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Bio- and Ecological Systems: Challenges, Accomplishments and Forecasts

"Status report prepared by the IFAC Coordinating Committee on Bio- and Ecological Systems"

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Abstract: The complexities of the dynamic processes associated with bio- and ecological systems offer many challenges for the control engineer. Applying dynamic modelling and control can aid understanding of their complexities. Moreover, using such complex systems as test-beds for new control methods can highlight their limitations (e.g. in relation to system identification) and thus act as a catalyst for methodological advance. This paper continues the theme of exploring opportunities and achievements in applying modelling and control in the bio- and ecological domains.

1. INTRODUCTION

The complexities of the dynamic processes and their control that are associated with bio- and ecological systems offer many challenges for the control engineer. Over the past decades the application of dynamic modelling and control has aided understanding of the complexities of their dynamics and control. At the same time using such complex systems as test-beds for new control methods has highlighted their limitations (e.g. in relation to system identification) and has thus acted as a catalyst for methodological advance. This paper continues the theme of exploring opportunities and achievements in applying modelling and control in the bio- and ecological domains, building on the earlier work reported in Carson *et al.* (2006).

Agricultural, biomedical, environmental and biotechnological systems are considered in turn. In section 2, current key problems for each of these four areas will be considered. Section 3 focuses on recent major accomplishments; and section 4 makes some forecasts for each of the areas as to where future development is likely to focus.

2. KEY PROBLEMS

2.1 Control in Agriculture

Renewable Energy: Because nature's way of converting solar energy into chemical energy is at the basis of agriculture, agriculture is going to be a serious player in the quest for renewable energy. The implications for farming and environment are just beginning to be understood (e.g. Kim and Dale, 2005). Biofuels, solid energy carriers, biogas, and other ways of obtaining energy from waste in the carbon cycle all have their roots in agriculture. Since land area and other resources are limited, cropping systems for bio-energy purposes will be in competition with food production. This may put the issue of optimising productivity back on the agenda. It will call for automation, high tech monitoring and scouting systems – for example early disease detection with swarming autonomous robots - , advanced crop protection, and better management decision tools. The competition between cropping for food or fuel may also be a stimulus for shifting a larger proportion of food production to protected cultivation. The other side of the issue is that global warming is going to change agricultural productivity, land use and policy, with definite impacts on the balance between intensive and extensive production regions (Olesen and Bindi, 2002), and the role of automation and control. .

Intensified food production: The necessity to feed the world will call for efficient use of resources. In addition, demand becomes more diversified, especially in the developed world, calling for less seasonally dependent production. Moreover, the food-fuel controversy may push the production of food for consumption towards more intensified systems. Protected cultivation is going to show a world-wide increase. New greenhouse designs are arising, aimed at minimising energy input and preserving water. The tendency is even to develop systems that can produce energy, or produce fresh water from grey water or sea water. Such systems will continue to have a need for advanced automation. Land based aquaculture is

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another area that could help to supply animal proteins, in much the same way as animal husbandry, but with less labour input, and easier to solve problems related to animal welfare. Aquacultural systems offer good opportunities for mechanisation and automation. One expects the number of cultivated fish species to decrease over time (similar to horticultural species), while more physiological information becomes available for each of the selected ones, thus offering opportunities for model-based control and optimisation.

Product Quality and Food Safety: Consumers will demand safe and healthy food of high quality. A great deal of improvement in this area will come from breeding, although modelling to guide engineering of new varieties is still in its infancy (White, 2006). On the other hand, production conditions will have a large impact as well. With increasing knowledge about the biochemistry of crops and animals, more opportunities will arise for model-based control, and there will be a growing need for advanced sensors. In the food chain, RFID tags will simplify tracking and tracing. Even if the product is perfect at the time of delivery, preserving quality during storage, transport, processing and final preparation by the consumer is of major concern. Monitoring, information processing, communication and automation – up till pre-programmed control commands within packages for micro-oven preparation, for instance – are going to play a significant role.

2.2 Biological and Medical Systems

Disease modelling and therapy modelling: Research into the modelling of disease, as discussed in an earlier report (Carson *et al.,* 2006), is now no longer limited to disease propagation within human populations, but is also very much an active research area in studying disease progression in individuals. Advanced biological technologies in the measurements of genes and proteins have led to systems biology as a new emerging area for disease modelling. Systems biology combines the molecular components of biological systems and subsystems into the corresponding interaction networks and formulates functionally integrated systems models with emergent factors related to disease (McCulloch and Patemostro, 2005).

