The innovative methodology and the ACODUASIS project

Francesco Donati

Politecnico di Torino (I), *francesco.donati@polito.it*

Abstract

The paper describes the innovative methodology for plant control design, which has been transferred from EICAS to the Partners of the ACODUASIS project. After having stated that the dynamic performance of an actual plant cannot be strictly described by any mathematical model, such a control design methodology adopts an approach based on the use of two models, respectively the plant simplified model and the plant fine model. The methodology aims at getting on the basis of the plant design data a plant control design, which offers guaranteed performance without need of experimental control tuning or other measurement data from the actual plant.

Keywords: automatic control design, robotic control application, experimentation results, industrial prototyping.

1 Introduction

The "one step further in the automatic control design" mentioned in the workshop title lies in an innovative plant control design methodology which, starting from the plant design data, allows to design a plant control system with guaranteed performance, without requiring experimental adjustments or parameter control tuning.

Since the first automated plants of the last century the control experimental tuning has an important role and it is considered as a strictly necessary step in the plant control design. A gap exists between control theory, which has been significantly developed, and control practice, which has not followed such a development. Sophisticated and powerful control algorithms can be designed in theory, but in practice simple control algorithms are adopted, because the more powerful algorithms are too sophisticated with so many degrees of freedom that they cannot be tuned by means of experimental trials.

The present gap between theory and practice is now better focused.

The automatic control theory concerns the design of the automatic control of "dynamic systems", where "dynamic systems" are mathematical objects defined by an axiomatic concept (the definition formulated by R.E. Kalman in 1969 is commonly adopted).

The practice of the automation concerns the design of the automatic control of "plants", where "plants" are physical objects belonging to the real world.

In both cases the control aim is to determine a sequence of values of the (dynamic system or plant) input variables in such a way that the (dynamic system or plant) output variables track stated reference signals within stated accuracy limits.

The bridge between theory and practice is given by the "plant mathematical model", which is a "dynamic system" used to describe the plant dynamic behavior.

The gap between theory and practice is in the fact that the "plant mathematical model" gives always only an approximate description of the plant dynamic behavior and consequently the following significant difference results between the automatic control design of "dynamic systems" and "plants":

- given an observable and controllable “dynamic system”, it is always possible to design an automatic control which gets any required performance. In case of linear, time invariant and finite order dynamic systems the control design is a quite scholastic problem.
- given a “plant”, conceived and designed in order to be automatically controlled, an upper bound to the best control performance of any feasible control system always exists. The plant designer does not know which is the above upper limit, that is got by tuning experimentally the control parameters of a sufficiently simple algorithm.

The aim of the methodology here presented is to overcome the above gap between theory and practice by means of an approach to the plant control design, which allows to design the plant control system from the plant design data and to evaluate its guaranteed performance without the need of experimental tuning.

2 Definitions and fundamental theorem

1.1 Notations

Plants and related models have, generally, multi-inputs and multi-outputs. The following notations are used:

- $u(i)$ is the vector of the input commands (which are common to plant and model),
- $d(i)$ is the vector of the unknown disturbance acting on plant,
- $y(i)$ and $ym(i)$ are the output vectors, respectively, of plant and related model,
- $r(i)$ is the reference output vector.

In the output vector space, to which the vectors y, ym and r belong, a norm is introduced which is assumed to be suitable to measure the differences between plant and model outputs (plant-model uncertainty) through $||y\text{-}ym||$ and between plant output and reference (control performance) through $||y\text{-}r||$.

1.2 Plant-model uncertainty definition

Models can give only an approximate description of the related plant dynamics, so that a plant-model uncertainty always exists as an effect of unknown disturbances acting on the plant (additive noise), of an inaccuracy of the model parameter values (model parameter error) and of the model structure which does not allow to give a full description of the plant dynamic behavior (structural uncertainty).
The result of the above uncertainty causes is an error $e(i)=y(i)\text{-}y_m(i)$ between the plant actual output $y(i)$ and the one $y_m(i)$ computed through the model (see Fig.1).

