Application

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2015-04393 **Rojas, Cristian** **NT-14**

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Information about application

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Descriptive data

Project info

Project title (Swedish)*

En beslutsteoretisk ansats till systemidentifiering

Project title (English)*

A decision-theoretic approach to identification

Abstract (English)*

Data-based modelling, or system identification, is an essential but rather expensive component in the process of designing, commissioning and re-tuning of controllers in industrial practice. This is indeed the case for the implementation of model predictive control (MPC), which is one of the most popular industrial controllers used worldwide, in particular within the petrochemical, automotive, aerospace, food processing and mechatronics sectors, reaching up to 90% of their total budget, so improvements in this step can be expected to result in substantial reductions in the commissioning cost.

In view of the above, modelling is an important and critical part of control. However, it is well known that an important theory/practice gap exists: while control theory is highly sophisticated, most industrial control applications rely on very simple implementations. The bottleneck lies in the modelling step: the standard frameworks for system identification suffer from several limitations, rendering them incapable of providing good enough models for advanced control in a cost/time effective manner. For example, the standard framework for identification assumes, via "separation principles", that it is possible to subdivide the control commissioning process into independently designed steps; this is just a way to simplify the control design task, but which may lead to long experiments and several iterations to obtain a reasonable control. A second issue is that, due to the inherent complexity of real-world applications, it is practically impossible to recreate the whole dynamics of even a simple physical system with a finite set of equations. This means that we should often content ourselves with simple models. On the other hand, most research in system identification is based on exactly the opposite assumption, namely, that it is possible to completely describe a given system with a (simple) mathematical representation.

The overall objective of this project is to boost the foundations of system identification, making them suitable for the modelling of complex, real-world industrial processes, and hence bridging the gap between the theory and practice of system identification. From some preliminary results, we have noticed that a natural setup for achieving this goal is to pose the entire process in a decision theoretic framework, that is, where the control and identification steps are designed jointly with a final objective (namely, to minimize the economic costs involved in the industrial process). In addition, several recent and highly innovative developments from statistics, mathematical finance and machine learning can be employed within this framework to boost the status quo in control, by properly accounting for the risks involved due to uncertainty and turn the control design process into a high-performance, tractable and cost effective activity.

In particular, for this project we will consider the introduction of two novel tools in the control commissioning process. Firstly, we will employ techniques from the modern theory of risk measures, which belong to mathematical finance and operations research, to properly account for the risks introduced by noise and uncertainty in the various stages of control commissioning, and to push the economic objective through the entire process; unlike the standard approaches, which account for either the expected performance or its behaviour with high probability, the new tools can properly account also for unlikely but very costly losses. Secondly, we will apply results from the "prediction with expert advice" framework to system identification and model-based control, to overcome the limitations imposed by undermodelling. This approach considers models as advisors or experts rather than as approximations to reality, and it provides algorithms for efficiently determining the best expert in a given pool in terms of its end performance, with (relative) performance bounds which hold irrespective of the behavior of the true process.

Popular scientific description (Swedish)*

Ingenjörsvetenskap innefattar metoder och teorier för att konstruera och analysera tekniska system, som till exempel en självkörande bil. Förutom den rent mekaniska måste bilen styras med hjälp av information från sensorer med mera, så den löser sin uppgift. Reglerteknik handlar om smarta algoritmer som använder sig av konceptet återkoppling för att se till att systemet löser sin uppgift på ett säkert och effektivt sätt. För den självkörande bilen handlar det om att automatiskt styra bilen via gas, broms och rattutslag, så den inte krockar och samtidigt kommer till målet på en säkert och bränsleekonomiskt sätt. För att lyckas med detta kombineras information från kartor med sensorinformation från GPS, radar, kameror mm. Man kan också låta bilar ”tala med varandra och infrastruktur” genom att utbyta information via trådlös kommunikation. När den självstyrande bilen väl känner till sin position, hastighet och vad andra bilar och gående befinner sig och planerar att göra, så fattas ett beslut i en dator om vad bilen nu skall göra (gasa, bromsa, svänga och så vidare.). Detta beslut implementeras sedan och motsvarande styråtgärd utförs. Detta förfarande upprepas sedan hela tiden. En utmaning är att förstå hur bilen och omgivningen uppför sig, det vill säga att kunna förutse framtida situationer så att man inte reagerar för sent eller för kraftigt. Felaktig återkopplad reglering kan orsaka instabilitet. En förare måste genomgå en körkortsutbildning med praktik för att lära sig att köra bil och förstå hur trafik fungerar. När man skall göra motsvarande för en självkörande bil med hjälp av datorer måste man ta fram matematiska modeller som beskriver sambanden. Man måste sedan använda sig av testkörningar för att systemet skall lära sig att köra bil genom att uppdatera och förbättra modeller och reglerstrategier.