Even with the availability of genetic and molecular information, it is a major challenge to develop an efficient approach to understand the complexity of signal transduction in regulation using mathematical and kinetic models (Babu *et al*., 2006). Furthermore, disease modelling requires comprehensive consideration in modelling across the spectrum from genes to cells for a small-scale model with extension to whole organs in the case of large-scale models.

There is now increasing interest in using models for evaluating the response to therapy and in the optimal design of therapy plans (Seibert *et al*., 2007). With an understanding of the kinetics of drugs, therapy modelling can be developed for achieving the best delivery schedule to treat disorders, and can also be integrated into disease models to study the interaction of the function of cells for more efficient chemotherapy (Alarcón *et al*., 2004).

2.3 Modelling and Control of Environmental Systems

Integrated water resources management: In many parts of the world, water demand is increasing while at the same time the availability and quality of water resources are decreasing, mainly due to human activities in connection with the growing world population, ongoing urbanisation, industrialisation and the intensification of agriculture. This development is often associated with general reductions in environmental quality and, as such, endangers sustainable development. Integrated approaches are required to identify and analyse such unfavourable and undesired developments and allow sustainable systems to be designed that integrate human society with its natural environment for the benefit of both.

It is generally agreed (Bonell and Askew, 2000) that integrated water resources management (IWRM, see Global Water Partnership 2003) plays a crucial role in this context and that a participatory approach would help to better control and accelerate the integration, make the decision process more transparent and comparable across various river basins and scales and increase confidence in an integrated model-based planning process. Though the popularity of IWRM as a concept has increased during the last decade, applications to real world cases of the paradigm mentioned in the literature are still remarkably few (see for instance Tortajada *et al.* (2004)), thus leading to a growing scepticism (Biswas, 2004) as to the real potential of this attractive approach.

The development of proper legislation and policy is a key issue for the dissemination of integration and participation into water management practice (Wolf, 2002). At a European level the IWRM paradigm has been adopted by the Water Framework Directive (EC-WFD 2000) that came into force in December 2000. The directive introduces a set of requirements to be fulfilled in order to reach an inland and coastal water "good status" by 2015 and sets out a detailed framework for the improved planning and management of water, including the development of River Basin Management Plans (RBMP) to be prepared within 2009 (WFD, Art. 13).

The Guidance Document for the Planning Process (EC-WFD-CIS-GD11, EU 2003) explains (page 5) how the term integration should be intended in the implementation of such plans. Integration must concern many aspects, among which the following are particularly relevant:

- Integration of environmental objectives;
- Integration of all water uses, functions and values into a common policy framework;
- Integration of all significant management and ecological aspects; and
- Integration of stakeholders in decision making, by promoting transparency and information to the public and by involving stakeholders in the development of RBMP.

Again the GD11 recognises that planning is a process. This requires the provision of procedural guidance on the production and development of River Basin Management

Plans supported by appropriate toolboxes should help to identify the possible trade-offs amongst quantifiable objectives so that further debates and analysis can be more informed. Moreover, the toolboxes must support planning as a systematic, integrative and iterative process. According to these requirements, a general procedure (see Fig. 1) for Participatory and Integrated Planning (PIP) has been developed (Castelletti and Soncini-Sessa, 2004), where the decision making process is emerging as a process of social learning, which has to be supported by a Multi Objective Decision Support System (MODSS), based on system identification, control and decision theories (Georgakakos, 2007).

