From the Control Systems Theory to Intelligent Manufacturing and Services: Challenges and Future Perspectives

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Abstract Control Science has played over time and still continues to have a key role for the development of human society such that, in the XX century, it has been recognized as an independent discipline. During the '50's, one of the first international scientific congress to address the area of control theory, namely, the "Convegno Internazionale sui Problemi dell'Automatismo", was held in Italy, at the Museum of Science and Technology in Milan, Italy. In this context, ten years later, the Automatic Control group of the Università di Ancona was born. In this chapter, we want to revisit the main results achieved in the last 50 years by the Automatic Control group of Ancona focusing, in particular, on the recent achievements about linear and nonlinear control; robust, stochastic, adaptive and optimal control; model predictive control; fault diagnosis and fault tolerant control; aerial, terrestrial and underwater unmanned vehicles control; automotive control; switching systems analysis and con-

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S. Longhi et al. (eds.), *The First Outstanding 50 Years of "Università Politecnica delle Marche"*, https://doi.org/10.1007/978-3-030-32762-0_5

trol; underwater robotics; intelligent manufacturing and cyber-physical production systems. The contribution aims to provide the main challenges on these topics and their future perspectives.

1 Introduction

Control Science has played over time and still continues to have a key role for the development of human society such that, in the XX century, it has been recognized as an independent discipline. During the '50's, one of the first international scientific congress to address the area of control theory, namely, the "*Convegno Internazionale sui Problemi dell'Automatismo*", was held in Italy, at the Museum of Science and Technology in Milan and, in 1969, Università di Ancona was born.

During the last 40 years of its history, the Università Politecnica delle Marche (formerly Università di Ancona) has seen the group of automation and control engineering growing first as a branch of the school of Antonio Ruberti, one of the founding fathers of Italian Automation and Control disciplines, and successively receiving contributions from other cultural areas. During the first years after the establishment of the Faculty of Engineering, research focused on the one hand on systems theory and on the other hand on the application field of motion analysis. The activity in both fields, fostered and coordinated at the beginning by Tommaso Leo [1, 79, 80, 82, 113] and, respectively, Osvaldo Maria Grasselli [88–91], ultimately developed, with the contribution of other scholars, in the main scientific areas of control and automation engineering. As a result, this gave birth to several research laboratories, namely the Motion Analysis Laboratory, the Automation Laboratory, the Robotics Laboratory, the Advanced Robotics Laboratory, the Interconnected Systems Supervision and Automation Laboratory, the Laboratory of Modelling Analysis and Control of Dynamical Systems and the Domotic Laboratory.

In these years, the research group has expanded its research interests, by developing them towards significant applications in the various production and service

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sectors, with the general objective to make these sectors, with which the University is connected, grow stronger. As a consequence, several research areas added during time to that of systems theory, such as fault tolerant control, robotics, industrial automation and intelligent manufacturing. This evolution lead the research group to collaborate with various national and international groups, and to develop significant partnerships with important companies, thus becoming a reference in the regional and national development policies of what is now commonly called “Industry 4.0”.

This chapter provides a quick overview of the main results achieved in the topics related to automation and control engineering, starting from the control systems theory up to the intelligent manufacturing systems, including the main areas of fault diagnosis and fault tolerant control, industrial automation and robotics.

2 Control Systems Theory

2.1 Time-Varying and Periodic Systems

The control system theory for linear time-invariant systems has been widely studied in the past and, thanks to the previous results, many researchers have made constant efforts to extend the theory to time-varying systems. The challenging problem of a time-varying system is that, the values of its output response depend on when the input is applied to the system. This is mainly due to the fact that the system parameters change as a function of time and, when these parameters periodically change in time, the system assumes a periodic behavior. The research group at the Department of Information Engineering started to investigate the time-varying and periodic systems starting from the 80’s, contributing on the topics described in the following subsections.

2.1.1 Periodic Systems

In the field of linear and non-stationary systems, interesting results have been obtained from the Automatic Control group both for the analysis and for the control of periodic discrete linear time systems. In particular, a geometric theory of control was developed for this class of systems. A first step in this direction was made by extending the concepts of controlled invariant sub-space and controllability subspaces to the periodic case and introducing two new geometrical concepts, namely, the externally controllable subspace and the internally controllable subspace. Moreover, the notions of outer and inner controllable subspaces are allowed to derive the necessary and sufficient solvability conditions for the disturbance-localization problem with output or state dead-beat control and to give synthesis procedures for the solutions [92–95]. The existing periodic geometric theory is then supplemented with the notions of outer reachable subspace and controllability subspace [98].

In order to further investigate the analysis and control of this particular class of non-stationary systems, the concepts of zeros and poles have been introduced in the case of multiple input and output variables and without the hypothesis of reachability and observability with its multiplicity. For the zeros, three different notions were introduced, the zero of transmission, the zero invariant and the geometric zero. The analysis of these notions was then extended by introducing the notions of zero of input decoupling and of zero of output decoupling. As for the stationary case, these notions are strongly correlated with the structural properties of the system. Both for these new notions of zero and for the notions of zero of transmission, zero invariant and geometric zero, opportune ordered sets of structural indices were introduced and a new method of calculation of these zeros and of the relative structural indices was identified [96, 97].