Modeller kan tas fram med hjälp av, till exempel, fysikalisk kunskap men också genom att lära från experiment och mät-data. Vad händer om man gör ett kraftigt rattutslag i hög fart för en tung lastbil? Den kan välta om man inte vet (har en bra modell som beskriver) hur mycket man kan svänga på ett säkert sätt. Förare lär sig detta genom erfarenhet, och det samma gäller när man använder sig av modellbaserad regering. Systemidentifiering handlar om att ta fram modeller av dynamiska system (system som minns vad det tidigare har varit utsatta för) genom att anlysera mätningar från tester. Att göra experiment kan vara mycket tidsödande och dyrt ifall man inte har bra metoder att i förväg väl planera experimenten. Detta gäller i synnerlighet system med långa tidskonstanter, till exempel medicineringar vid sjukdomar eller komplicerade kemiska processer i industrin. Man kan också ha problem med att mätningar inte alltid är tillförlitliga, det vill säga man har mätfel och andra osäkerhet. Att ta fram bra modeller för kan vara en dyrbar och tidskrävande process. Samtidigt så krävs bra modeller när man skall styra system med komplicerad dynamik.

Det är mycket viktigt att koppla kvalitén på modellen till tillämpningen av modellen – man behöver inte ha en bättre beskrivning än en som löser uppgiften. Själva principen återkoppling kan hantera modellfel, men blir de för stora kan det orsaka instabilitet. En förare behöver inte förstå i detalj vad kopplingen är mellan rattutslag och bilens rörelse, men om detta samband ändras radikalt kan man inte längre köra bilen.

Genom att samordna reglering och experimentella tester kan man radikalt snabba upp arbetet att ta fram bra modellbaserade reglerstrategier!

Det övergripande målet med projektet är att dramatiskt öka förutsättningarna för effektiv systemidentifiering för att ta fram modeller av komplexa dynamiska system, och därmed minska klyftan mellan teori och praktik av systemidentifiering. Från preliminära resultat föreslår vi en ny integrerad ansats där systemidentifiering och reglering utformas tillsammans för att minimera de total ekonomiska kostnaderna för att ta fram säkra och effektiva regleralgoritmer. Vi kombinerar nyutvecklade metoder från statistik och maskininlärning med vår forskning i reglerteknik och systemidentifiering för att utveckla effektiva algoritmer som samtidigt lär sig modeller och motsvarande reglerstrategier. Målet att radikalt minska tid och kostnader för att utveckla intelligenta och säkra tekniska system, som självkörande fordon.

Project period

Number of project years*

4

Calculated project time*

2016-01-01 - 2019-12-31

Deductible time

Deductible time

Cause	Months

Career age: 77

Career age is a description of the time from your first doctoral degree until the last day of the call. Your career age change if you have deductible time. Your career age is shown in months. For some calls there are restrictions in the career age.

Classifications

Select a minimum of one and a maximum of three SCB-codes in order of priority.

Select the SCB-code in three levels and then click the lower plus-button to save your selection.

SCB-codes*

2. Teknik > 202. Elektroteknik och elektronik > 20202. Reglerteknik

2. Teknik > 202. Elektroteknik och elektronik > 20205. Signalbehandling

Enter a minimum of three, and up to five, short keywords that describe your project.

Keyword 1*

System identification

Keyword 2*

data-based modelling

Keyword 3*

complex systems

Keyword 4

Keyword 5

Ethical considerations

Specify any ethical issues that the project (or equivalent) raises, and describe how they will be addressed in your research. Also indicate the specific considerations that might be relevant to your application.

Reporting of ethical considerations*

None.

The project includes handling of personal data

No

The project includes animal experiments

No

Account of experiments on humans

No

Research plan

A Decision-Theoretic Approach to Identification

1 Purpose and Aims

Modelling, in particular based on real data, is an essential but rather expensive component in the process of designing, commissioning and re-tuning of controllers in industrial practice. This is indeed the case for the implementation of model predictive control (MPC), which is one of the most popular industrial controllers used worldwide, in particular within the petrochemical industry [24] (where it originated), as well as in the automotive, aerospace, food processing and mechatronics sectors. It has been reported that the most expensive and time consuming part of MPC commissioning is the process modelling, which is generally viewed as a highly inefficient step. In particular, estimates of the cost and time of commissioning related to modelling range up to 90% [34], so improvements in this step can be expected to result in substantial reductions in the commissioning cost.