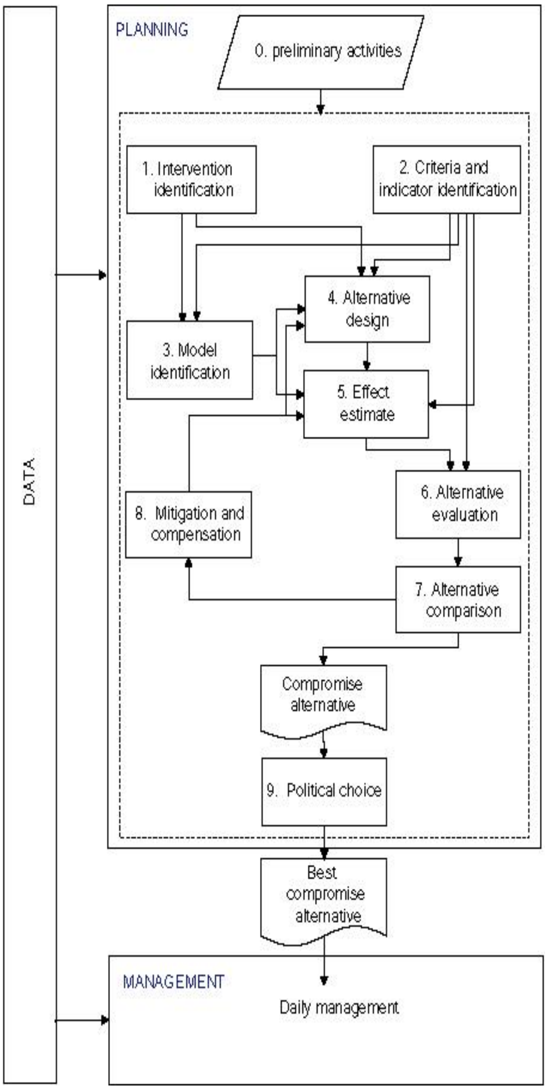

Fig. 1 The PIP procedure.

Furthermore, Water Reservoir Management systems are emerging as a fundamental component in the design of new dams as the best reply to flood and drought events that the 'greenhouse effect' is going to make more and more frequent.

Other environmental sectors: Also, in other environmental sectors, such as air pollution, solid waste disposal and CO_2 emissions, the need emerges for behavioural models for complex decision analysis (Tamura, 2005), conflict resolution and the design of policy: e.g. a policy for nations on CO_2 emission trading.

2.4 Biosystems and Bioprocesses

The results of research performed at the academic level are now in a number of cases being transferred to industry (Alford, 2006; Wold *et al.* 2006). Nevertheless, much improvement is still needed not only in monitoring, sensing and controlling the bioreactors that lie at the heart of the process, but also the downstream and upstream process sections (quality of inocula).

One of today's major challenges for bioengineering lies in the understanding of how biological systems really work. Much effort has been directed towards understanding how the different cell elements interact between themselves in metabolic networks and cell signalling pathways. Improved knowledge of the control structure within organisms is expected to help to design new drugs that are needed to fight illnesses such as cancers or pathogen-related diseases such as nosocomial infections, for which multi-drug resistance is causing considerable alarm. A special case is quorum sensing regulation pathways which enable bacteria of the same kind to coordinate their action. By judicious action it might be possible to interfere with pathogenic bio-film development and virulence factor production (Heurlier *et al.*, 2003; Zhu *et al.*, 2007; Parsek *et al.*, 2007). Efforts towards the modelling of the quorum-sensing networks need to be amplified (Karlsson *et al.*, 2007).

Environment-related bioprocesses remain a source of challenges. Two fields can be identified. The first is wastewater treatment as regulations concerning treated water discharged into the environment are becoming ever stricter. At the same time people tend to move to urban centres, which create mega-cities with huge sanitary problems to be solved, especially in developing and emerging countries. This is not just the problem of the "classical" pollutants (carbon, nitrogen and phosphorus), but also of "new" pollutants such as pharmaceutical substances, personal care products, etc. Even in the case of the "classical" pollutants, control issues still remain to be solved in order to maintain treated wastewater within discharge limits whatever the important variations in flow and composition at the inlet of the process. This is also true for large-scale continuously operated plants (Stare *et al.*, 2007) or smaller plants, operated in a discrete manner (Casellas et al., 2006; Wu *et al.*, 2007; Hong *et al.*, 2007). Due to concerns regarding energy, optimal control strategies in terms of efficiency and cost need to be designed.

3. RECENT MAJOR ACCOMPLISHMENTS

3.1 Control in Agriculture

The advancement of systems and control methods in agriculture keeps pace with developments in the areas of sensors, including monitoring and image processing systems, modelling, new equipment design and actuators, and control in general. The recent CIGR Handbook presents these general developments in a form amenable for agricultural application (van Straten and van Willigenburg, 2006; Schueller, 2006) or for life support in space (Fleisher et al., 2006). Some of the specialist overviews that it contains are summarised below, with particular emphasis on the most recent developments as they relate to agricultural and horticultural applications.