Defined a suitable norm in the output signal space, the plant-model uncertainty can be measured by the norm $||y\text{-}y_m||$. The uncertainty is said to be *“norm bounded”* if finite D and E exist, so that the following inequality holds:

$$||y\text{-}y_m|| < E\,||y_m|| + D \qquad (1)$$

for any $u(i)$ belonging to the admissible input set, for any disturbances $d(i)$ belonging to the admissible disturbance set and for any plant admissible operating condition, as they are defined by the control technical requirement specifications.

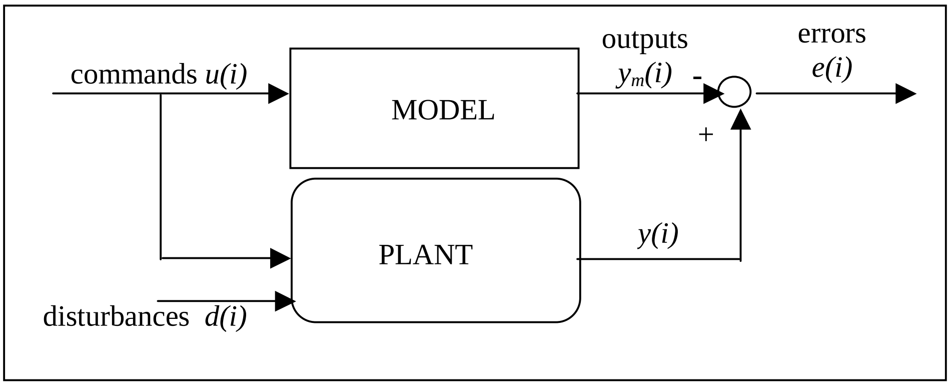

Fig. 1 Plant – model uncertainty

1.3 Control performance definition

Given a reference signal $r(i)$, the closed loop control aim is to determine the command $u(i)$ in order that the output variable $y(i)$ tracks the stated reference $r(i)$ (see Fig.2).

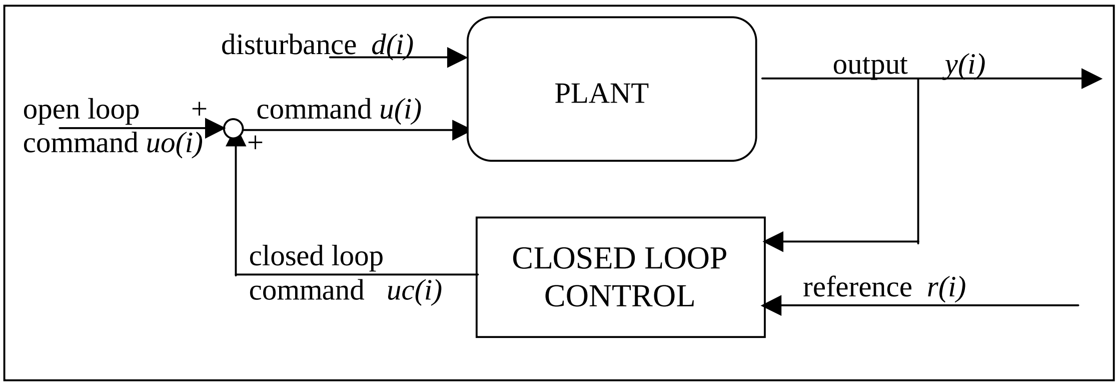

Fig. 2 Plant closed-loop control

The aim of the control is to make small the reference-output error $ey(i)= r(i) - y(i)$ given by the difference between reference and output. Then, the closed loop control performance is measured by the reference-output error ***attenuation factor Q***, defined by the following relation (where $y_o(i)$ is the expected plant output in the absence of any closed loop control ($uc(i)=0$) and $y(i)$ is the output in the same working conditions but in the presence of closed loop control):

$$|| r - y || < Q \, || r - y_o || \qquad (2)$$

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for any reference *r(i)* belonging to the admissible reference set *R*, any disturbance *d(i)* belonging to the admissible disturbance set *D* and any plant admissible operating condition, as they are defined by the control technical requirement specifications.