In view of the above, data-based modelling, also called *system identification*, is a very important and critical aspect of control, which has lead to a very intense research activity in the field during the last four decades, and will very probably continue so for a very long time. On the other hand, it is well known that an important gap exists between the identification/control theory and its practical implementation [9]: while the theory of control has evolved formidably during its entire history, most applications of control in industry rely on very simple implementations (relative to the level of technical/mathematical sophistication of standard research articles in journals such as *Automatica* or *IEEE Transactions on Automatic Control*). One of the main reasons for this gap lies in the modelling step: the standard theoretical frameworks for system identification suffer from several limitations, which render them incapable of providing good enough models for advanced control in a cost and time effective manner. In particular, this framework relies on assuming several so-called "separation principles" (such as the ones between modelling and control, and between observers and state feedback) to subdivide the control design process into sub-modules which are designed almost independently of each other; furthermore, the modelling steps rely on the crucial assumption of "no-undermodelling", which means that the model structures used are good enough to encompass the relevant dynamics of the plant to be controlled. Both (1) the assumption of *separation principles* and (2) the assumption of *no-undermodelling* are questionable: (1) regarding the former, the use of some separation principles leads to sub-optimal performance, as it forces the modelling stages to be designed relatively independently of the final purpose of the model and in particular of the economic implications of a potentially badly tuned controller, and (2) regarding the latter, due to the high complexity of many industrial processes, which typically consist of several stages containing nonlinear and/or spatially distributed components, their full dynamics cannot be described by a simple low dimensional lumped model. Therefore, imposing these assumptions leads to costly and very slow implementations, as they require experiments of very long duration and multiple trials to achieve model-based controllers of acceptable performance.

The overall objective of the project is to boost the foundations of system identification, making them suitable for the modelling of complex, real-world industrial processes, and hence bridging the theory/practice gap in the control field.

To achieve this goal, it is necessary to re-build the standard framework of system identification, *i.e.*, to base it on techniques and methods which do not rely on unrealistic assumptions, and which take the entire control commissioning process into account, instead of imposing the independent design of heavily dependent stages. A natural setup for this reconstruction is given by posing the entire process in a decision theoretic framework, where the roles of the control designer and nature (the source of uncertainties), and the goal of the controller are clearly specified. Within this framework, several recent and highly innovative methods and theory have been developed in fields such as statistics, mathematical finance, game theory and machine learning, which can greatly improve the status quo in control by properly taking into account the risks involved due to uncertainty and their economic implications, and turn the control commissioning process into a high-performance, tractable and cost effective activity.

2 Survey of the field

Broadly speaking [31], the foundations of mainstream system identification [22] come from those of frequentist parametric statistics [13]: the goal of an identification method is to select a model (considered as a member of a family of probability density functions $p(\cdot;\theta)$, parameterized by a finite-dimensional vector $\theta \in \Theta$) based on N samples of input-output data. This model is used as an intermediate step towards the final goal, *e.g.*, designing a controller. In this framework it is usually assumed that there is a $\theta_o \in \Theta$ such that $p(\cdot;\theta_o)$ describes the input-output data exactly; this is an assumption of *no undermodelling*, *i.e.*, that the *true* process can be represented by a member of the model structure. Furthermore, due to its reliance on $p(\cdot;\theta)$ as an intermediate step, mainstream system identification benchmarks estimation methods based on performance measures defined directly in terms of the parameter θ, vaguely related to the final purpose of the model and its performance, expressed for instance in economic terms.

Due to the inherent complexity of real-world applications, it is practically impossible to recreate the whole dynamics of even a simple physical system with a finite (and small) set of equations. Therefore, we should often content ourselves with simple models which do not capture the full complexity of a real system, but only those aspects that are relevant to the final application [16]. This means that the standing assumption of no undermodelling and the performance metrics considered in mainstream system identification should be carefully revisited.

There have been a few attempts in the literature to address undermodelling situations in statistics [19], system identification [21], econometrics [33] and control [7]. In statistics and other fields, some work has been developed to understand how standard algorithms perform in the presence of undermodelling, instead of designing methods specifically targeted to address this issue; one exception is data-driven control, which avoids the use of explicit model structures, even though there is still no solid underlying theory (*e.g.*, specifying optimality or efficiency in terms, for instance, of number of samples or batches used) and current algorithms are often outperformed by model-based techniques. Within identification, models are considered from the 1970's, unlike in statistics, as "approximations" to reality, so the goal of estimation is to find a good approximation to the underlying mechanism generating the data, rather than trying to find the "true" mechanism. In addition, several approaches have been proposed, such as set-membership / $\mathcal{H}_\infty$ / bounded-error-modelling [25]. However, these alternatives have their own shortcomings: even though they are deterministic (and hence do not rely on possibly unfounded probabilistic assumptions), they are typically pessimistic and may require unrealistic sample lengths to achieve good performance [27]. In addition, standard tools such as the prediction error method have been modified using weights or prefilters to shape the bias or systematic error due to undermodelling [32]; these modifications indeed improve the results obtained in the face of undermodelling, but are still restricted to the use of an explicit model as an intermediate step. These approaches belong to the sub-field of *identification for control* [15], which started in the early 1990's and attempted to reduce the theory/practice gap by bringing identification closer to control applications.

