequent information extraction.

Large antennae as for example used in radio astronomy and satellite tracking applications achieve the alignment between radio waves and antennae structure through positioning the antennae surface accurately in both elevation and azimuth. The precision with which these angles have to be achieved in modern radio astronomy is extremely high (errors are measured in arcsec, of which there are 3 600 in a degree or 1 296 000 in a full circle; an arcsec is approximately 4.85 microradian).

In the case of radio astronomy the reference trajectories for the elevation $\theta^{\mathrm{r}}(t)$ and azimuth $\phi^{\mathrm{r}}(t)$ angles that describe the path of the object(s) to be tracked (or points of the sky to be explored) are typically provided by the operators of the facility to the control unit as an ordered list of timed reference angles (time series) in a table:

$$(t_k, \theta_k^{\mathrm{r}}, \phi_k^{\mathrm{r}}) \quad \text{for } k = 0, 1, 2, \ldots$$

where t_k are the specified times, θ_k^{r} the required elevation angle and ϕ_k^{r} the required azimuth angle at that point in time. This table is to be interpolated over time to arrive at the actual reference angle as a function of time, (the angle has to be a continuous function of time). For example using linear interpolation (this is too simple in general, but used here to illustrate the idea) and with the above list the reference for the elevation angle becomes the following piece wise linear function of time, as displayed in Fig. 3.9.

The servo control problem is to ensure that the actual pointing angle of the antennae dishes follow the prescribed path with great accuracy despite disturbances such as a variable wind load (Evans et al. 2001). This is quite challenging because typically the drive system as well as the antenna structure exhibit multiple, poorly damped, resonant modes. Moreover, there is a wide variety of reference trajectories.[3]

[3] To learn about system frequency properties and resonances go to Sect. 5.7.2.

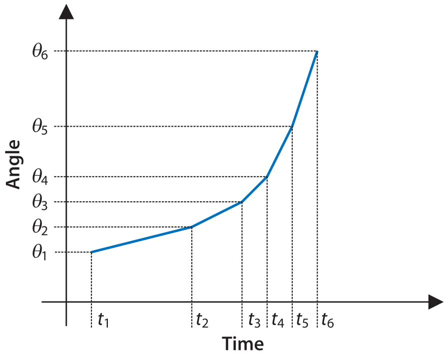

Fig. 3.9. Piece-wise linear interpolation of data points

Fig. 3.10. Some of the antennae in the Australia Telescope Compact Array, Culgoora, New South Wales, Australia (© Commonwealth Scientific and Industrial Research Organisation, CSIRO)

Figure 3.10 displays some of the antennae of the Australia Telescope Compact Array (ATCA); for more information visit *http://wwwnar.atnf.csiro.au/*. The antennae in this array were used for some of the experimental results described below. They have a diameter of about 22 m and weigh about 60 tons.

The control of large fully steerable antennae has been the subject of practical and theoretical studies for over five decades. The actuation and sensing subsystems pose significant challenges and determine to a large extent the limits of accuracy that feedback design may achieve.

The key mechanical design questions pertain to the maximization of the structural resonances (Wilson 1969) whilst trying to keep the cost of the structure low. The trade-off is to achieve a high mechanical stiffness with a low overall weight, so the antenna can move faster and work harder for the radio astronomer. The lowest structural resonance frequency must be sufficiently high so that normal wind conditions cannot induce vibrations that render the antennae useless. The antenna is very much a large sail. Also, the lowest structural resonance frequency should be larger than the fastest angular velocity of the reference trajectories that are to be tracked with precision, otherwise the references would excite these resonances[4].

Most of the wind energy is found below 0.5 Hz. See Fig. 3.11.

The overall control design is greatly assisted by using high gear ratios (gear ratios of the order of 40 000 : 1 are not uncommon), such that the entire inertia is dominated by the drive motor's rotor rather than the wind loaded dish. This means that accurate positioning of the rotor of the drive motor implies accurate positioning of the antenna dish provided of course that the structural resonances are not excited. The drive train resonances can be actively dampened using feedback control.

The backlash[5] (see Fig. 3.12) in large gear trains is unavoidably large. Backlash is due to a necessary gap between the gear teeth of the driven and driving gear. When the motor force reverses, there is a period of time that the teeth do not mesh; so the motor moves but the driven gear does not move until such time the gear teeth mesh again. Nevertheless, the negative effect of the backlash on the tracking accuracy can essentially be eliminated

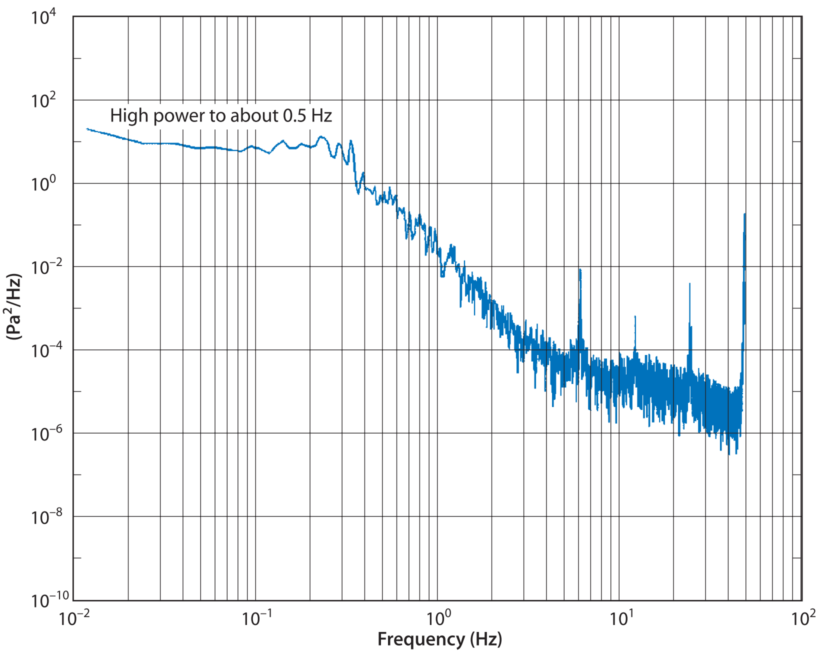

Fig. 3.11. A typical power spectrum for wind load on a large antenna structure

[4] See Sect. 4.3 for a definition of power spectrum.