2.1.2 Analysis and Control of Linear, Uncertain, Time Varying Systems

This is a particularly wide field of research including several topics: robust stabilization of time-invariant systems through switching control, supervised switching control of systems under highly variable operating conditions, gain scheduling control technique based on the perturbed frozen time approach for slowly time varying systems, numerically efficient LMI based robust stabilization of interval time varying systems, stability analysis of time varying systems in terms of "average" parameter variations, stability analysis and stabilization of linear uncertain polynomially time-varying systems, control of uncertain linear parameter varying (LPV) systems. The results of these topics can be found in [68, 103, 104, 108]. Among the above topics, it is emphasized the novelty and the importance of stability analysis and stabilization of linear uncertain polynomially time-varying systems. The new approach proposed is based on the physically meaningful assumption of a dynamical matrix with smoothly time varying elements. This makes it possible to well approximate the parameter variations with a polynomial time function, and, as a consequence, to transfer the uncertainty domain from the parameter space to the polynomial coefficient space. The significant advantage of this point of view is the possibility of dealing with uncertain plants whose parameters are not confined inside a relatively small region: unlike all the other methods, both parameters and their first derivatives up to a fixed order may take values over arbitrarily large sets and theoretically unbounded dynamical matrices can be considered.

2.2 Structural Methods for Analysis and Control of Complex Dynamical System

In many interesting situations, the standard paradigms of linear system and control theory can be suitably adapted or reinterpreted to deal successfully with dynamical structures which are much more complex than linear ones. In particular, the structural and geometric approach originally developed in the linear framework have shown to be particularly effective in dealing with analysis and control problems that involve singular and neutral systems; time-delay systems; systems with time-varying or uncertain coefficients, nonlinear systems; hybrid systems; jumping (or impulsive) systems. The work done along this line by the researchers of the Università Politecnica delle Marche in the past 30 years has produced many key results in each of the above areas, it has provided valuable solutions to specific problems and, more important, it has contributed to the development of a better insight of solvability conditions.

A first step for extending structural methods was that of considering dynamical systems whose coefficients belong to a more general algebraic set than the field of rational number: namely to a ring. Dynamical structures such as delay-differential systems, parameter dependent systems, time-varying systems, uncertain systems can be conveniently modeled as dynamical systems with coefficients in a ring. The main advantage of this choice is the possibility of dealing with finite dimensional state spaces, although these are no longer vector spaces over a field, but modules over a ring. Finite dimensionality, make it possible to develop geometric structural tools and methods and to construct efficient computational procedures to synthesize solutions to several problems. In this way, solvability conditions for noninteraction and observation problems (including decoupling problems; model matching problems; tracking and regulation problems; inversion and functional reconstruction problems; observation and fault detection problems) that involve systems of the above-mentioned classes, as well as singular and neutral time-delay systems, have been stated and constructive procedure to find solutions have been given using algebraic and geometric algorithms [33, 38–42, 44, 46, 47, 51, 125–130]. This work has in addition contributed to define suitable notions of zeros and of relative degree in the considered situation and to understand their structural and dynamical meaning.

Application of structural methods to nonlinear dynamical systems was also successful in providing solutions to classical control problems [121, 133]. Further developments were made possible by exploiting the use of differential algebra and related methods in dealing with nonlinear differential equations. This approach was pioneered in [43] and completely developed in [34] and in its second revised edition [36]. The book was translated in Slovak [35] and more recently in Chinese [37]. The differential algebraic perspective is complementary to, and parallel in concept with, the classic differential-geometric point of view. In many cases, it makes possible to derive specific results that would be very difficult, if not impossible, to obtain by a different approach. The main topics discussed in [34, 36] include: the realization of input/output maps in a nonlinear context; the analysis of accessibility and observability properties within a differential-algebraic setting; the discussion and solution of basic feedback problems, like input-to-output and input-to-state linearization, noninteracting control and disturbance decoupling, together with results about dynamic and static state and output feedback.

More recently, the interest focused on switching and on jumping (or impulsive) systems that model complex, hybrid dynamical structures. In extending structural methods to this framework, stability issues have been taken into account. This has provided original solvability conditions and procedures to synthesize solutions to output regulation, disturbance decoupling and model matching problems for switching systems [45, 48, 123, 131, 160, 161] and for jumping systems [50, 132, 162, 163]. Observation problems have been tackled using a dual, in a sense, approach, obtaining new insightful results on the construction of observers both for switching [49] and for jumping systems [52].

2.3 Optimal Control Techniques

In the field of optimal control, the research activity has been developed along different lines with the purpose of providing methodological contributions advancing the state of the art in the respective appliances. The main research topics of the research group of Ancona, addressed during the years, belong to the following lines of research:

- Event based sporadic control [105].
- Achievement of a very accurate transient tracking through numerically efficient techniques [107, 109, 110].
- Efficient implementation of the pseudo-inversion method for the solution of constrained optimal control problems [111].
- Near decoupling problem for linear, possibly uncertain, plants [106].