Regarding the final purpose of control and its economic implications in industry, only recently has the actual economic cost of a controller started to be considered in the control design, specifically for MPC control; this has given rise to the concept of *economic MPC* [2]. However, this body of work deals mainly with deterministic processes, assuming perfect knowledge of the plant. *To the best of our knowledge, nobody has considered economic costs including risks due to uncertainty throughout the entire control commissioning process.*

Within the identification community, the final purpose of the model (e.g., control) has been considered in the subfield of identification for control [25], and more specifically, in the area of *experiment design*, where several approaches have been attempted [10, 17][C27][1]. One particular framework is *application-oriented input design* [17][C27], where the input is designed so that it has minimum effect on the system (*e.g.*, minimum input power) while the experiment resulting from applying the input would give, with high probability, a model leading to a low degradation in performance (compared to having the "true" system, according to the final purpose of the model). The phrase "with high probability" refers to the uncertainty and noise present during the identification experiment and controller testing phases. However, these approaches do not properly consider the risks due to these uncertainties, in particular, in the event that the estimated model does not give a satisfactory performance these approaches do not bound the total loss (which can be catastrophic, if, *e.g.*, the model leads to a de-stabilizing controller when applied to the true process).

In order to understand the current limitations of identification and the existing theory/practice gap, Figs. 1 and 2 show block diagrams with the ideal procedure for controlling an unknown plant (optimal stochastic adaptive control [5]), and a sketch of the standard procedure used in industrial practice, respectively. Optimal stochastic adaptive control is computationally intractable in general [14], and standard implementations of (dual) adaptive control may lead to instability due to undermodelling [30], so practitioners often prefer a "batch" approach, where an experiment is designed (based on some prior knowledge) and performed, an identification method is applied to the gathered data and a model is conceived, based on which a controller is designed and tried. If the performance obtained is not good enough, the procedure is repeated; in such a case, this process is explicitly repeated multiple times, by redesigning an input signal, performing an experiment and re-tuning a controller, this scheme is called *Iterative Identification and Control* [1]. *These two approaches are very different, hence the practical, batch approach often leads to suboptimal and rather conservative results.*

3 Project Description

Our proposal is to bridge the theory/practice gap in control by improving the existing design procedures in a robust manner, from the system identification side. The specific goals of our proposal, in order to achieve the overall objective, are:

[1]References starting with J, C or B come from the applicant's list of publications.

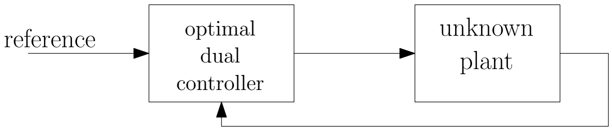

Figure 1: Ideal procedure for controlling an unknown plant.

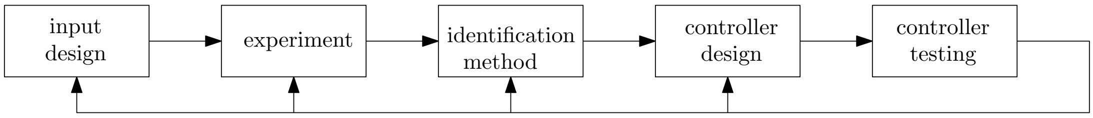

Figure 2: Standard scheme for designing a controller.

Objective 1: Establishing economically motivated performance measures for the design of the multiple stages of the control design process, while accounting for the risks due to uncertainty sources.

If in Fig. 2 we disregard the arrows in the bottom (denoting the need to repeat some steps if the control performance is not good enough), the resulting scheme is a multi-stage decision problem, whose design stages can be optimized using dynamic programming [8]: the last design block (controller design) is optimized given a model (and an estimate of its error) and a control performance measure; the optimal cost at this stage is taken as the performance measure to be optimized by the identification method, given the experimental data; and so on. Even this non-adaptive solution is not usually implemented in practice, due to its high computational cost; instead, several implicit approximations are considered, *e.g.*, assuming that the sample size in the experiment phase is large enough, maximum likelihood is usually chosen as the identification method, as it is asymptotically efficient [22], irrespective of the performance measure. This simplification, however, is valid only if the process and the noise distribution are properly modelled, so in general the multiple stages of the control commissioning process cannot be decoupled from each other nor from the control performance measure. Furthermore, there are several sources of uncertainty in the commissioning process, e.g., in the experiment and controller testing phases; taking the risks associated with these uncertainties is crucial for a successful commissioning. Proper tools for dealing with risk have been developed quite recently within mathematical finance and operations research.

Our goal is to introduce tools from the modern theory of risk measures, to properly account for the risks introduced by noise and uncertainty in the various stages of control commissioning, and to push the economic objective through the entire process.

Objective 2: Overcoming undermodelling issues by posing the identification problem within the prediction with expert advice framework.

As mentioned above, one of the fundamental tenets of system identification is the assumption that the considered model structure is flexible enough to capture the dynamics of the true system. In order to overcome undermodelling problems, a key role is played by the input signal used during the experiment phase [17], which is to reveal system properties that are important for a particular application, and at the same time to hide those properties which are not important; as a very simple example, if one is interested in the static gain of a complex system, it is enough to apply a constant input and to measure its steady-state output to estimate such quantity. This key role of the input has been studied and exploited in several publications of the applicant [J5,J9,J11,J18], where we have shown the real potential of tuning the experimental conditions to reliably estimate properties of interest in the face of undermodelling.