[5] Backlash is a non-linear effect, which appears whenever there is a gap between some mechanically coupled components.

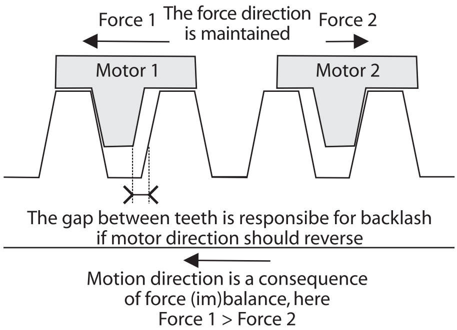

Fig. 3.12. Backlash and backlash elimination by dual drives in large gear trains

through the use of dual drive motors that work in a torque-share-bias mode. At each motor the force direction is maintained, so that one motor drives, whilst the other one is actively braking, as illustrated. Because the motor forces never reverse direction, the gear teeth mesh at all times, and the effect of backlash is all but eliminated[6]. All the antennae used in the experimental results below were built along these lines. The main limiting factor remaining in the drive train is stiction, which is a consequence of the large mass supported by the gear train. Stiction fundamentally limits how slow the antennae can move. The motor drive must provide a minimum imbalance before the motor forces induce motion. Once motion starts, the friction force drops dramatically creating a speed up effect being balanced by a reduction in force and consequently stiction takes over, the process repeating itself creates a limit cycle[7]. In the Australia Antenna Telescope stiction induced limit cycles consume 50% of the position error budget.

To achieve accurate tracking, precision sensors for the actual pointing angles of the antennae are required. Measuring the pointing angle of a large antenna is non-trivial. Recent antenna designs employ high accuracy position sensors, like 22 bit angle encoders that resolve angle position to within 0.3 seconds of arc.

The resonance frequencies of the antenna structure depend on the actual dish position, a low elevation angle will result in a lower resonance frequency. This is illustrated in Fig. 3.13. It shows how the resonance frequencies vary with the elevation angle in one of the Australia Telescope antennae. More generally, the resonance frequencies are a function of the geometry of the antennae, and every time the structure is updated or changed these resonances change as well. This implies that the control strategy must be able to cope with these variations. In a general setting, that means different process behavior in different modes of operation, requiring different control actions.

Following the experience with the Australia Telescope (Evans et al. 2001) several alternative servo designs were completed and tested on different large antennae. Under the assumption that the gear train has been properly designed to minimize stiction

[6] Nature makes extensive use of such arrangements. Two components of opposing effect are present at all times and their balance determines which effect dominates.

[7] A limit cycle implies maintained oscillations around an equilibrium point. This is typical in forced oscillators and it only appears if the system behavior is non-linear.

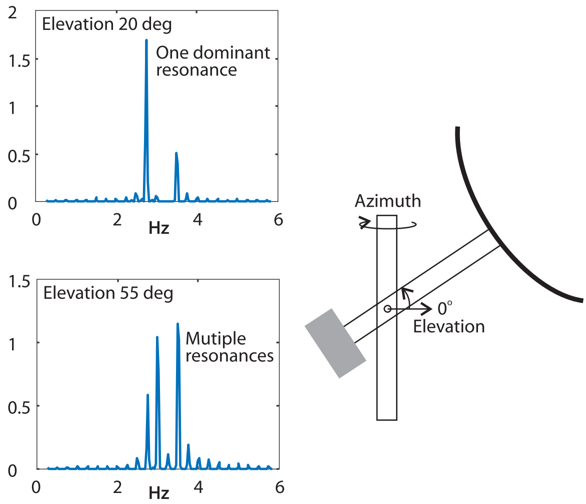

Fig. 3.13. A low elevation angle implies a lower resonance frequency. Observe the multiplicity of resonances as an indication of the complexity of these antennae structures

and that a back lash compensation drive scheme is employed, a cost effective servo design consists of four hierarchically organized feedback loops (see Chap. 8):

1. a very fast, high gain, current feedback loop, such that from a tracking perspective the motor drive is a pure torque source. This loop operates up to about 100 Hz.
2. surrounded by a medium bandwidth[8] velocity feedback loop, which dampens the main gear resonances. This loop is effective to about 10 Hz.
3. enclosed by a low bandwidth position tracking loop, which ensures set point regulation whilst avoiding resonance vibrations. This loop is active to just under 2 Hz, just below the slowest resonance frequency. (Notice that set point regulation is not enough, as the reference trajectory is not a constant, but a function of time!)
4. finally, the slowest outer loop minimizes the remaining tracking error. This loop effectively compensates for the variation in the resonance modes by adjusting a feed forward gain from the reference trajectory. Moreover it ensures that arbitrary reference trajectories, not just constant functions of time, can be followed with acceptable tracking error. It is called an *adaptive loop*. This loop operates to about 1 Hz, about twice the typical bandwidth of the wind disturbance, and well above the required rate for the reference signals (stars do not move that fast across the sky!).

Such a control structure, is called a *cascade*. The idea is illustrated in Fig. 3.14. The above discussion focuses on the local control objective for the radio antennae. There

[8] Formally, the bandwidth refers to the range of frequencies a signal is composed of. In colloquial terms, the larger the bandwidth the faster the signal changes. If referred to a process, for instance a loudspeaker, its bandwidth denotes the range of sound frequencies it reproduces with good fidelity.