1.4 Fundamental theorem about control performance in presence of model uncertainty

The plant control guaranteed performance can be evaluated by the theorem stated in [1] and [2], which is here recalled.
Let us consider a plant *P* described by an approximate mathematical model *M* . Then, let us consider a closed loop control *H* designed on the basis of the model *M*, which, when applied to the model, attenuates the reference-output error, caused by additive disturbances, of a factor Q_o (according to the above definition (2)).
If the plant-model uncertainty is "norm bounded" (see eq. (1)) and it results $E<1/(1+ Q_o)$, then, the same feedback control *H*, when applied to the plant *P*, gives an attenuation factor *Q* with the following upper bound:

$$Q < Q_o/(1- E (1+ Q_o)) \qquad (3)$$

The above inequality states the worst value of the plant control attenuation factor *Q* given the model control attenuation factor Q_o and the plant-model uncertainty coefficient *E* within the condition $E<1/(1+ Q_o)$. Because Q_o is always very small, in the following the above required condition is approximated by the simpler one: $E<1$.

3 Unavoidable limits in plant modeling accuracy

Stated, on the basis of the control theory, that the attenuation factor Q_o of the reference-output error can be made as small as required for any controllable and observable dynamic system, from the above fundamental theorem it follows that if $E<1$, then, also *Q* can be made as small as required.

But an important question arises: can plant models be constructed which are compliant with the requirement E<1?
The answer is negative. Given a "plant" (strictly a physical object belonging to the real world) it is never possible to construct a mathematical model which describes it within the constraint E<1.

The reason is at the same time philosophical and technical. The impossibility is due to the fact that an infinite quantity of information is required to describe the dynamic behavior of an actual plant (considered as a mapping from an input set of time functions to an output set of time functions) when signal classes with infinitesimal time resolution or, equivalently, with infinite frequency bands are considered. Indeed, the dynamic behavior of an actual plant in high (going to infinite) frequency band cannot be derived by the knowledge of the plant behavior within a finite low frequency band, because any a priori assumption that actual plants can be strictly modeled by a finite order dynamic system must be rejected. Then the quantity of information necessary to describe the plant dynamic behavior is going to infinite with the considered frequency bandwidth.

Then, given an actual plant and any finite order dynamic model of it, it can always be found an input signal with energy distributed at so high frequency values that the error $||y - ym||$, between the responses *y(i)* and *ym(i)*, respectively, of actual plant and its model, is larger than the model output $||ym||$ and that causes $E>1$.

But, on the other side, a plant automatic control design is never required to attenuate the reference-output error in the whole frequency domain up to infinite frequency values.
Then, when the interest is focused over a limited frequency domain, it becomes possible to construct plant models and to design plant control which can guarantee a stated performance within the above limited frequency domain. Such a result may be obtained by means of a suitable state observer design as proposed in [2].
Let us consider the scheme of Fig. 3.