The next step in beating undermodelling consists in properly interpreting and exploiting the role of model structures in system identification. Since the 1970's, models are considered to be approximations to reality, and the goal of estimation is to find a good approximation within a model structure [21]. Recent developments in statistics, machine learning and information theory, in the framework of "prediction with expert advice" [12], have taken this interpretation even further: instead of being approximations to reality, models are considered as mere experts or advisors, whose performance is directly measured with respect to the end goal of the decision problem (*e.g.*, control or prediction) instead of as intermediate blocks with good approximation properties. The goal of modelling is then to combine the predictions of the models (experts) so as to compute a "prediction" which is almost as good as the best model (irrespective of how good or bad such best model is as an approximation); this notion of performance is called *regret*, and is a natural measure to consider for the design of prediction algorithms, unless additional assumptions are imposed to guarantee a given level of performance for the best model. Furthermore, several algorithms developed in this framework are known to achieve asymptotically optimal regret performance. Some simple applications of this framework to control have appeared in the literature [20, 26, 28], but they have not reached the level of maturity yet. *Our goal is to apply, in a systematic manner, results from the prediction with expert advice framework to system identification and model-based control, to overcome the limitations imposed by undermodelling.*

A more detailed description of these two objectives will be provided in Section 5, after discussing some preliminary findings in these fronts.

4 Significance

The standard protocol for designing and implementing controllers in practice has remained unchanged for decades: As shown in Fig. 2, the control engineer has to design/implement several stages, from experimental design to control implementation, and to this end he/she relies or assumes separation principles allowing the design of each step relatively independently of each other. This leads to a tractable but highly costly procedure. Naturally, many researchers have tried to remedy this by proposing a variety of schemes, but practitioners have learned to distrust them due to their lack of robustness. This proposal is based on the realisation that the reason behind these failures is that the basic assumptions of the modelling paradigms used until now, in particular the hypothesis of no-undermodelling, are unrealistic and that to solve this problem the entire commissioning process must be taken into account, instead of relying on separation principles. By realising these crucial points, we have the conviction that the only way to bridge the theory/practice gap is by re-building the standard modelling framework, where the notion of a model is relaxed from being an intermediate step to achieve the end goal by acting as reasonable approximations to reality, to an "expert" with a secondary role in the framework whose performance is measured relative to end performance, and by looking at the entire commissioning process as a whole, designed in a risk-coherent, decision-theoretic manner.

The project involves several elements from fields outside systems and control, such as risk-theoretical tools from mathematical finance, economics and operations research, and expert-based prediction and deterministic multi-armed bandits from statistics, game theory and machine learning, in addition to diverse tools from the system identification and control fields. This is the first time many of these techniques have been used to re-consider the entire commissioning process, and exposes the inherent multidisciplinary character of the proposal. However, based on our deep insight into the entire commissioning process, starting from the experiment design stage and finishing at the control implementation, in addition to the availability of excellent inter-disciplinary expertise at the environment we are affiliated with, will ensure the success of the project.

5 Preliminary Results and their Planned Extensions

In relation to the overall goal of this proposal, the applicant has been working for several years on the problem of handling the effects of undermodelling, by focusing mainly on the input signal, as explained above. Regarding the specific objectives of the project, some promising results obtained by the applicant are described below:

1. Use of risk-coherent performance measures for the control commissioning process.

The disciplines of mathematical finance, operations research and economics deal with the problem of decision-making under uncertainty, and a notable amount of research effort has been put into properly defining the notion of risk (starting formally with the work of Nobel prize winner H. Markowitz [23] on mean-variance trade-offs). In particular, during the last 15 years, a modern theory of risk measures has been developed, based on a series of "coherency" axioms reflecting desirable properties of such measures [4] (*e.g.*, that diversification of assets reduces risk); one of the niceties of these axioms is that coherent measures must be convex, *i.e.*, easier to optimize that most incoherent measures. Curiously, some standard measures such as VaR (Value-at-Risk) do not satisfy these requirements; some standard approaches in identification, such as the least costly [10] and application-oriented [C27] input design frameworks, can be seen as approximations to chance-constrained problems, which are also risk-incoherent.

In the modern theory of risk, several superior, coherent measures have been proposed. One of them is CVaR [29] (conditional value-at-risk), which measures the expected value of losses above a given user-defined quantile. Current approaches in control and identification merely attempt to restrict the loss to be below a given value *with high probability*, without caring about how large the losses might become when such threshold is overcome. In extreme cases, such neglected low probability region may lead to enormous losses, *e.g.*, when designing a controller for a plant based on a model, it may happen that with low probability the controller may lead to an unstable loop, which according to many performance measures is completely unacceptable; in these cases it is fairly important to account for those improbable but potentially harmful losses. As a simple example, consider the problem of designing an input signal $\{u_t\}$ of unit variance to estimate the resonant frequency $\theta \in [0, \pi]$ of a second order discrete-time system of the form

$$y_t = \frac{q}{q^2 - 2r\cos(\theta)q + r^2} u_t + e_t$$

where $\{e_t\}$ is standard Gaussian white noise, q is the forward shift operator and $\{y_t\}$ is the output; here $r = 0.95$ is known, but θ is unknown and assumed to have a uniform prior distribution in $[0, \pi]$.