2.3.1 Event Based Sporadic Control in the Case of Unmeasurable State

This line of research concerns the so called "sporadic control", which is of a paramount importance for networked control systems. The purpose of sporadic control is to reduce the network occupation without appreciably degrading the control system performance. Many authors considered this problem in the general framework of event-based control and proposed several communication logics (CLs) whose common feature is invoking a message among the control system components only if a "significant" event occurred. The main drawback of these methods is the restrictive assumption of a measurable state. This hypothesis is removed in the proposed event-driven CL. The SCL is based on the computation of a quadratic functional of the tracking error and of a corresponding time-varying threshold: a network message from the sensor to the controller is triggered only if the functional equals or exceeds the current value of the threshold. The CCL is directly driven by the SCL: the dynamic output controller sends a feedforward message to the plant only if it has received a message from the sensor at the previous sampled instant. Formulation of the controller in discrete-time form facilitates its implementation and provides a minimum inter-event time given by the sampling period. Future developments concern the extension of the proposed event based sporadic control to the class of LPV systems affected by noisy parameters measurements.

2.3.2 Achievement of a Very Accurate Transient Tracking Through Numerically Efficient Techniques

Achieving a very accurate transient tracking is a long standing problem which has been generally addressed using stable inversion techniques. Classic stable inversion methods are very complicate and require a very long pre-actuation which tend to infinite for near non hyperbolic systems.

To alleviate these drawbacks, the so-called "pseudo inversion" approach, has been proposed. The stable inversion of the possibly non minimum phase plant is obtained as the solution of an optimal control problem. The control input is "a priori" assumed to be given by a piecewise polynomial function. Once the desired trajectory to be tracked has been specified, this allows the computation of the parameters describing the unknown input as the approximate least squares solution of the Fredholm's integral equation corresponding to the explicit formula of the output forced response.

The main advantages of the pseudo inversion approach are: (1) the initial conditions can be arbitrary and possibly uncertain; (2) the method does not require pre-actuation; (3) the approach can be extended to the class of non-hyperbolic systems; (4) the method applies to the more general tracking problem of a switching reference; (5) the approach allows the definition of a multi-functional for the simultaneous fulfillment of several control requirements. Future developments concern the application of pseudo-inversion approach to Model predictive Control (MPC). The purpose is to reduce the technical difficulties deriving from two typical and major issues of MPC: the complexity of stability analysis and the very demanding computational effort due to the on-line optimization.

2.3.3 Efficient Implementation of the Pseudo-inversion Method for the Solution of Constrained Optimal Control Problems

This topic is the natural continuation of the previous one. Shaping the external reference and the control effort as B splines functions allows the development of very efficient pseudo-inversion algorithms for the solution of constrained optimal control problems. The key point is to translate hard constraints on some physical variables to hard constraints on their optimal approximations. If the approximation is really satisfactory, also the actual control variable is expected to exactly satisfy the constraints. To this purpose, B-splines have been used because of their appealing features: (1) they belong to the convex hull generated by control points, (2) B-splines are defined in such a way to automatically satisfy the continuity constraints at knot points. Property (1) can be exploited to impose the approximating spline to exactly satisfy hard constraints. Property (2) can be exploited because it allows an arbitrary increase of knot points without increasing the number of continuity constraints to be satisfied. These features allows the B-spline to practically overlie the function to be approximated.

2.3.4 Near Decoupling Problem for Linear, Possibly Uncertain, Plants

This research line concerns the near decoupling problem for linear, possibly uncertain, multivariable plants. This problem consists of achieving an independent set point tracking for the controlled outputs and is of a fundamental importance for industrial applications.

In this regard, a major critical issue to be faced is the complexity of the design procedure of a MIMO controller simultaneously fulfilling both the usual control specifications and the further requirement of a nearly decoupled closed-loop output response. The new proposed decoupling scheme is given by a closed-loop control system endowed with a twofold feedback loop. The internal feedback action is designed to satisfy the usual control requirements, the purpose of the external feedback loop is to yield an overall control system with an enhanced degree of approximate decoupling, still keeping internal stability. In this way, the usually complex design procedure for the simultaneous achievement of common control specifications and near decoupling is decomposed into two independent and simplified sub-problems.

3 Fault Diagnosis and Fault-Tolerant Control

The increasing availability of sensors of reduced dimensions, good performances and at low cost, together with the exponential growth of computational power of modern microcontrollers, have been modifying the way in which automation is designed. The classical automation pyramid, which separates the field, control and supervision levels is now evolving into a more comprehensive and fuzzy paradigm, in which field, control and supervision levels strictly interact together. This new paradigm permits to address new challenges, and among them one of the most promising is to cope with faults in real-time, in order to increase reliability and autonomy of the controlled/supervised system. From a formal point of view, a fault can be seen as an unforeseen deviation of at least one characteristic property of the system from the acceptable, usual or standard condition [102]. A Fault Detection and Diagnosis (FDD) system is thus responsible for detecting possible faults before they degenerate into a failure, i.e. a permanent interruption of a system to perform the required fucntion, and to provide information on the faults (such as time of occurrence, magnitude, severity). A FDD system can therefore be thought of as a data processing system based on information redundancy. Depending on the type of data and how they are processed, FDD methods can be classified into three categories [72]: model-based (or online data-driven), signal-based (or data-driven) and knowledge-based (or history-data-driven). Once a fault is correctly detected, isolated and identified, it is possible to exploit its knowledge

- in the so-called active fault-tolerant control paradigm, where the control law is modified in order to guarantee the satisfaction of desired specifications even in presence of the fault;
- at supervision level, for condition monitoring and/or prognosis purposes.