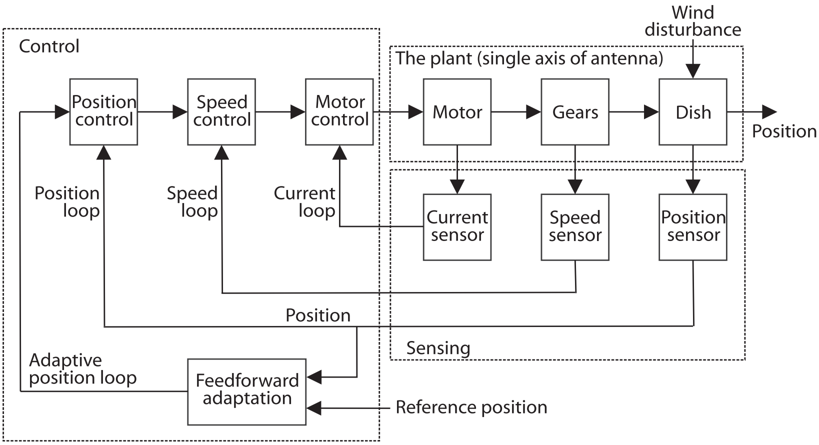

Fig. 3.14. The servo mechanism's control structure: four cascaded loops. The external input signals are the reference position and the wind disturbance

are however other aspects that need to be catered for in any operational control system for such antennae:

- Scheduling of the experiments, this provides the reference trajectories for all the objects to be tracked, as well as the start and stop times for each of these.
- Supervisory control, to start and stop the operation of the antennae, as well as interrupting normal operations and stowing the antenna when the wind load is outside the antenna's operational envelope or when faults are detected in the drive or sensor units.
- Tracking mode, as described above, where the antenna tracks a given reference over a set period of time.

Observing the Sky

Watching space requires precision instrumentation and infrastructure:

- large antennae spread over a large geographic area (the radio telescope),
- precision communication between antennae to coordinate these,
- skilled operators,
- appropriate and precisely surveyed locations (no radio interference),
- excellent computing facilities,

and the antennae themselves must be complemented with

- precision mechanics (drive train),
- precision instrumentation, inter alia measuring position,
- dynamic models of antenna behavior and wind load conditions,
- control design to track a large range of signals (stars) under a wide variety of wind conditions (robust control).

3.5 Simple Automata

There are many common processes where the overall behavior can be adequately captured using only binary valued signals (on/off, stop/go, open/close). In such circumstances it is often possible to implement the control also only using binary valued signals. An important class of such systems is called the *automata*[9]. Examples range from a simple vending machines to the complexity of a digital computer.

Just to illustrate the idea, let us consider a car washing system, as represented in Fig. 3.15.

The system operation starts when a coin or a token is introduced in the machine slot. The sensor *M* turns on the green light *LV*. The system is ready to operate as soon as the user clicks on *P*. This action will turn on motor *C1*. The belt will move the car until it reaches the positions sensed by *S0*. This event will start the motor *C2*, activating the displacement of the attached belt and turn off the green light. The car enters the washing area. Its presence is detected by the sensor *S1*. The car is then soaked with soapy water dispensed through the pump *AJ*. After a predefined time *t1* the front washing rollers start to work (motor *MR1*).

The sensor *S2* will detect the approach of the car and will start the following section, activating the belt *C3*. Once the car is in the new section, the green light is turned on allowing the entrance of a new car into the car wash. Sensors W_i are placed at the exit.

A similar process is repeated in the rinsing and drying sections.

A number of additional binary signals verify the overall operation to prevent accidents from occurring. In particular, there is always an emergency stop button that the user may activate if something untoward is happening.

Factory automation is often much like this example, only more complex. Home automation like in a dish washer or washing machine is also of this form.

Process Automation

Factory and process automation are common.

Even complex automation can often be restricted to binary signals, for analysis, design and implementation.

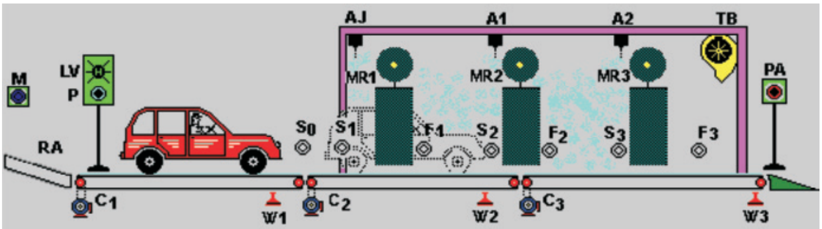

Fig. 3.15. The automated operation of a car wash

[9] Automaton: a device or machine designed to follow automatically a predetermined sequence of operations. The modern analysis of automata can be traced back to John von Neumann and Alan Turing.

3.6 Homeostasis

Homeostasis is a term used in the context of biology, with reference to maintaining the same desirable condition. Indeed, life as we know it depends on the existence of a well-regulated chemical and physical environment inside the cells. This chemical and physical balance is maintained through active feedback mechanisms. In most examples of homeostasis we can distinguish all the functions we find in an engineered control application: sensing, communication, signal processing and actuation. In the body the control sub-system is an integral part of our body to the extent that usually we are not consciously aware of this activity, apart from those times when we become sick. There is a huge variety of interacting feedback loops in the human body. Feedback is at the core of such vital things as our body temperature, the amount of oxygen in our blood, the amount of glucose (the fuel we use in our cells) and so on. There is at least one feedback loop for almost any particular chemical that exists in any of our cells.

It is not surprising to find these feedback loops well organized according in a hierarchy of feedback loops, just as in engineered systems. There are local, fast acting, control loops that maintain certain variables within acceptable margins. There are supervisory control actions that monitor vital symptoms and kick in secondary feedback mechanisms in case of major trauma (like bleeding, dehydration, overheating) or abnormal conditions due to failures in sensing or actuation, or because of bacterial or viral invasions. Finally, there is the conscious decision level, where we decide things like what to eat or drink, or when to exercise or go to sleep all of which have a major impact on our body functions and require specific intervention by all the lower level control loops in order to deliver homeostasis.