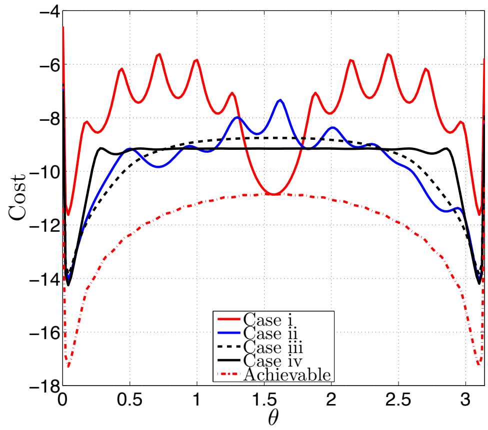

Figure 3: Comparison of optimal input designs.

Fig. 3 shows the cost $\log \operatorname{var} \hat{\theta}$ ($\operatorname{var} \hat{\theta}$= normalized variance of an asymptotically efficient estimator of θ) when using inputs designed by minimizing different cost functions: (i) $-\log I_F(\theta_0)$, where $I_F(\theta_0)$ is the information matrix evaluated at a nominal value $\theta_0 = \pi/2$; (ii) $-E_{\theta\sim \text{Unif}[0,\pi]}\{\log I_F(\theta)\}$; (iii) $\text{VaR}_{0.98}(-\log I_F(\theta))$, *i.e.*, the minimum $z \in \mathbb{R}$ such that $-\log I_F(\theta) \leqslant z$ with probability at least 0.98; and (iv) $\text{CVaR}_{0.98}(-\log I_F(\theta))$. Also shown, as "achievable", is the design based on the knowledge of the true value of θ (which is unrealizable, but shown as a benchmark). The results show that while the nominal design (i) is optimal for $\theta = \theta_0$, its performance worsens considerably around $\theta = \pi/4, 3\pi/4$. The expected design (ii) produces better results, but VaR (iii) reduces the probability (in θ) of obtaining bad designs (with costs above -9). Finally, CVaR (iv) manages to reduce the cost obtained by VaR over the central frequencies, by pushing down the cost over the region of low probability neglected by VaR (around $\pi/2$).

In this project, we plan to integrate coherent risk measures such as CVaR into control design techniques like MPC, and then to propagate, in an approximate manner, the optimal value of the risk measure attainable by the control design stage to the preceding stages (identification method and input design), according to the optimality principle of dynamic programming.

2. Development of identification and control methods based on the prediction with expert advice framework.

The framework of prediction with expert advice [12], in its basic form, can be described as follows: Consider a game being played repeatedly by two players: the control engineer and nature. At each iteration t, the engineer chooses a quantity $\hat{y}_t \in D$ while nature chooses $y_t \in D$, and the engineer suffers a loss $l_t(\hat{y}_t, y_t)$. In order to make his/her decision, the engineer can consult a group of *experts*, who present him/her with their own predictions y_t^i, $i = 1, \dots, N$ (where N is assumed finite for the moment), and the engineer has access to their previous losses $l_k(y_k^i, y_k)$, $k = 1, \dots, t-1$, assumed to be real-valued and bounded. The goal of the engineer is then to minimize his/her *regret* $R_t = \sum_{k=1}^t l_k(\hat{y}_k, y_k) - \min_{i=1,\dots,N} \sum_{k=1}^t l_k(y_k^i, y_k)$. A strategy for the engineer is said to be of *no-regret* if $R_t = o(t)$.

Notice that the framework is entirely deterministic: the losses l_t can be completely arbitrary, as well as the choices of nature and the experts. Since nature can be adversarial, the engineer needs to rely on either the space D being convex or on randomizing his/her response (based on the suggestions of the experts) to keep a low regret. However, it is not possible to guarantee a low accumulated loss (in an absolute, rather than relative, sense), because we make no assumptions on the quality of the experts.

A standard no-regret strategy is the *multiplicative weights update* or *weighted-majority algorithm* [3], where the engineer chooses $\hat{y}_t = y_t^i$ with probability w_t^i/Φ_t $(i = 1, \dots, N)$, $\Phi_t = \sum_{i=1}^N w_t^i$, and the weights are chosen according to $w_t^i = w_{t-1}^i[1 - \eta l_{t-1}(y_{t-1}^i, y_{t-1})]$, for some $0 < \eta \leq 1/2$.

In some cases, the previous losses of all the experts are not known a posteriori, but only that of the chosen expert. This is a *non-stochastic multi-armed bandit problem* [6]. To solve it, one can replace the losses of the experts in the multiplicative weights update method by unbiased estimates and add a constant term to the weights [3].