The first papers on fault diagnosis and fault-tolerant control of dynamical systems were published in the early 70's: from that time on the interest of the scientific community increased and now it is regarded as a specific field of research. The research group at the Department of Information Engineering started to investigate these aspects in the first half of the 2000s, and focused its activities on the following topics: model-based fault diagnosis and fault-tolerant control, and data-driven fault diagnosis.

3.1 Model-Based Fault Diagnosis and Fault-Tolerant Control

This activity concerns the study and implementation of algorithms for the detection and isolation of faults, affecting the input or output channels, in the case of systems described by specific models, both linear and nonlinear. For the linear case, the main results regards the methodology, and in detail the use of the geometric approach to solve the problem of detecting faults in periodic discrete-time systems [114, 115]. An observer-based residual generator is designed in [136], where each residual is sensitive to one fault, whilst remaining insensitive to the other faults that can affect the system. In case the linear system is affected by non-Gaussian noise, the state estimation and thus the fault detection results a challenging problem which could be improved using a Kalman-like filtering approach [78]. For the nonlinear case, the main results are of applicative nature, and related to the use of nonlinear observers to detect faults in unmanned vehicles [83, 85], and the use of structural analysis to detect and isolate faults on unmanned ground vehicles [118, 119].

Once a fault is correctly diagnosed or estimated, it is possible to exploit the information contained in it to modify the control algorithm. By following a model-based approach, the study and implementation of fault-tolerant control algorithms have been investigated in the case of systems modelled by nonlinear differential equations. This activity is mainly focused on adapting existing techniques in order to apply them for the control of unmanned vehicles. Marine vehicles, ground vehicles and aerial vehicles have all been investigated: a brief description of the main results is proposed in the following. In [112] the problem of fault tolerance is faced on a specific unmanned aerial vehicle, namely a quadrotor vehicle, in case of actuator loss. The paper proposes a solution to this loss of control action by spinning the vehicle in the yaw direction, thereby maintaining flight control of a spinning vehicle: flight control is achieved through the combination of robust feedback linearization and H_∞ loop shaping technique. When the vehicle has more actuators than degrees of freedom, control allocation can be used to deal with faults without modifying the control law [70]. This is the case faced in [4], which presents a strategy for trajectory control of a Remotely Operated Vehicle (ROV) in case of actuator failures: Dynamic Surface Control is used to achieve trajectory following, where a fault-tolerant allocation policy is used to distribute the load on the motors, assuming that the fault information is known. In [69], an actuator fault-tolerant control scheme, composed of the usual modules performing detection, isolation, accommodation, is proposed and designed for a class of nonlinear systems, and then applied to an underwater remotely operated vehicle used for inspection purposes.

3.2 Data-Driven Fault Diagnosis

This research activity takes into consideration the study and implementation of algorithms for the detection and classification of faults for systems where a significant input-output dataset of samples is available. From a methodological point of view the research involves mainly statistical analysis, while the application fields are that of rotating machines and industrial plants.

In detail, [24] proposes a new method, called *Statistical Spectral Analysis*, which allows robust diagnosis of faults in rotating machines by analysing a data set, even in case of poor signal-to-noise ratio, different time segmentation and different operating conditions. The research on industrial plants, instead, aimed at finding solutions to overcome to the growth of complexity in the analysis of process faults that typically involve many variables and where variables may exhibit a slightly different behaviour from the training case due to different environmental and/or operative conditions. The system combines the Principal Component Analysis (PCA) approach, Cluster Analysis and Pattern Recognition techniques [146]. The development of a rigorous way to determine the dimension of the PC subspace is a major contribution of this research which is particularly effective when approaching fault diagnosis problems with PCA techniques in real contexts such as refinery plants. The proposed Principal Component (PC) selection method is based on the statistical test ANalysis Of VAriance (ANOVA); furthermore, an innovative procedure based on the power spectrum of the input signals, provides adaptive thresholds used to identify a fault condition. Finally, Cluster Analysis and Patter Recognition has been combined to develop an automatic procedure, implemented in a Fuzzy Fault Classifier. Classification of the most probable faults has been performed taking into account the data correlation by the use of the Mahalanobis distance metric [142]. This sensitively increased the performances of the overall system.