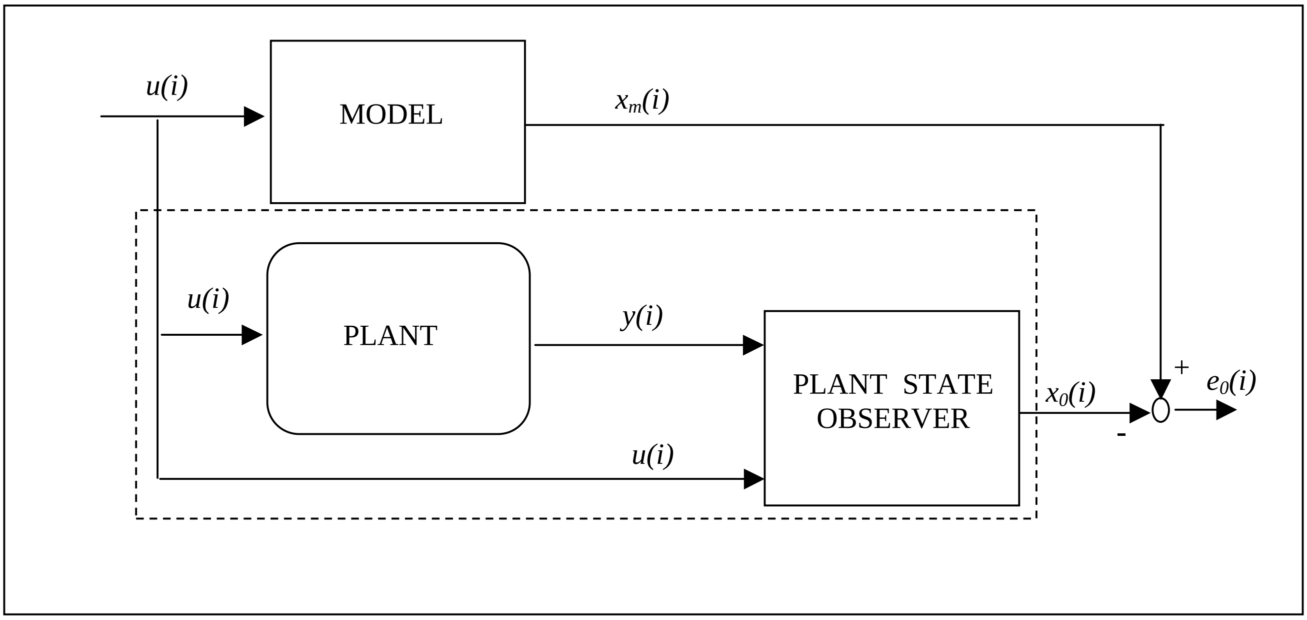

Fig. 3 The cascade of plant and state observer is compared with the plant model

A plant state observer is designed on the basis of the plant model and the system resulting from the cascade of plant and related state observer is considered. The aim is now to have a good model of the above system composed by a plant and its related state observer in order to design a closed loop control of the observed state variable $x_0(i)$. The modeling error is then evaluated by comparing the plant observed state value $x_0(i)$ with the model state value $x_m(i)$ under the same input *u(i)*.
The modeling uncertainty limits are, then, expressed by the parameters E_o, D_o determined in such a way that the following inequality holds

$$||x_m - x_o|| < E_o \, ||x_m|| + D_o, \qquad (4)$$

for any *u(i)* belonging to the admissible input set and for any plant disturbance within the set of the plant admissible working conditions.
Given a model (finite order dynamic system), describing in a sufficient accurate way the plant dynamic behavior from continuous up to a limited frequency range, the constraint $E_o<1$ can be always imposed by a suitable design of the plant state observer. The proof is trivial, indeed it is sufficient to use a plant state observer which has been designed for the plant model with a fre-

quency bandwidth limited to the frequency range within which the model gives a sufficiently accurate description of the plant behavior. In fact, in such a condition outside of the observer frequency bandwidth, within which the plant has been correctly modeled, the error $e_0(i)= x_m(i) - x_0(i)$ tends always to zero.

Stated the inequality (4) within the constraint $E_o<1$, then, on the basis of the above fundamental theorem, a closed loop control designed on the basis of the model can be applied with guaranteed performance to the system resulting from the cascade of the plant and its state observer.

In the following Fig. 4 the complete scheme of the plant control is drawn.

Let us point out that the plant observed state value $x_0(i)$ has been subjected to closed loop control and, then, the above guaranteed performance is not directly related to the plant reference-output error $e(i) = r(i) - y(i)$, but to the error $ex(i)= rx(i) - x_0(i)$, where $rx(i)$ is the state reference value. Having a guaranteed small error $ex(i)$ a constraint can be derived for the plant reference-output error $e(i)$, but only within the state observer frequency bandwidth.