Optimised crop cultivation: The optimal control of greenhouse crop production, aimed at offering direct economic benefit to the grower, and having a more respectful use of resources such as energy and water, has received more attention. (van Ooteghem *et al.*, 2005; Pucheta *et al., 2006;* Blasco *et al.* 2007). In moderate climate regions, where energy is an important issue, several developments are seen to reduce energy consumption by better designs, among others by levelling energy demand throughout the year by means of heat storage (van Ooteghem *et al.*, 2005; Sethi and Sharma, 2007). Similar developments are seen to conserve water in arid regions, and to provide new systems for cooling and heat storage (e.g. Dawoud *et al.*, 2006). Van Henten *et al.*(2006) are using a sweet pepper model that predicts fruit set in an optimal control setting to break the synchronous production that is typical for greenhouse cultivated sweet pepper. While integrated optimal control in the presence of appropriate models provides the best possible control, it may have advantages in practice to separate the problem into different hierarchical levels (Ferentinos *et al.*, 2006).

Truly optimal control requires good models. In crop modelling, the trends are continuing on the one hand to use more detailed descriptions of crop development processes, while on the other hand more work is done to put the models in state-space form suitable for use in control (e.g. van Straten *et al.*, 2006). The issue of how to select the appropriate parameters for calibration of crop models on data has also been tackled (Ioslovich *et al.*, 2004) and progress was made in assessing model uncertainties (Cooman and Schrevens, 2006), and their effect on optimal control (van Henten, 2003). It is also interesting to see further developments on the idea that plants behave in some optimal way themselves. Optimal control can be applied in this way as a means to model crop development (Ioslovich and Gutman, 2005).

Various aspects of crop growth and development, such as bud formation, fruit set and fruit load, can be seen by the grower, but are difficult to model. Therefore, an alternative approach to greenhouse climate control involves trying to exploit the knowledge of the growers. This leads to rule-based approaches (Tchamitchian *et al.*, 2006), or to fuzzy modelling and control (Salgado and Boaventura Cunha, 2005). A novel approach is to use field programmable gate array hardware to realise cheap and easy to implement fuzzy controllers (Castañeda-Miranda *et al.*, 2006). Modern electronics and photovoltaic energy supply provide solutions for remote sites and low-cost greenhouses (e.g. Yano *et al.* 2007).

Whatever the control method, really good results require feed-back from the plant. The general concept is sometimes coined the 'speaking plant' or 'speaking fruit' concept (Hashimoto *et al.* , 2006). It can be expected that general developments in bio-sensors will offer new opportunities (Wilson and Gifford, 2005; Velasco-Garcia and Mottram, 2003), but up till now there are not many real applications.

On the nutrient and water side more work is being done on automated irrigation and fertilizer supply. Irrigation based on feed-back is either based on moisture sensors in the soil (Krishna and van Iersel, 2006), or on advanced inference of the plant water status (Yang and Ling, 2004; Prenger *et al.,* 2005; Thompson et al., 2007). Automated fertigation has been investigated using feed-forward based on crop models (Elings *et al.* 2004), a mix of feed-forward and MPC (Brajeul *et al.*, 2006), or using optimal control and feed-back by ion-selective sensors in the drain (Gieling *et al.*, 2005, van Straten *et al*., 2006).

Precision Farming and Intelligent Machinery: While precision farming is believed to be the only efficient and sustainable farming system for the future (Manu*future*, 2006) its progression into practice is only moving forward gradually. Methods for remote sensing and site-specific sensing are becoming more common. This also brings controlled management closer (e.g. van Liedkerke *et al*., 2006) There is a tendency towards plant-specific treatment, somewhat in contrast to the ever increasing size of agricultural machinery. On the other hand, there is much progress in making this machinery smarter. In particular, automatic guidance receives much attention and practical solutions are provided using the CAN bus (e.g. Darr, 2005, Griepentrog, 2006). This is possible as a result of the reduction in cost of GPS equipment, and also because visio-based methods become more and more mature (e.g. Kise *et al.*, 2005). Weeding in the row is, however, still a problem. In horticultural engineering there have been several developments related to automation. Belforte *et al.* (2006) summarise the characteristics that robots in greenhouses should have. Leaf picking (van Henten *et al*., 2006) and spraying (Subramanian, 2005) are just a few examples of operations that can be performed by robots Work on autonomous robots has been reported for forests (Anderson *et al.*, 2005) and citrus groves (Subramanian, 2006), using fuzzy control.