4 Industrial Automation

4.1 Model Predictive Control

The research activity of LISA (Laboratory for Interconnected Systems Supervision and Automation) is focused on the study of Advanced Process Control (APC) techniques aimed at applications oriented to energy efficiency achievement and improvement for energivorous process industries [148]. Studies about theoretical and practical aspects of APC have been conducted, focusing on Model Predictive Control (MPC) techniques. A proprietary APC framework based on a two-layer linear MPC architecture has been developed, based on a linear state space approach that provides an explicit time delays compensation. The developed APC scheme has been suitably characterized: innovative contributions concern a coherent and consistent formulation of the two MPC modules within the two-layer scheme, together with improvements on the online cooperation policy between them [152]. Specific methodologies for parameters and constraints changes handling have been formulated and infeasibility prevention has been achieved [155]. Additional contributions about input-output time delays handling have been provided. In particular, in order to perform an efficient handling of critical situations due to the presence of different time delays on single inputs-output channels, the lower layer of the MPC scheme has been redesigned performing a structural decoupling on output variables constraints softening [151]. Additional innovative contributions in the controller formulation concerned the online inhibition of selected control inputs with respect to defined outputs [154] and the online introduction of process variables status values [124]. In the developed APC framework, a status value for each process variable has been introduced and included in the two-layer MPC formulation, in order to correctly manage the process variables in all conditions. An innovative unified approach has been formulated for the inhibition specifications and the status values information related to control inputs and outputs [153]. The developed APC framework has been customized for its installation on real industrial processes, represented by steel industry billets reheating furnaces and cement industry clinker rotary kilns. These processes are characterized by high energy consumption and large energy efficiency margins have been observed [147]. With regard to steel industry billets reheating furnaces, specific needs for the plants conduction have been taken into account and a customized APC framework has been developed [3]. Considering the lack of information on billets temperature within the furnaces, a virtual sensor based on a first principles adaptive nonlinear model has been introduced. In order to introduce the billets temperature information within the customized linear MPC scheme, a Linear Parameter-Varying (LPV) model has been accordingly derived [149]. Methodologies for online adaptation of the time horizons have been provided. Furthermore, as additional issue, an ad hoc stoichiometric ratios control method has been developed introducing a tailored linear formulation [153]. The formulated control method for steel industry billets reheating furnaces has been awarded with an Italian patent. Up to now six installations on reheating furnaces located in steel industries of various European countries have been commissioned. In all real applications energy efficiency certificates have been obtained, together with improvements on process control. The developed APC systems received the Industry 4.0 Certification. The customization of the developed APC system for the cement field confirmed the validity of the proposed constraints softening decoupling strategy oriented to time delays handling [151]. An additional contribution has been provided with regard to the usage of sporadic feedback information related to clinker quality (free lime laboratory analysis) in the MPC scheme, establishing a direct relationship between the sporadic feedback and the constraints of selected control inputs [157]. The customized cement industry APC system has been installed on several cement industries [158]. The resulting fuel specific consumption reduction allowed obtaining energy efficiency certificates [156].

4.2 *Robust Control Design*

This research activity was carried on for several years as the result of cooperation between Università Politecnica delle Marche and Università di Camerino. In addition to the authors of the present contribution, the scientific activity involved several researchers in both universities, whose names can be found in the references list. The main subject of this partnership has concerned the control of electrical, electromechanical and robotic systems characterized by a considerable degree of uncertainty. The most significant results have been achieved in the field of robust control design for Electrical Drives and for Wind Energy Conversion Systems (WECS).

4.2.1 Electrical Motors

As is well known in literature, parametric uncertainties and disturbances are a crucial issue when dealing with electrical motors control design. As a consequence, a robust control approach is needed to have a feasible control system with satisfactory performances. Another important aspect to be considered is the introduction of suitable observers, or estimators, to get an estimation of mechanical variables not convenient or impossible to be measured, such as the rotor speed. In order to cope with these topics, in [62] a robust speed estimator has been presented, to get the rotor speed using the position measurements supplied by an encoder. The proposed estimator, based on a sliding mode approach, guarantees a bounded estimation error and good performances, as fare as tracking precision is concerned. The solution reported in [62] has been extended in [23], by the introduction of a neural network aimed at evaluate the system uncertainties, obtaining a significant improvement in the overall control system performances. Finally, the contribution [61] is based on a suitable and innovative sliding mode observer-controller couple, ensuring the estimation and tracking errors boundedness.

4.2.2 Power Converters

Power electrical devices have been given a growing attention in recent literature, since they can be used in several applications and their features make possible a better use of the electrical energy. Also in this field it is essential to develop robust control strategies, in order to improve the system performances. In the paper [26], the classical passivity based control techniques have been extended and applied to boost converters operating in an interleaved mode, while a similar approach is introduced in [28] for converters operating both in CCM and in DCM mode. Finally, in [27] a unified current observer is presented for sensorless control of DC-DC converters.

4.2.3 Wind Energy Conversion Systems

Control problems for Wind Energy Conversion Systems (WECS) has been the more relevant activity carried on within the research collaboration between Università Politecnica delle Marche and Università di Camerino. In particular, wind turbines with variable speed have been considered, in order to make wind turbines to work at the maximum efficiency point for a large range of wind speeds. As a first contribution, paper [64] solves the problem described above without using any wind measurements, by the introduction of a robust sliding mode observer of the aerodynamic torque. This observer generates the reference signal for the field-oriented control system, regulating generator electrical currents, in order to supply the required electromagnetic torque. As a development of this approach, a robust fully sensorless control system for wind turbines equipped with a permanent magnet synchronous generator is presented in [63], whose extension to the case when the drive-train is present is proposed in [65].

Another important aspect of WECS control concerns the high wind speeds region, the so called region 3, where control of blade pitch is typically used in order to limit the captured wind power, so that safe electrical and mechanical loads are not exceeded. In [66], a wind robust observer and a sliding mode pitch controller are used, in order to minimize the error between the rated wind turbine power and the actual one.

Finally, the problem of faults in the generator electrical currents is solved in [67], using a robust control approach.