By way of example we consider somewhat superficially the condition of diabetes mellitus, when glucose regulation fails. This section is adopted from Santoso and Mareels (2002) and Santoso (2003). The word diabetes is derived from Greek and means as much

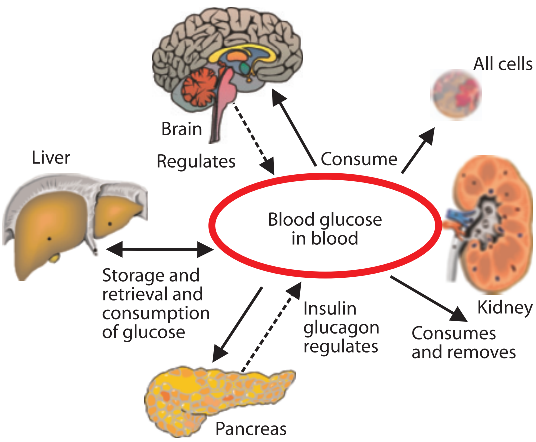

Fig. 3.16. Glucose regulation in the human body

as *passing fluid* and mellitus is Latin for *honey-sweet*. The word diabetes was coined in AD 130 by Aretaios of Cappadocia in his book about the disease. Excessive and sweet urine is indeed a characteristic of having too much glucose in the blood and no appropriate insulin mechanism to control it, which triggers a secondary feedback through the kidneys to remove the excess glucose from the bloodstream. The first reference to diabetes is found in Egyptian literature from 1550 BC. Other early references are found in Chinese, Japanese and Indian writings. The disease did not receive an effective treatment till the discovery of the insulin treatment by Banting and Collip in 1922.

Glucose is the most important fuel in the human body. All our organs, not to mention our brain require the right glucose supply to function properly. Glucose is transported to the cells via the bloodstream. Maintaining the right amount of glucose in the blood stream

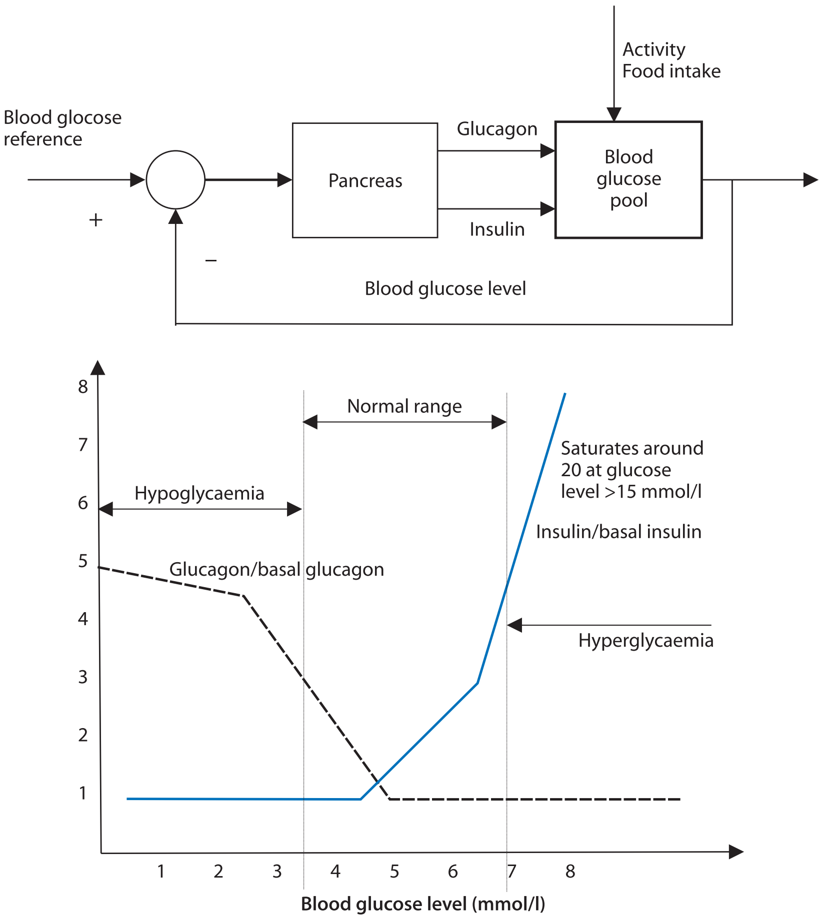

Fig. 3.17. Insulin and glucagon production with respect to glucose levels in the blood of a healthy person

is achieved through an intricate feedback. Too little glucose (hypoglycaemia[10]) and our body stops functioning normally (loose consciousness for example), and too much glucose (hyperglycaemia) leads to the awful late-onset complications diabetes is feared for (especially when our cells are exposed to it over prolonged periods of time).

The supply of glucose is derived from our food, which in our digestive system is remanufactured into glucose $C_6H_{12}O_6$. The release and storage of glucose is regulated through hormones (see Fig. 3.16). The brain acts as the main controller and the liver acts as the main glucose storage. Glucose enters the cells through their surface requiring a glucose concentration gradient being higher in blood than inside the cell. *Insulin*, a hormone produced in the pancreas, is responsible for re-moving glucose from the bloodstream. It acts on the cell's membrane allowing the flow of glucose as well as storing any excess glucose in the liver (and some gets stored inside our muscle tissues as well) in the form of glycogen (a polymer derived from glucose) for later use. Extra glucose is flushed out in urine through the action of the kidneys.

The pancreas also produces the hormone *glucagon*, regulating the amount of glycogen. If more energy is required, glycogen is converted back into glucose and released into the bloodstream. The pancreas maintains a base level of insulin and glucagon in the bloodstream, regardless of blood glucose levels (remember the dual drive in the antenna Sect. 3.4).

The pancreas increases the insulin in the bloodstream when the glucose levels rise above 5 mmol/l and similarly increases the glucagons level when blood glucose level drop below 4 mmol/l (see Fig. 3.17). Physical or mental activity also influence the glucose level, mainly determined by the intake of food. In healthy individuals blood glucose is maintained through this mechanism within the range of 3.5 to 7 mmol/l. Less than 3.5 mmol/l is considered hypoglycaemic and more than 10 mmol/l is considered hyperglycaemic. In a healthy individual, the level of glucose varies with physical activity and food intake. A typical 24-hour record of blood glucose is displayed in Fig. 3.18.

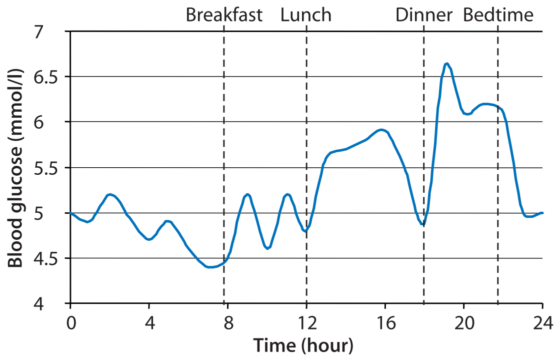

Fig. 3.18. A blood glucose signal of a healthy person

[10]This is derived from the Greek, glykys = sweet and haima = blood and hypo = below.