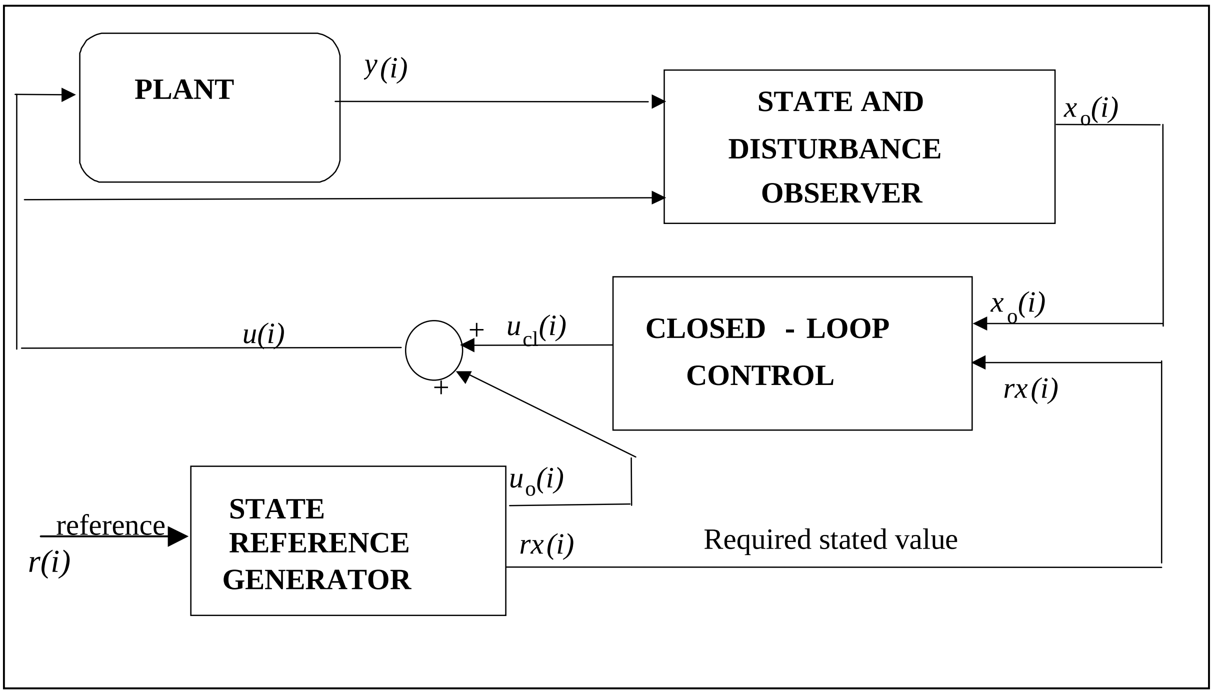

Fig. 4 The functional scheme of the plant control

The conclusion is that the plant control performance is strictly related to the goodness of the model used to describe its dynamic behavior. Since, given a plant, it is not possible to build a mathematical model of its dynamic behavior as accurate as required, it results that given a plant it is not possible to design a plant control which performs as accurately as required.
The above result is very important in the automatic control applications because it states that for any actual plant it exists an a priori upper bound to the best control performance that can be got.

The above upper bound cannot be overcome by improving the automatic control design, but only by improving the plant design.

4 Assessment of the plant-model uncertainty limits and plant control design

One of the aims of the illustrated approach to the plant control design is to get control guaranteed performance, avoiding the need of experimental tests to be carried out on the plant. Only in such a case, in fact, the control design can be developed at the same time of the plant design and the plant control guaranteed performance can be known before that the plant has been built.
For this reason the experimental identification of the model and of the plant-model uncertainty limits is not here considered. The only data, which are considered available, are the plant control required performance and the plant design data. Then, the approach to the plant control design is shortly outlined.

Given the above input data the designer has to choose a first tentative plant model on the basis of his own experience. Then, the control design is carried out and, if necessary, iteratively repeated, varying the tentatively assumed plant model.
The design approach is based on the following three main steps:

- plant-model uncertainty limit evaluation,
- plant control design,
- guaranteed performance evaluation.

The ***plant-model uncertainty limit evaluation*** is performed by building a new plant model more accurate than the previous one tentatively assumed.
The first plant model is denoted as the “plant simplified model” and has to be used as a basis of the control design. For such a reason, considering that the closed loop control design does never need a very accurate model and that the control of linear dynamic system is quite easy to be performed, typically the “plant simplified model” is assumed to be a linear, finite low order, time invariant dynamic system.
The second more accurate plant model is denoted as the “plant fine model”. It is used to point out the uncertainty which affects the “plant simplified model”. For such a reason the “plant fine model” is built starting from the “plant simplified model” and adding to this one the modeling of the neglected dynamic plant aspects, which are considered to be the most important ones from the control design point of view. The “plant fine model” results to be always of an higher order than the simplified one and typically non-linear and time-variant. Even if the “plant fine model” is yet a raw description of the actual plant, with respect to the “plant simplified model” it should be practically equivalent to the actual plant, in such a way that if a control designed only on the basis of the “simplified model” is so robust to get the required performance when applied to the “fine model”, then it has to get the same performance also when applied to the actual plant.
The use of two different models of the plant to design the plant control algorithm is a fundamental point of the innovative methodology. The “plant simplified model” is the main basis of the control design. The “plant fine model” is strictly related to the previous one, having the aim of showing the limit of the field within which the “plant simplified model” gives a description of the plant behavior sufficiently accurate from the point of view of the control design.