Advanced Livestock Farming: There is a growing tendency to consider bio-responses of animals as the basis for design and control of climate for livestock housing. This is designed both to enhance animal welfare, and also to achieve better production conditions. Animal discomfort can be observed by analysing cough sounds (van Hirtum and Berckmans, 2004). More generally, methods for time-frequency analysis for biosystem engineering have been reviewed by Marchant (2003). Also imaging techniques are used to observe animal behaviour, such as cow behaviour in an automatic milking system (Kaihilahti *et al.*, 2007) and for the detection of diseases in chickens by line-scan imaging (Yang *et al.*, 2006). There is also growing recognition that what really counts are the conditions in the immediate environment of the animals (van Wagenberg *et al.*, 2005, Berckmans and Vranken, 2006). Control systems have been developed for natural ventilation (Hoff, 2004), and for evaporative cooling by a fogging system (Haeussermann *et al.*, 2007) in pig houses.

Post-Harvesting and Processing: Work is progressing in the area of model-based storage, with more advanced 3D models, whilst also exploiting external conditions by using weather forecasts. Various traditional operations, such as drying, are being revised to better fulfil the requirements of customers who demand the preservation of freshness, aroma and taste, whilst at the same time recognising that energy consumption has to be reduced (e.g. Li *et al.*, 2006; Djaeni, *et al.*, 2007). Apart from control problems related to the usual processing activities, one currently sees more operations that are dynamic by nature, such as, for instance, pulse electric field pasteurisation (Cserhalmi *et al.*, 2006). These kinds of problem pose interesting challenges for the control community.

3.2 Biological and Medical Systems

Imaging-based modelling: With the development of new imaging probes and new animal models, imaging-based modelling is now a feasible approach to providing insight into pathological process and specific receptor binding (Thorwarth *et al.*, 2005) through functional imaging modalities such as positron emission tomography (PET) and magnetic resonance imaging (MRI).

Kinetic analysis and system identification are still classical approaches to deriving biochemical/biophysical parameters in biological processes. However, one trend is that of estimating voxel-by-voxel parameters, i.e. three-dimensional parametric maps/images. Efforts have been made to improve the reliability of parameter estimates and reduce computational cost using different approaches. Both prior knowledge (Kimura *et al*., 2006) and statistical frameworks (Kamasak *et al*., 2005) have been applied to generate reliable parametric images as well as achieving enhancement in the temporal and spatial domains (Wen *et al*., 2007).

The relatively new PET-CT (Computer Tomography) imaging modality provides detailed noiseless anatomical images, improving the quality of functional images. Motion correction, especially for respiration, is another emerging area to remove mismatches led by motion between the functional and anatomical data, for example using a breathing model (El Naqa *et al*., 2006).

Systems biology and systems physiology: Genetic regulation is a critical component in systems biology to adjust the production of proteins viable for cell function translated from genetic information. Development of analytical and computational methods for the modelling of gene regulation can substantially aid understanding gene function and the biological regulatory mechanisms (Ivanov and Dougherty, 2006). Recently systems biology toward whole organs has emerged to develop structurally and functionally integrative predictive models of the dynamic physiology of biological systems (Alarcón *et al*., 2004; McCulloch and Paternostro, 2005). The increased understanding in molecular and cellular biology, with the recent development of systems biology, has inspired traditional physiological modelling to develop towards a multi-scale framework of modelling, which is referred to as systems physiology. Systems physiology offers a new opportunity to study the organisation and interactions of the human body across spatial (from nanometres to whole body) and temporal (microseconds to human life) scales (Hunter and Nielson., 2005). As an integrative computational framework, systems physiology has hierarchical levels of modelling from tissue to whole body. The Physiome Project is such an ongoing project to model human physiology (Hunter, 2006). Meanwhile, dynamic feedback pathways have been achieved to implement automated regulation at the levels of organ and tissue (Xie *et al*., 2004; Banaji *et al*., 2005).

Bioinformatics: Advances in information technology are capable of modelling large and complex network models, allowing further investigation of relationships and patterns of regulation at global and local levels. As an emerging knowledge representation approach, graph theoretic modelling of biomedical information has become increasingly important in the bioinformatics field, providing a new insight into the development of medical information systems (Bales and Johnson, 2006).

Biologically based computational modelling is another emerging area to understand the myriad complexities of human cognition and intelligence. The approaches of automated network systems and regulatory feedbacks are expected to address the challenges in cognition from immediate recognition to long-term memory. Biological neural network systems are in progress using the dynamic control mechanism to achieve dynamic variable binding in the cognition to trigger the update of memory representations (O'Reilly 2006).