When suffering from Type I Diabetes Mellitus, the pancreas does not produce enough insulin and the presently prevailing treatment consists in providing insulin through subcutaneous injections in response to measured blood glucose levels, expected food intake (more food requires more insulin) and levels of activity (more activity requires less insulin).

Compared to a normally functioning pancreas, a regime of regular subcutaneous injections (see Fig. 3.19) is at a serious disadvantage to regulate glucose. The pancreas monitors the blood glucose level continuously, in closed loop, and applies near instantaneous feedback. In the injection regime, the glucose level is in open loop behavior for extended periods of time (between injections). A typical rule-based control algorithm, as implemented by the patients, on how to decide how much insulin to inject is graphically represented in Fig. 3.20.

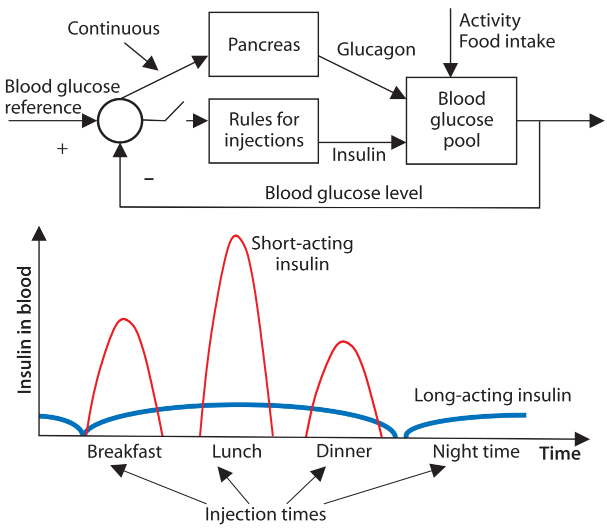

Fig. 3.19. Insulin injection regime using slow and fast acting insulin preparations

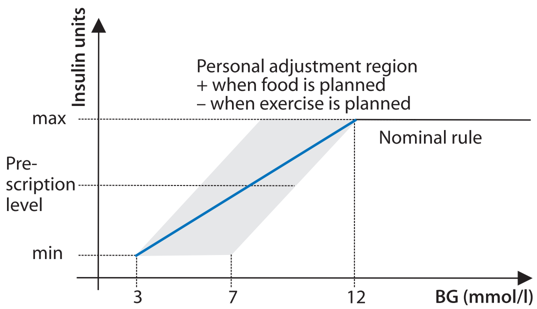

Fig. 3.20. Insulin injection rule, showing how an individual may vary the recommended dosage of slow and/or fast acting insulin

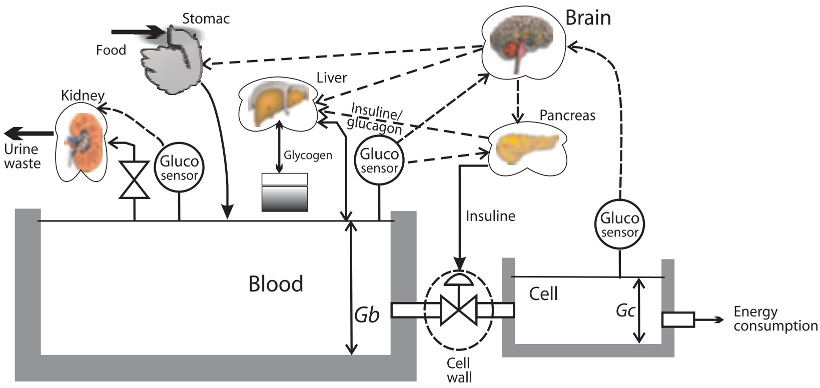

Fig. 3.21. Glucose regulation

Figure 3.21 illustrates the glucose regulation. The main goal is to regulate the level of glucose inside the cells, *Gc*, and this level depends on the cell's workload. The brain (and the sympatic nervous system acting as the central controller) receives demands from the cells as well as information about the glucose level in the bloodstream, *Gb*. This glucose level is also sensed by the pancreas to determine the production of insulin or glucagon. The kidney has a rough sensor of the glucose level (by osmosis) to extract excess glucose. Under normal operation, any time food is processed, the level of glucose increases, the pancreas generates insulin and glucose starts to be stored as glycogen in the liver as well as muscles. This glycogen will be used to regenerate glucose in periods without food intake, or whenever extra energy is required.

The cell membrane can be considered as a one-way valve (see actuators in Chap. 9). The insulin acts as to open the valve allowing glucose into the cells. Diabetes is here illustrated as an inability to open the valve.

The actual system is much more complex. A more careful consideration of glucose regulation will reveal a plethora of different feedback loops organized in a hierarchical structure.

Homeostasis and Feedback

Our body relies on feedback. From motor activities, such as standing, walking, grasping, reading a book, to any other human conscious and unconscious activity (e.g. metabolic) feedback plays a fundamental role.

3.7 Social Systems

Feedback plays an important role in our society, recall for example the teacher-student example from the Introduction, see also Fig. 1.1. Feedback plays a role at the level of an individual, but also at the level of a collection of people. In a societal context feedback, and its analysis, always experiences a serious problem: what information is actually measured? Many social variables of interest are only expressed in a qualitative and often in purely subjective way (Barbera and Albertos 1994). This makes it difficult to compare and understand social behavior: even when seemingly identical information is available, the (feedback) action may be completely different. Some important variables are easily measured, like age, salary, unemployment rate. In those instances, the measuring unit is clear, and it is relatively easy to obtain reliable data. But concepts such as, what is aesthetically pleasing, what is humor, attitude, sadness or even concentration are subjective and only understood at a qualitative level. In some cases we may be able to order a concept like good, better and best to compare different observations, but in other instances even that may be problematic, like an appreciation of food.

In a social system it is common to have a mixture of signals, some quantitative, some qualitative. This does not preclude a modeling approach. Relationships between the variables can lead to a valid understanding of the behavior of the system of interest. Models in this case will need to relate qualitative and quantitative signals and most likely will themselves be qualitative in nature. This does not invalidate their usefulness. After all, we all construct such models (somewhere in our brains) all the time.