It is worth to be noticed that the work on WECS has been supported by the National Grant PRIN 2015, called “Smart Optimized Fault Tolerant WIND turbines”.

5 Robotics

Research and development of robotic systems has been attracting the interest of both the academic and professional world since the early 60’s, when robots were employed for the very first time in industrial applications. Since then, they have experienced an exponential growth, which led to modern robotic systems ranging from industrial to medical, and from exploration to service applications. The research group of Università Politecnica delle Marche focused its activity mainly in the fields of marine robots, wheeled robots, robotic manipulators and assistive robots.

5.1 Marine Robotics and Applications

Almost all activities that are carried on nowadays in marine research and in marine industry make use of robotic systems and platforms. In this field, problems to face are numerous and more difficult if compared with those encountered in other application areas of robotics. In the past 25 years, the research activities carried on at the Laboratory on Modelling, Analysis and Control of Dynamical Systems (LabMACS) of the Department of Information Engineering of the Università Politecnica delle Marche have addressed control, modelling and data acquisition and processing problems that are related to the construction of Navigation, Guidance and Control (NGC) systems for unmanned underwater and surface robotic vehicles.

In 1999-2001, the LabMACS team coordinated the National Research Project "NGC VERAS: Navigation Guidance and Control of Robotic VEhicles for Submarine Activities". The project addressed several problems in control and guidance of underwater unmanned vehicles and, in that framework and in the following years, the LabMACS team concentrated on the study of different control laws for depth control, attitude control and trajectory tracking of underwater vehicles exploring the potential of various nonlinear, robust and fuzzy control techniques. Visual control techniques for navigation and guidance and the use of acoustic sensors for positioning and obstacle avoidance [29, 32, 54–57, 137, 150] were also investigated. The project put the basis for a strong cooperation between national research groups that continues today.

In 2006–2008, the LabMACS team took part in the "VENUS: Virtual ExploratioN of Underwater Sites" European research project. The aim of the project was to set new standards in the use of robotic tools and methods in the exploration of underwater archaeological sites. The LabMACS team contributed significantly to the development of advanced best practices in the exploration of fragile underwater environments and of scientific methods and tools for their reconstruction in virtual reality. These results were achieved by introducing logic feedback loop in the execution of exploration missions and in merging navigation information with visual and acoustic images of the explored site in order to facilitate its 3D reconstruction [31, 74–76, 140]. Cooperation between European partners with expertise in various disciplines produced practical efficient procedures for the use of underwater robots and control technologies in underwater archaeology and it fostered further advances in that discipline.

More recently, starting from the experience of several missions at sea, the LabMACS team coordinated the National Research Project "ROAD: Robotics for Assisted Diving" [53]. The aim of the project was to develop robotic and automatic devices and systems to monitor the behavior and the physiological conditions of divers during the dive. The main product was the development of a wearable patented device [Italian Patent n. 102015000053133] that, evaluating the response of a subject to a flickering light, can detect abnormal and dangerous stress conditions [135]. Other results are related to the development of a hybrid surface/underwater robotic platform consisting of a small autonomous surface vehicle (ASV) that can deploy and recover a micro underwater vehicle (micro-ROV) [30]. The platform serves to collect behavioral and physiological data of divers to be sent to a remote supervisor and to provide assistance in moving and positioning in the underwater environment.

Activity has further grown in recent years thanks to participation in a number of European research projects (EPOCH [143], Sunrise-OptoCOMM [20]; Green Bubbles [139, 159]; Lab4Dive [141]; EUMR-Marine Robotics) and cooperation with the Interuniversity Centre for Marine Environment-ISME, the NATO and the Italian Navy. The main results are the development of electro/optical underwater modes for the construction of underwater communication networks that may support an IoT structure in the underwater environment; the development and testing of data acquisition procedures and data processing algorithms that can produce accurate, geo-referenced 3D reconstructions of underwater sites during the mission time; the study and development of underwater scooters that can assist divers in a number of tasks.

Thank to cooperation with marine biologists, archaeologists, oceanographers, professional and recreational divers, the research effort in the framework of the above-mentioned projects has contributed to enhance the use of robotics and of control technologies in scientific and industrial communities that operate in the marine and underwater environment. To promote further this action, the LabMACS team has recently engaged in the development of innovative curricula and tools to teach eSTrEM (environment Science Technology robotics Engineering Math) in a comprehensive STEM education framework. The primary product of this work is a biomimetic underwater autonomous robotic vehicle (AUV) that replicates the aspect and the locomotion system of a fish, developed, in cooperation with the Department of Industrial and Mathematic Sciences Engineering, within the OpenFISH.science Project. The AUV is a cost effective, modular and highly extensible platform that students can use to design and test new technologies for underwater robotics and its applications in exploring, surveying and the monitoring underwater environment [22, 71, 138].

Always remaining in the field of Marine Robotics, the activities carried out at the Robotics Laboratories focused instead on the control of single and multiple vehicles. In detail, in collaboration with Snamprogetti for the development of an underwater vehicle, various control systems were analyzed and developed taking into account that the dynamic model of the vehicle is non-linear and with parameters strongly dependent on operating conditions [58, 100, 116, 117]. The formation control of a fleet of unmanned underwater vehicles is faced in [84]: a networked decentralized model predictive control algorithm is developed, which can cope both with communication faults and vehicle faults, namely when the communication between two vehicles is lost or one of the vehicles can no longer function properly. Recent results regard the development of a control strategy to face the dynamic positioning of an offshore supply vessel [6].