3.3 Modelling and Control of Environmental Systems

Large scale systems: A number of advances are apparent in the way in which modelling methods are being applied to increase understanding of environmental systems. These include composite models being used to predict and estimate important environmental variables and to explore efficient environmental strategies and management schemes. They are also being used in assessing influences and impacts for environmental change; how changes of input variables and/or environmental variables influence mutually the variables of the climate system, ecological systems, socio-economic activities, human lifestyle and others. More generally there is now evidence that policy decision making in this arena is increasingly being based on assessment models. Examples include the exploration of scenarios and the evaluation of policies designed to mitigate the effects of global warming.

Identifiability of large simulation models: Large models are over-parameterised and so many different sets of parameter values will provide a similar explanation of the available data (*equifinality*). The alternatives are to use simpler, identifiable models; or constrain the parameters in some manner to a user-specified region of the parameter space (based on "expert" knowledge), either deterministically or stochastically (e.g. a numerical Bayesian approach) (Young, 1998, 2003; Taylor *et al*., 2000; Young *et al*., 2002).

In the last few years there has been a significant re-emergence of the 'top-down' approach as an alternative to reductionist, 'bottom-up' approaches. This is supported by a growing number of scientists and modellers, including the Chairman of the UK Natural Environment Research Council (NERC). Moreover a growing interest in numerical Bayesian methodology, or in simpler alternatives as a tool in modelling and data assimilation, has to be noted.

It is unlikely that the problem of identifying large simulation models will be resolved (since the ambiguity cannot be removed). However, it will be realised that: (a) simple models are, in any case, best for time series forecasting (e.g. flow and flood forecasting) so the difficulties with the larger models are not too important; (b) simple models can also form a basis for the construction of large simulation models (required for the purposes of "what-if" planning and design studies) that at least have an identifiable "core" which explains the "dominant modal dynamics"; and (c) such large simulation models can then be handled using a numerical Bayesian approach or, preferably, a computationally simpler alternative.

Data-Based Mechanistic Approach: In order to overcome the limitations of simulation modelling in the context of environmental systems, where planned experimentation is difficult, if not impossible, a *Data-Based Mechanistic* (DBM) approach to modelling was proposed (Young, 2000). The approach starts with the construction and evaluation of a simulation model which reflects the scientists' perception of the physical, chemical and biological mechanisms that characterise the environmental system. Then a critical evaluation of the model in both stochastic and response terms is performed and, by providing insight into the strengths and limitations of the simulation model, "it provides a prelude to the exercises in DBM modelling from real data that becomes possible when data are available on the response of the environmental system to natural or anthropogenically induced perturbations.

It is suggested that, wherever possible, the parametrically efficient (or 'parsimonious') DBM model should provide a description of the core mechanisms that dominate the observed behaviour of the environmental system under study. Moreover, it should also provide the basis for the *final* construction of a *stochastic* model that reflects this core behaviour, but may involve other, more speculative elements that are required for 'what-if' simulation and planning exercises. The advantage of this DBM 'moderation' of the simulation model is that the relative confidence in the historically validated DBM core (when sufficient data are available) can be balanced with the reduced confidence in the more poorly validated speculative elements. Thus the results of any analysis can be better evaluated with these relative uncertainties in mind. For instance, if the model contains nonlinearities that have not been well-validated during DBM modelling over the historical period, but are thought to be of potential importance in the future, then the large level of uncertainty in this regard must be reflected clearly in any predictive application of the model" (Young *et al*., 2007).

Industrial Applications: Developing trends can also be observed at the level of different types of industry, where environmental control challenges are having to be met. For instance, over the past two decades the car industry has not only successfully cleared regulations for exhaust gas emissions, but has also reduced fuel consumption by means of computer controlled devices.

In the area of water quality control, design challenges for sewage plants include those of regulating the total quantities of nitrogen and phosphorus being transmitted from the waste plant to the river. In this context, precise and detailed mathematical models are needed and are being developed to estimate the water quality and quantity. These include models to describe changes in water quality and quantity from rainfall to the sewage plant, and models describing the decomposition of organic substances by bacteria and the removal of phosphorus.

The purpose of such mathematical models is to estimate and predict the changes over time in water quality and quantity, to design a sewage treatment plant control system, to realise an on-line control and tuning algorithm based on the model, and so on. However, whilst progress is being made, there are still methodological challenges to be overcome, relating to the proper treatment of bacterial reaction, with their nonlinear dynamics and spatially wide processes.