Let us consider an example of human-with-environment interaction from a control system point of view.

From a control engineering stand-point, the human-environment interaction has all the ingredients that make a closed-loop system. There is sensing, communication, controlled behavior, decision processes, goals to achieve, disturbances to be rejected and so on. Can the systems engineering formalism be used as an advantage to probe this system? With Wiener (1961), we will accept on face value that cybernetics or systems engineering indeed provides a framework that can be used, and perhaps should be used, in the psychological analysis of the human-environment system.

The comparison between the behavior in a human-environment interaction system and the behavior of an engineered control systems will allow one to

- better understand the cognitive processes and their implications,
- develop new theoretical ideas and formulate new hypotheses about psychological processes based on analogy with the easier understood, simpler engineered systems,
- apply control strategies to this challenging field,
- highlight differences and similarities between different psychological approaches.

In the human-environment system, purposeful human behavior requires the formulation of goals, the implementation of actions to reach them, and the ability to evaluate the attainment of these goals. There is an obvious parallel with a control system (Barbera and Albertos 1996). The whole point of a control system is to achieve a control objective (regulate glucose, produce a ceramic tile, point an antenna or deliver irrigation water). There must be sensors that observe whether or not the control objective has been realized. At the core of the control system is a control law or algorithm to compute from the observations which actions the actuators have to take in order to move towards the realization of the control objective. That the analogy is complete must not come as a surprise. Indeed we may well argue that it is our own experience that has dictated the structure of our engineered control loops.

In human behavior there is often a multiplicity of goals, often conflicting goals that guide the behavior at any one point in time. The goals are dynamic, and influenced by the environment. Through our senses, our cognitive processes distill information about both our own actions and internal processes, and the environment. We constantly form some model that enables us to decide on the next actions to take. The model is adapted as new information comes available, and our intentions and our implemented actions are adjusted accordingly. This is really a complex system.

Intentions of course do not always lead to actions. An intention is a necessary but not a sufficient condition to act (Kuhl and Beckman 1992). This level of complexity and sophistication is not often found in engineered control systems, or biological homeostasis. Nevertheless, as control system complexity increases the control system is organized in a hierarchical way. Under such circumstances it is not inconceivable that a local control output, which would normally result in the next actuator action, is not implemented and instead a higher level controller switches in a different command. This is very much like the intention-action model commonly understood in human behavior. As intentions are generated by the model, their enactment is mediated by

- personal perception on how the action may lead to personal goal attainment,
- personal perception on how the action will be judged by the environment, and contribute to the goals valued by the community,
- personal value judgment, which allows one to construct a partial ordering of all intentions and possible alternative actions (Barbera and Albertos 1996).

Actions are neither instantaneously, nor univocally determined by stimuli. Moreover, even under similar external conditions, actions will show great variability across a population of individuals, as each individual will bring a totally different world model to the present observations. This world model is determined by the total past experience of this individual as well as its genetic (memory) make-up.

The idea that emotions are fundamental to any motivational analysis is shared by many psychologists (Zajonc 1984). Emotions are an integral part of our own world model. They are the result of (our personal) processing of the past, comprising all the external inputs, our internal reasoning, all our performed actions, and so on. In this sense our present emotions are seen to be a part of our internal *state*.

The similarities between psychological variables and those in a basic control loop are shown in Fig. 3.22.

These psychological variables are difficult to quantify. Accordingly there is much research and development effort going into trying to correlate these variables with neuronal levels of activity, using for example functional magnetic resonance imaging techniques. Other numerical models are based on carefully crafted tests. Notwithstanding, these variables are often more accurately and more sensibly captured using language, or perhaps using ideas from probability theory or fuzzy set theory (as a tool for approximated knowledge representation). These approaches provide a suitable methodology to capture subjective meaning, which is quite difficult to achieve with purely quantitative procedures.

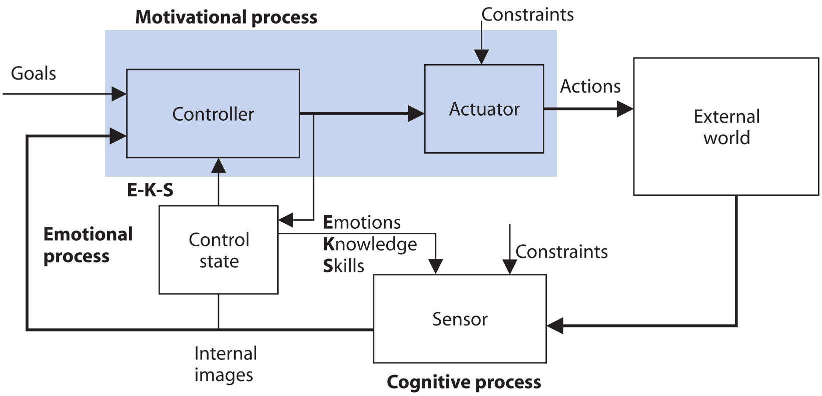

Fig. 3.22. Psychological processes

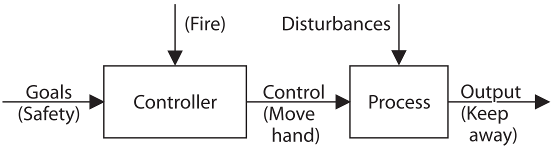

Fig. 3.23. Open-loop control

3.7.1 Simple Control Structures

Let us consider some basic control structures and see how they are relevant in motivational processes (Barbera and Albertos 1996).

Open-loop control. A system without feedback operates in open loop. Figure 3.23 illustrates this.

Some psychological processes referred to as involuntary processes, or reflexes fall into this category. Examples include the celebrated experiments by Pavlov[11], or the reflex we execute when our hand comes in contact with fire or extreme heat (variables shown in brackets in Fig. 3.23). In this case, our actions are not mediated by volition and they are highly repeatable. The trigger for the reflex may be based on feedback, but the action itself is played out without the intervention of further feedback, and the reflex action occurs in open loop.