5.2 Wheeled Robots

The main research activities on wheeled robots are related to the problems of localization and navigation, and the main results are described in [2, 13, 73, 101]. In detail, [2, 73] propose the LabMate mobile robot and its real-time system for the solution of the tracking problem in a real context with environmental disturbances and parameter uncertainties. Localization is performed by using internal sensors like odometers and optical fiber gyroscopes, and three simple localization algorithms based on different sensor data processing procedures are presented in [101]. A modular navigation solution for electric wheelchairs is proposed in [13] by using commercial and low cost devices.

5.3 *Robotic Manipulators*

Robotic manipulators have been designed in order to replace workers in challenging industrial activities, such as moving heavy or dangerous objects, assembling mechanical structure, and others. At present, industrial robots are transforming into collaborative robots, and both kinematic resolution and dynamics control are increasing their importance.

5.3.1 Kinematic Control

In [86] the redundancy analysis of two cooperative manipulators is presented, showing how they can be considered as a single redundant manipulator through the use of the relative Jacobian matrix. In this way, the kinematic redundancy can be resolved by applying the principal local optimization techniques used in the single manipulator case. In [122] the problem of cooperative manipulation of a rigid object when the manipulators are subject to joint constraints and priority task policy is faced. In [87], instead, a scheme is proposed for the fault-tolerant control of a two-arms system subject to faults on the actuators: the scheme provides both fault estimation via non-linear observers, and compensation at the kinematic level.

5.3.2 Dynamics Control

In [59] a discrete time sliding mode controller has been coupled with a robust observer, able to make an on-line estimation of the uncertainties characterizing the plant. This solution allows to improve the control system performances, especially when load variations or torque disturbances are present. A different approach is presented in [60], where a sliding mode controller, coupled with an efficient training algorithm for neural networks, based on Kalman filtering, guarantees the boundedness of the tracking error also in the presence of large parametric uncertainties.

5.4 *Assistive Robotics*

Assistive technology is defined as any item, piece of equipment, or product, whether acquired commercially, off the shelf, modified, or customized, that is used to increase, maintain, or improve the functional capabilities of individuals with disabilities [13]. The research activity on assistive robotics is projected towards human-robot cooperation, such that people who need assistance can be monitored by service robots [5] or in assisted environments [120], localized indoor [25], assisted during rehabilitation [21] and supported during their movements [13, 81].

6 Intelligent Manufacturing

6.1 From Control Theory to Intelligent Manufacturing

Control theory made significant strides in the last 100 years, since fifties (a few years before the foundation of the Università Politecnica delle Marche) the new mathematical techniques made it possible to control, more accurately, significantly more complex dynamical systems than the starting ones. The complex control processes that regulate the daily life of the human beings have represented a motivation and a blueprint not only for the control theorists but also for the modern robotics and automation disciplines, the information and communication technologies, the computer science, and eventually the artificial intelligence. All the former disciplines, since a decade, have been collected under the unified framework of the cyber-physical system (CPS) modelling and design. CPS are at the groundings of the new developments in all the entities of the systems that range from the single mechatronic or electronic device to the large scale of hierarchies and interconnected networks of them. Such systems and their complexity are studied today with a system of systems approach in the context of the Industry 4.0 and the automotive sector.

In the previous context, Bonci et al. [17] proposed a lightweight framework for the modeling, control, simulation, planning, optimization, and scheduling of industrial processes. It is based on the pervasive use of relational database systems that actively support the transmission, storage, and elaboration of information across the multidimensional levels defined in the new reference architecture RAMI 4.0 that covers all the ranges from sensing and actuation to the management of a network of enterprises across the whole life-cycle and sustainability issues. It was developed to include new generation of mechatronic actuators [19], smart sensors and multiagent systems [14], but mostly the proposed infrastructure and framework is the key enabling prerequisite for the inception of new computation means in the CPS as the systems of systems. In [18], with the use of proper distributed and recursive computation approaches, the complexity of the control of the CPSoS (cyber-physical systems of systems) is attacked through a unified and human-centered simple framework that introduces the automation of the management by means of knowledge-based performance metrics. The technique has been already challenged in industrial robotics [99], in highly flexible and human-centric manufacturing [144], in service processes [145], and in the construction and building automation sector [134].

The former technique is also a fundamental tool in the new grand challenges of the management cybernetics, which needs the introduction of embodied artificial intelligence at the core of the CPSoS seen as viable living system [16], constituted pervasively by autonomous multiagent systems [15].