3.4 Biosystems and Bioprocesses

Significant accomplishments have been achieved in a number of areas of application over the past few years. These include:
- the development of high throughput systems, where several reactions are run in parallel, to optimise cultivation media and conditions or to test new strains, where control strategies as well as reactors should be scaled-down (Knorr *et al*., 2007)
- the direct use of the information provided by comprehensive metabolic network modelling in the development of control strategies (Gadkar *et al*., 2006; Henry *et al*., 2007)
- the use of PAT not just for final product quality assessment but also to control bioreactors (Schenk *et al*., 2007, Streefland *et al*;, 2007) as well as downstream process (Degermann *et al*., 2006; Caillet *et al*., 2007). PATs have found application across the whole spectrum of activities in bio-product development (Lundstedt-Enkel *et al*., 2006; Doherty and Lange, 2006)
- the development of benchmarking platforms such as BSM2 for wastewater treatment (Jeppsson *et al*., 2006): they allow for the comparison of control strategies at the level of the plant, i.e., considering not only the key bioprocess section

(activated sludge in the case of BSM2) but also the downstream section (sludge treatment and recycles of reject water).
- improvement in the robustness of control strategies (Renard *et al*.,2006, Jenszch *et al*., 2006; Jenszch *et al*., 2007) as model-based control remains a challenge due to bioprocess uncertainties and the lack on on-line sensors.

4. FORECASTS

4.1 Control in Agriculture

Perception (monitoring, sensing, data collection, interpretation): Agriculture can benefit tremendously from what the control community has to offer. One of the bottlenecks in the sensing – control/management – actuating loop is the availability of reliable, appropriate and low-cost sensors or sensing/actuating networks. Several new developments in nanotechnology and bio-nanotechnology may open many new possibilities. The current development of MEMS (Micro-electro-mechanical-systems) and the emerging research in nano-sensors-actuators devices will bring, in the near future, new integrated devices capable of collecting, processing, and communicating large amounts of data with minimal size, weight, and power consumption. It will also call for more advanced data fusion and observer methods (for instance non-parametric particle filters).

Modelling and Control: The full potential of existing classical and modern control methodology (such as model-based control methods like adaptive control, robust control, optimal control) has not yet been fully exploited in the agricultural area. The availability of better sensors, and more detailed temporal and spatial data will offer further opportunities for these methods. Handling a wide range of time and space scales is an issue of considerable interest. Here, theory on model reduction and hierarchical control can find its way towards agricultural applications. As most agricultural systems are non-linear, non-linear control theory including feed-back linearisation is likely to find more applications in our area. Because of the complexity of biological systems, there is a need for efficient methods for sensitivity analysis, parameter estimation and optimisation of input signals in experimentation. Better models will allow the application (economically) of optimal control methods, but the handling of uncertainty and risk, and of multiple objectives will require further attention. We will see a further application of mechatronics, especially in the area of automated agricultural operations on the field, and in horticulture.

Agricultural Automation: The position paper Manu*future* (2006) sketches a future of agricultural production, characterised by a move away from treatment of the whole to treatment of the individual. In precision livestock farming, free ranging animals will be steadily monitored by sophisticated sensors connected by wireless networks. In precision crop farming site-specific treatment will be dominant, supported by on-line sensors and autonomous field scouts. Human supervision is still foreseen to persist in otherwise highly automated and smart machinery. Greenhouses in moderate climate zones will have novel designs that reduce energy input tremendously. Optimal control and novel dehumidification systems will eventually lead to zero energy greenhouses.
From farm to fork: All this will be supported by wireless communication and web-based support systems. Monitoring with RFID tags and a digital farm repository will provide important input to chain management and to safeguard food safety in the chain as a whole. The tendency for more sustainable production methods, with more use of solar energy and other sustainable sources will continue. Storage will be reduced where possible, but perishable seasonal food will still need methods for preservation to level off peaks in demand. Consumer value will be added by advanced processing, with more attention to health, while offering convenience. There is no doubt that systems and control methodology and technology will be a major enabling technology for the future.

4.2 Biological and Medical Systems

In the field of bioinformatics, data mining is expected to employ diverse systems and models to automatically extract intrinsic biomedical information and discover the nature of relationships. The understanding of new knowledge in the bioinformatics field will ensure the quality of health care, in order to deliver maximised benefits to patients and facilitate the development of advanced medical information systems.