Closed-loop control. Some processes that are considered as instinctive, but of a more elaborated nature than a pure reflex, are of this type. For example, when hungry, a baby searches for its mother's breast to feed. As the initial objective is achieved, and milk starts to flow, the baby's goal oriented behavior changes to obtaining enough milk. Its

[11] Ivan Pavlov, Russian Nobel Prize winner, 1849–1936, famous for his study of conditioned reflexes. His work prepared the way for the science of behavior.

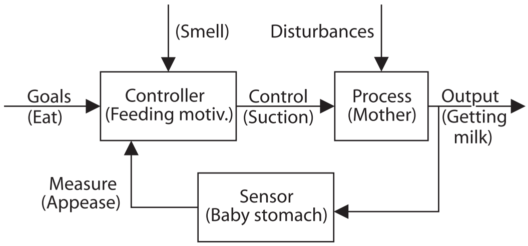

Fig. 3.24. Closed-loop control

suction action will decrease as the hunger is stilled. The feedback in the process is obvious, suction intensity depends on a direct comparison between the goal and the obtained result. Once satisfied, food loses its priority and immediate value and the baby's behavior focuses on something else.

The generic structure is shown in Fig. 3.24. The sensor block in the feedback path executes a relatively complex cognitive process that from the sensory inputs (touch, smell, taste) and responses from the digestive system determines the baby's need for further feeding. This is then translated into motor control to obtain the necessary milk.

Most motivational processes have this closed-loop structure. In particular all those involving volition. The basic characteristic is that action is determined by a comparison between the desired goal and the present state, as determined through our senses.

In applied psychology, it is well-known that feedback plays an important role in successful dieting. The mere goal or need to lose weight rarely results in successful weight loss. Clearly first the need must be established, in that the person must be convinced that there is a need to loose weight. The drive to maintain the diet and its success over time however depends mainly on continuous feedback about progress. As each person reacts differently, feedback must take on different forms. For some peer pressure and regular public *weighing* sessions are essential. Others only need regular self-feedback.

Feedforward control. When disturbances can be measured, predicted or effectively estimated, control can take pre-emptive action to counteract them. Much of our behavior is based on our ability to foresee circumstances. For example, driving a car is almost entirely achieved through feedforward control with little feedback actions required.

In applied psychology effective treatments to give up smoking or other addictions, feed forward plays an important role. According to the Action Control Theory (Kuhl and Beckman 1992), it is important to estimate future disturbances and act on these, either to eliminate these circumstances, or to provide strategies to deal with these. For example it is much harder to give up smoking when constantly exposed to a smoking environment. In such circumstances, effective self regulatory strategies have to be developed to reach the goal of quitting. The use of medication to keep the addiction in check may be essential. Feedback plays an important role too. People feel rewarded and maintain their focus when they have successfully dealt with a difficult situation, like having a meal with close, smoking friends. It is important to prepare for such

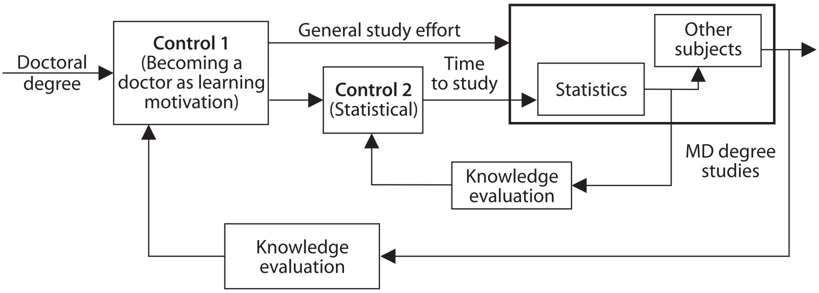

Fig. 3.25. Cascade control: Getting the doctor of medicine (MD) degree

situations and schedule them carefully if at all feasible. These are some of the feedforward strategies that can be put in place.

Cascade Control. Another typical control structure is the use of cascaded control loops, such as encountered in the antenna tracking problem, where four cascaded loops are used to achieve acceptable antenna servo behavior. In general, an inner control loop regulates an internal variable in order to simplify the control actions to be taken in the outer loop, where the actual control objective is achieved. Feedback simplifies the overall behavior, and this is exploited in the cascade structure. The idea is illustrated in Fig. 3.25, where it models the behavior of achieving a medical degree.

The ultimate goal is to become a medical practitioner and to meet this goal one must complete the university studies leading to the bachelor of medicine. The curriculum prescribes a subject in statistics. This results in a sub-behavior in which the required statistical knowledge is assimilated as a matter of completing the medical training. For many, the entire motivation to complete the subject is completely divorced from the subject matter, and entirely driven by the end goal.

As before, the control loop blocks in Fig. 3.25 refer to cognitive processes.

Selective or hybrid control. When control must pursue multiple and perhaps inconsistent goals, selection or hybrid control plays a role. The word hybrid here refers to the mixture of logic or discrete valued signals (like yes or no, or true and false) and analogue signals. As long as goals do not conflict, a single objective that combines all the goals in some meaningful way can be pursued. When goals do conflict we may resolve this conflict by making a choice, or by prioritizing the goals. For instance, we may be motivated to be very fit and exercise in the gym to achieve this purpose. However fitness and gym exercises become irrelevant when the doctor prescribes complete rest because our body must overcome a flu. The control structure involves a new process, as part of its overall control law, namely the process of choice. The point is illustrated in Fig. 3.26.

In Fig. 3.26 the blocks, apart from the process, represent cognitive processes. In general, the goals have a priority that is defined a priori (although we can imagine

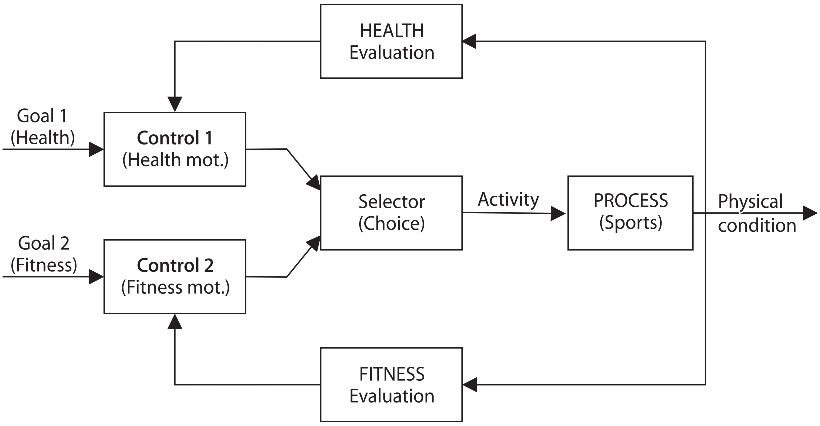

Fig. 3.26. Physical exercise motivation

further cognitive blocks providing the function of prioritization based on past experience). The selector block acts like a guard, deciding which of the alternative strategies have to be followed.