Using these tools, our plan is to pose several data-based / model-free control schemes in a regret framework, *i.e.*, by defining suitable "experts" and an appropriate loss leading to a regret function that can be interpreted as a sensible control or identification performance measure. Notice that in this setup, experts do not need to be models as in standard system identification, where they play an intermediate role in the control commissioning process: experts can be input signals (*e.g.*, sinusoids of specific frequencies, as discussed soon) or the final controllers themselves, as in data-driven control. To keep the formulation simple enough, we start by considering an iterative identification / control approach, *i.e.*, where one works with one batch of data at a time (instead of pursuing immediately an adaptive approach). For example, the problem of measuring the $\mathcal{H}_\infty$-norm of a linear dynamic system is an important step to estimate the size of a modelling error [J18] (by considering such system as the difference between a real plant and its nominal model). This problem can be naturally posed in the prediction with expert advice framework, *e.g.*, by considering each expert as a sinusoid of a particular frequency (and unit amplitude) to be applied to the system, and as loss the negative of the magnitude of the output of the system at such frequency. Applying the multiplicative weights update method to this problem generates input sequences whose spectra correspond to the weights over the group of "experts", and which iteratively selects the best expert, *i.e.*, the frequency at which the system achieves the largest gain; a sketch of the result of such a procedure is shown in Fig. 4, where the frequency response of a resonant system is shown, together with the spectra of input signals generated at several iterations by a procedure based on the multiplicative weights update algorithm, which ultimately converge to a Dirac impulse (*i.e.*, a sinusoid in the time domain) at the highest peak of the frequency response. Here, each input spectrum corresponds to the distribution of weights selected by the algorithm for the experts (frequencies).

In our proposal, we will consider other more elaborate forms of data-based control, such as virtual reference feedback tuning (VRFT) [11] and iterative feedback tuning (IFT) [18], where the groups of experts would correspond to the sets of parameterized controllers considered by these methods. Here it is important to notice that the resulting algorithms will indeed be data-driven / model-free control schemes, but, unlike the current approaches in this area, our algorithms will be provably sample optimal (in the sense of achieving the best asymptotic regret rate).

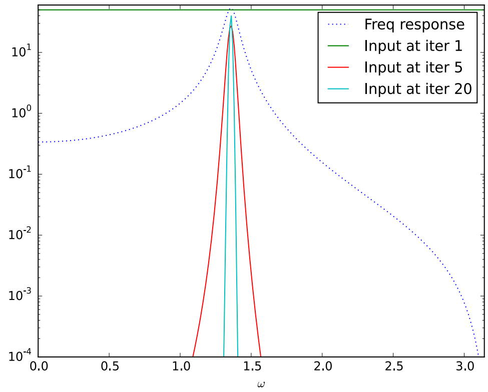

Figure 4: Sketch of an iterative procedure for gain estimation.

6 Independent Line of Research

The applicant belongs to the Department of Automatic Control, at the School of Electrical Engineering, KTH, where he collaborates closely with Profs. Bo Wahlberg and Håkan Hjalmarsson (from the same department), as part of a research group on system identification. He currently holds a VR Project grant for Young Researchers on "Robust Modelling of High-Order Systems", which fitted well with other previous projects of the system identification group (funded by VR, Vinnova, EU and ERC), all of which have or will have ended by the end of 2015. Thanks to this current VR funding, the applicant has a PhD student with whom he has developed an independent line of research on input design for nonlinear systems, in line with the original goals of the VR project.

Part of the current proposal can be seen as a continuation of the applicant's goal of overcoming the problem of undermodelling in system identification. However, the methods envisaged for this proposal, namely, risk-coherent measures and prediction with expert advice, are virtually unknown to the system identification community, and completely unrelated to the tools considered for the previous VR proposal and the other projects of the system identification group. Thus, the applicant expects, with this current proposal, to further pursue his goal of developing a strong independent research group, while still keeping his existing links to researchers at KTH.

7 Form of Employment

The applicant has, from 2014, a tenured Associate Professor (Lektor) position at the Department of Automatic Control, with the School of Electrical Engineering at KTH.

8 International and national collaboration

In terms of research networks, during his career the applicant has had the opportunity of working with many researchers at an international researchers, such as Profs. Graham C. Goodwin and James S. Welsh (his PhD supervisors), Prof. Arie Feuer (Technion, Israel), Dr. Juan Carlos Agüero (U. of Newcastle, Australia), Dr. Tom Oomen (Eindhoven TU, The Netherlands), Prof. Ricardo Rojas (UTFSM, Chile), Prof. Xavier Bombois (Delft TU, The Netherlands), Prof. Roland Hildebrand (U. Joseph Fourier, France), Prof. Thomas Schön (Uppsala U., Sweden) and Prof. László Gerencsér (MTA SZTAKI, Hungary).

At KTH, the applicant has been working closely with Profs. Håkan Hjalmarsson, Bo Wahlberg, Peter Händel, Mats Bengtsson, Saikat Chatterjee and Magnus Jansson. In addition, he is a faculty member of the ACCESS Linnaeus Centre at KTH, a consortium consisting of, at present, over 30 faculty researchers from 7 groups at KTH.