A better understanding of the regulatory functions in systems biology is expected to provide insights in studying the mysterious origin of biological abnormalities. Systems physiology will progress in building efficient models for organ systems, paving a path to establish global functional and structural systems models. The trend of systems physiology will integrate developments in systems biology into the micro-level and optimise the corresponding interactions and feedbacks to model the progression of disease.

The limited availability of medical imaging has also given rise to demands for extending dynamic kinetic analysis to simplified reliable parameter estimates for static studies. The combined PET-CT imaging offers the opportunity to achieve this objective using the mutual information.

4.3 Modelling and Control of Environmental Systems

Integrated Water Resources Management will expand from the first experimental case studies developed by universities and research institutes, with the first steps being taken towards systematic application in real world situations. In fact the new Water Frame Directive of the European Union requires the adoption of a River Basin Management Plan within the time frame up to 2009 for all the basins in the Union. This will afford great opportunities of work for consultants and engineering companies, together with new research challenges. Moreover the IWRM scheme will not only be adopted in the EU, but will also be distributed all over the world, due to the intensive dissemination action that the EU is planning. This will be facilitated by the emerging trend to create a large modelling support system on the web.

In the Water Quality Control Field it can be expected that the trend towards the adoption of automatic control of the whole treatment process will continue, resulting in the emergence of a number of new products in the market.

The availability of cheap computing power, especially through parallel computing facilities, will enable the diffusion of real time distributed controllers for the management of complex water reservoir networks. The automatic control of water reservoirs and regulated lakes will eventually move towards becoming standard practice.

4.4 Biosystems and Bioprocesses

The development of new drugs will increasingly be based on a better understanding of the control principles associated with metabolic pathways. Such activity will benefit from closer co-operation with researchers working in the fields of biological and medical systems and from improvement in the control strategies of bioprocesses related to environmental problems. The production of bio-fuels such as bio-ethanol (Demirhas, 2007) and bio-hydrogen (Hawkes *et al*., 2002; Han and Shin, 2004; Ren *et al*., 2006) should (again) become an issue for control applications. These processes are attracting new attention due to concerns regarding greenhouse gases. The production of bio-hydrogen based on anaerobic digestion requires control of operational conditions. Experience gained with methane production could be very valuable in this context (Dixon *et al*., 2007).

The development of control strategies for specialty bioprocesses such as drugs or probiotics Lavermiccocca, 2006) remains a topic of interest where further advance is likely. Besides the requirement to ensure the highest quality in relation with human use – through for example the development of control strategies based on PAT – optimisation in terms of energy consumption could be partly achieved by means of more efficient control. The latter would apply also to bulk bio-products.

5. CONCLUSIONS

This paper has reviewed some of the challenges and opportunities that arise, from a control engineering perspective, when dealing with processes and systems across the bio- and ecological spectrum, together with advances that have been made. From the foregoing sections it is clear that in a variety of ways they all exhibit complexity. Yet despite this complexity, much has been achieved through the application of systems, modelling and control methods and techniques that is of benefit to industry and society, as well as to the research community.

Model-based analyses of bio- and ecological systems have yielded much insight into the nature of this complexity, in turn enabling control system approaches to be applied with greater effect. Analytically, much quantitative understanding has been achieved in relation to control mechanisms, both at the physiological or process level as well as in relation to system management. Here there are both similarities and differences across the different application domains. For instance, control in the context of resource management is an area of on-going development in agricultural and environmental systems, as also in the case of hospital management. Automation is increasingly applied not only in biotechnological processes and systems, but also in agriculture. Advances in the understanding of disease control, from a control system perspective are major ongoing achievements in both the biomedical and agricultural sectors. Endeavours aimed at process optimisation are current in agriculture (the growth of both crops and animals), in biomedicine (e.g. optimising drug therapy), and in biotechnological processes.

In terms of modelling methodology, the complexities of biological and ecological systems continue to offer challenges to the mathematical modeller, particularly in relation to identification, parameter estimation and validation. As already discussed, over the past three decades these application domains have highlighted limitations in existing methods and have paved the way for a range of methodological advances.

In summary, the control engineer is responding in a variety of ways to the many challenges offered by the complexities bio- and ecological systems. Much has already been achieved for the benefit of the agricultural, biomedical, environmental and biotechnical industries and organisations, and for society more generally. We may expect such progress to continue over the coming years.

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