3.7.2 Other Control Approaches

Many concepts in control systems theory have a clear counterpart or interpretation in psychological processes. It is obvious that those control approaches that go under the generic umbrella of intelligent control systems (control systems conceived by the use of artificial intelligence techniques) are closely related to human behavior, as they are indeed inspired by our remarkable cognitive abilities.

Learning control. When there is no clearly defined target, or objective, we must learn what our options are and explore the environment to build up experience. From this experience we may decide where to explore further or perhaps deduce a valid objective. There are special control theories devoted to such schemes, like identification for control (Hjalmarsson et al. 1996; Gevers 1997; Lee et al. 1993).

How we learn to play sports provide an example of such control strategy. At first we are rather tentative and try to improve the required motor skills in some basic way. As our motor ability improves, we develop strategies for co-operative or competitive game play.

In psychology the concept of intention reinforcement plays an important role. This idea is very much related to control schemes such as adaptive control systems (Mareels and Polderman 1994; Astrom and Wittenmark 1988).

Multicriteria and hierarchical control. Human behavior is often motivated to attain a wide range of different goals simultaneously. One particular behavior hypothesis is that people follow after an infinity of different goals (Hyland 1989).

As observed before, in the case of conflicting objectives, choice or priority breaks the dead lock. When there are multiple reinforcing objectives to be pursued they are often hierarchically organized.

Where multiple objectives appear at the same level of importance, we try to strike a balance between the various goals. In optimal control this is known as multi-criteria optimization. A classical example is the natural time-based conflict that arises when someone tries to be a top professional and maintain meaningful family relationships at the same time. Assuming that we indeed do not make an either/or choice between professional recognition and family recognition, our cognitive processes will provide us with a status of the partial attainment of either goal. This information is then used at a local level to further improve achievements towards either goal, but at a higher level decisions are made as to which resources and at what time either goal receives priority. The decision process presents itself naturally in a hierarchical way. Hierarchical control appears under many guises. The classical Maslow's (1954) pyramid provides a good overview.

A particular hierarchy developed for the mind considers:

- Level 1. Unmonitored reflexes and automatic pre-programmed pattern generation, the *open-loop* responses.
- Level 2. *Feedback control* where sensing information is minimally processed and used for rapid tasks. This is typical for our motor skills. Writing, reading and walking are good examples.
- Level 3. The *information-processing* level, where past stimuli are integrated in more complex representations and more complex plans are formulated. It is at this level where we anticipate future actions (the feed-forward). Much of our internal models about behavior, our emotions and the various goals we formulate reside at this level.

It is at levels one and two of the control hierarchy that much of the important work in experimental psychology has taken place.

In a different hierarchy four types of processes are identified:

1. a cognitive process that maps circumstances to notions and knowledge,
2. an affective process which changes the circumstance-action mapping that is currently in force,
3. a cognitive learning routine which builds up the series of circumstance-action rules, and
4. an affective learning routine which builds up the repertoire of reactions and rules by which changing circumstances are related to emotions and moods, generating alterations in the circumstance-action pattern.

Feedback in Social Systems

To some extent, in most of our behavior, we act in order to receive feedback and most of our actions are initiated by feedback.

Life without feedback would be rather boring.

3.8 Comments and Further Reading

It should be clear that the examples we touched upon are but the tip of the iceberg as far as feedback, control and automation goes. The examples simply reflect some of the personal interests and experiences of the authors.

Process control and automation in manufacturing is a very serious research and development topic in its own right, with many important contributions. A popular introduction is Shinskey (1996), especially useful in a fluid process context. Domain knowledge is critically important in making automation work, and this is reflected in the literature. There are specialized books on automation for just about any branch of industry. Industries that have had a major impact on automation are the automotive, aerospace and defence related industries. Steel (e.g. Kawaguchi and Ueyama 1989) mining and petrochemical industries equally have had major developments as do the utilities, like power and telecommunication. The latter are well-known as examples of *large scale systems* (Siljak 1991), at least from an engineering perspective. The internet, and computing systems more generally are perhaps the first examples of engineered systems that approach biological systems in terms of their complexity. As the technology to interconnect almost any sensor and actuator in our engineered environment into an internet-like communication network becomes ubiquitous the complexity of control systems will increase dramatically, but so will the capacity to manage our environment.

The theory and practice of adaptive systems (Astrom and Wittenmark 1988; Mareels and Polderman 1994; Goodwin and Sin 1984; Anderson et al. 1986b) has a rich history in systems engineering, starting from the early work around the so-called MIT rule (Whitaker 1959) for adaptive control. Learning control, iterative control, extremum seeking control are all variants starting from this simple idea of a self-optimizing control law.

The automata and finite state machines as well as their extensions in event-based systems have equally a long history with many important contributions (Cassandras and Lafortune 2008). This whole line of work builds on the contributions by Von Neumann and Turing, who clearly saw their work in the light of cybernetics, see for example Turing (1992) and Von Neumann (1958).

Equally our discussion of homeostasis is but scratching the surface of where feedback and systems engineering play a role or are important to understand biological processes. Mathematical biology has a rich history, and the developments in systems biology are just too explosive to be able to do them justice here. For some of the earlier work where feedback clearly takes center stage, see for example Mees (1991) and Goldbeter (1997).

The use of systems engineering ideas in social systems and psychology is a natural extension of the early cybernetics ideas. The origin of which may be found in the MACY conferences, held between 1946 and 1953 (see, for instance, the American Society of Cybernetics: *http://www.asc-cybernetics.org/*). For a contribution discussing cybernetics at the level of the behavior of a society, by Norbert Wiener himself, see for example Wiener (1954).