The ***plant control design*** consists of two main steps, the *state observer design* and the *state controller design*.
The *state controller design* is performed on the basis of the “plant simplified model” without considering the plant-model uncertainty, with the aim of getting in absence of any model uncertainty an attenuation factor Q_o which must be stated larger than the required value, in order to keep into account the deterioration caused by the presence of the model uncertainty according to the upper bound (3) stated by the above fundamental theorem.
The *state observer design* must be, on the contrary, specifically oriented to reduce the effect of the plant-model uncertainty and its design requires both the “plant simplified model” and the “plant fine model”. All the high frequency range, where the “plant simplified model” does not give a sufficiently accurate description of the plant dynamic behavior, must be cut out by limiting the state observer frequency bandwidth. In order to get such a result, the upper limit to the observer frequency bandwidth must be derived through the comparison of the simplified model with the fine one.

The ***control guaranteed performance*** is evaluated by a set of trials performed in a simulated environment by applying the designed control to the “plant fine model”. In order to optimize the control performance a tuning of the control parameters can also be performed in the same above simulated environment.
In such a way the obtained guaranteed performance is effectively related to the simulated “plant fine model” and not to the actual plant. It is the correct choice of the “plant fine model”, which, performed in a conservative way, allows to guarantee that the control performance related to the actual plant cannot be worse than the one related to the adopted “plant fine model”.

5 The ACODUASIS experience

As a partof the ACODUASIS project the above described methodology has been transferred to European companies and universities working in the industrial robot field and it has been widely tested. A set of plant control designs has been developed supporting the design by the use of EICASLAB, a professional tool, developed by EICAS specifically for its own use in automatic control design.
The results are illustrated by the papers [3],[4],[5],[6],[7],[8],[9] which are presented at this same workshop.
The main results and conclusions may be summarized as follows.

The two models approach appears as a powerful method to state on the basis of the plant design data the plant dynamic description given by the “plant simplified model” and the uncertainty limits of such a description specified by the “plant fine model”. Then, a suitable design of the plant state observer, assessed and tuned in a simulated environment by means of the plant fine model, allows to obtain a really guaranteed performance of the plant control.

The experience has proved that plant controls designed according to the described methodology does not need experimental parameter tuning in field and that the control performance is never worse than the one obtained with the classic design approach after a long experimental parameter tuning. But, on the contrary, typically, the obtained control performance is significantly better than the one obtained by methods based on experimental control tuning.

Another interesting result is the fact that plant simplified model and related plant fine model maintain always the same mathematical structure for all the plants belonging to a same technological family. That allows to create libraries both for the plant fine model simulation and for the plant control design, which can be reused in future plant control design with appreciable time saving.

Moreover, the facilities offered by EICASLAB to support the plant control design have been successfully tested. Among these facilities the “Automated Algorithm Generation” has to be particularly mentioned. Given the plant simplified model, the above facility allows to design automatically the plant control algorithm, avoiding the need that the designer may have to go deep in the automatic control algorithm design.
The “Automated Algorithm Generation” together with the “Numerical Control Parameter Optimizing” and the “Automated Code Generation” allows to get automatically the control application code of an optimized plant control once the designer has stated the plant simplified model and the related plant fine model.

As a conclusion let us point out that the most critical step in the plant control design is the choice of the plant simplified model and of the related plant fine model. Such a model selection requires deep expertise in the control design in the technological sector to which the plant belongs and, moreover, requires a clear understanding of the control performance requirements. The following control design steps can be largely automated and supported by a professional software tool like EICASLAB.

6 References

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