6.2 How Control Theory Has Influenced Automotive Manufacturing: Case Study

Automotive is key relevant in the European manufacturing system. Intelligent Manufacturing and Services in Automotive will be more and more pervaded by intelligent control systems supported by ICT technologies. Over the last decades the automotive sector has been experiencing great technological innovation contributing to improve performance, efficiency and mostly, vehicle safety. This also thanks to the support of the control systems theory. Thinking about the near future, we expect autonomous and connected cars to make their way onto the roads with consequent benefits of reduced accidents as well as better traffic management and driver comfort. A virtuous trend is being established among technologies providers, manufactures and governments such that it is encouraged the need for enhanced regulations making important safety features mandatory for vehicles. An example of what EU (European Union) proposes in order to reduce deaths and fatal injuries on the roads is reported in [77]. Among innovative safety devices, in the spotlight are the Intelligent Speed Assist, the Advanced Driver Assist system and the Intelligent Emergency Braking. These devices will strengthen the vehicle safety by collaborating with wellknown active systems such as ABS (Anti-Lock Braking System), TCS (Traction Control System), ESC (Electronic Stability Control System) for cars or MSC (Motorcycle Stability Control).

Notoriously, the evolution of the technological trend for cars have also paved the way for two-wheeled vehicles, although with some delay. Indeed, starting from 70', when BMW conceived the first helmet as passive safety system for the rider, commercial motorcycles deployed their first ABS only in 1988, by the same manufacturer, the TCS in 2008 and the first stability system controller (MSC) in 2014. Nowadays, top level devices such as the MSC, are far from being regulated for two-wheeled vehicles and their deployment is still prerogative of high-end motorcycles.

In addition to safety issues, the impact of the vehicles on the environment is no longer considered as a feature of secondary importance. The Eco-friendly requirement is leading to an increased share of market of electric cars and that is expected to happen to motor-cycles as well. Even though the concept is not new in the field, advanced traction systems for motorcycles with electric actuation may become appealing if we look at the proven benefits brought by the active torque distribution in a four-wheeled car.

In this scenario, the automation group of the Università Politecnica delle Marche is engaged on the modelling and control of the dynamics of two-wheeled vehicles

(PTWs) and cars. Over the last years, the state of the art on the motorcycle models proposed in literature have been further shifted towards the development of motorcycle models with minimum complexity [7, 11], which still offer sufficient accuracy in the simulation of the major motorcycle's dynamics. In particular, the proposed tools represent the first attempts present in literature to address analytically the dangerous falls such as the Lowside and the Highside falls [13, 14]. The critical dynamics that arise and favour the falls may put at serious risk the life of the rider. Such dynamics are usually sparked by important phenomena such as the wheels slippage in cornering due to abrupt accelerations, braking or adverse road conditions. These critical driving situations can be well described by the proposed models thanks to the inclusion of an adequate nonlinear characterization of the tyres [12]. The models were validated using commercial multibody software. Also, the study of the structural properties of the are undergoing. The same tools may be also deployed in a model-based design of vehicle stability controllers for active safety devices.

In the context of the issues relative to the vehicle safety, the researches are addressing the development of traction control systems. A first traction controller for two-wheeled electric vehicle with rear traction has been designed and proposed in [9]. This controller acts on the longitudinal dynamics of the vehicle and it is based on a nonlinear model predictive approach (NMPC). The designed controller prevents the driven wheel from spinning out when accelerating in order to maintain driving performance and comfort. An alternative traction control was developed and sliding mode approach was followed [8].

Further investigation on the non-trivial and complex effects of a longitudinal traction control on the lateral dynamics of the vehicle was proposed in [10]. Here the optimal controller still follows the NMPC approach with a simple rider model driving the vehicle along a chosen circular trajectory.

With the goal of designing safety devices increasingly performing, the automation group will be concerned on providing faithful vehicle models. Furthermore, more efficient drive solutions based on electric systems and involving torque distribution among more wheels will be considered.

Looking more further, it will expect to deal with alternative systems for the vehicles' movements, e.g. involving the reconfigurability of the treads, as long as the classic wheel is still considered the interface between the vehicle and the road. Of course, a bunch of innovative and clever systems such as the Bosh jet thrusters applied on the motorcycle are making their way in a competitive scenario where the vehicle safety will be the primary concern.

7 Conclusions and Future Challenges

In this chapter, the main results achieved in the last 50 years by the Automatic Control group of Ancona have been revisited emphasizing, in particular, the recent contributions which range from control system theory, to fault diagnosis and fault-tolerant control, industrial automation, robotics and, finally, to intelligent manufacturing.

Although there are many successful embodiments of control theory and automation, there are still significant scientific challenges that have be to overcome in the next future where the control and automation are going to play a key role for the enhancement of the society. In a time where people and things will be more and more connected by network, the automation and control engineers will have new opportunities making use of the huge amount of available data. One challenge will be to exploit this huge information to develop new and more accurate process identification techniques. Knowledge-based method will probably become more reliable and fast. The challenge, then, will be to select the right features among those available, and to fuse knowledge-based method together with signal-based and model-based. The availability of huge amount of data (big data) will permit diagnosis to evolve to prognosis, which will be used to change the paradigm of maintenance from planned to on-demand according to the real state of the monitored plant. In the next future, techniques of Artificial Intelligence will be applied to control system design, providing new control structures where controllers will be able to learn and to self-organize whenever the system structures change. Similarly, robotic research will benefit from the above mentioned techniques, and this will open the way towards full autonomy of robotic systems.

Acknowledgements We would like to thank and to remember Prof. Tommaso Leo, passed away in 2014, for his strong leadership and mentoring when he was for many years the dean of control systems theory group at Università Politecnica delle Marche.

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