During the execution of this project, the applicant expects to collaborate (partly in relation to the project goals) with Profs. Håkan Hjalmarsson and Bo Wahlberg (from KTH), and also with Profs. Thomas Schön (Uppsala U., Sweden), Tom Oomen (Eindhoven TU, The Netherlands), Simone Formentin (P. di Milano, Italy), and Diego Eckhard (UFRGS, Brazil).

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Interdisciplinarity

My application is interdisciplinary

☐

An interdisciplinary research project is defined in this call for proposals as a project that can not be completed without knowledge, methods, terminology, data and researchers from more than one of the Swedish Research Councils subject areas; Medicine and health, Natural and engineering sciences, Humanities and social sciences and Educational sciences. If your research project is interdisciplinary according to this definition, you indicate and explain this here.

Click here for more information

Scientific report

Scientific report/Account for scientific activities of previous project

The applicant currently holds a VR Project Grant for Young Researchers, entitled "Robust Modelling of High-Order Systems", file number 621-2011-5890, for 3.280.000 SEK over 4 years (2012-2015), which will end before the present VR proposal may be funded. The funding provided by the grant has been used to cover part of the applicant's salary, as well as a PhD student (Patricio Valenzuela) whose main supervisor is the applicant.

The aforementioned VR project had as objective to investigate the effects of the input signal used during an experiment in system identification, in particular regarding its potential to mitigate undermodelling. The outcomes of this project have resulted in multiple publications, including the following articles in top control journals (in addition to several conference publications):

[J14] C. Mueller, C. R. Rojas, and G. C. Goodwin. "Generation of amplitude constrained signals with a prescribed spectrum". Automatica, 48(1):153-158, 2012.

[J15] J. C. Agüero, C. R. Rojas, H. Hjalmarsson, and G. C. Goodwin. "Accuracy of linear multiple-input multiple-output (MIMO) models obtained by maximum likelihood estimation". Automatica, 49(4):632-637, 2012.

[J16] C. R. Rojas, J. C. Agüero, J. S. Welsh, G. C. Goodwin, and A. Feuer. "Robustness in experiment design". IEEE Transactions on Automatic Control, 57(4):860-874, 2012.

[J17] B. Sanchez, C. R. Rojas, G. Vandersteen, R. Bragos, and J. Schoukens. "On the calculation of the D-optimal power spectrum for impedance spectroscopy measurements". Measurement Science and Technology, 23(8):085702, 2012.

[J18] C. R. Rojas, T. Oomen, H. Hjalmarsson, and B. Wahlberg. "Analyzing iterations in identification with application to nonparametric H_inf-norm estimation". \emph{Automatica}, 48(11):2776-2790, 2012.

[J20] D. Katselis, C. R. Rojas, M. Bengtsson, and H. Hjalmarsson. "Frequency smoothing gains in preamble-based channel estimation for multicarrier systems". Signal Processing, 93(9):2777-2782, 2013.

[J22] D. Eckhard, A. S. Bazanella, C. R. Rojas, and H. Hjalmarsson. "Input design as a tool to improve the convergence of PEM". Automatica, 49(11):3282-3291, 2013.

[J23] D. Katselis, C. R. Rojas, M. Bengtsson, E. Björnson, X. Bombois, N. Shariati, M. Jansson, and H. Hjalmarsson. "Training sequence design for MIMO channels: An application-oriented approach". EURASIP Journal on Wireless Communications and Networking, 2013:245, 2013.

[J24] B. Sanchez and C. R. Rojas. "Robust excitation power spectrum design for broadband impedance spectroscopy". Measurement Science and Technology, 25(6):065501, 2014.

[J25] T. Oomen, R. van der Maas, C. R. Rojas, and H. Hjalmarsson. "Iterative data-driven H_inf-norm estimation of multivariable systems with application to robust active vibration isolation". IEEE Transactions on Control Systems Technology, 22(6):2247-2260, 2014.

[J28] D. Katselis and C. R. Rojas. "Application-oriented estimator selection". IEEE Signal Processing Letters, 22(4):489-493, 2015.

[J29] P. E. Valenzuela, C. R. Rojas, and H. Hjalmarsson. "A graph theoretical approach to input design for identification of nonlinear dynamical models". Automatica, 51(1):233-242, 2015.

[J30] D. Katselis, C. R. Rojas, B. I. Godoy, J. C. Agüero, and C. L. Beck. "On the end-performance metric estimator selection". Automatica (accepted for publication), 2015.

Most of these publications consider different aspects of input design, such as the input realization problem [J14], its effects on bias and variance [J15,J16], applications to electrical bio-impedance measurements [J17,JJ24] and communications [J23], and their extension to nonlinear systems [J29]. The input signal has been discovered to be useful not only for improving the statistical performance of a model, but also for facilitating the computational task of finding such model, by convexifying the likelihood function / prediction error cost function [J22]. In addition, some iterative identification schemes, based on the idea of iteratively tuning the input signal to estimate a specific property of a system in an almost model-free manner, have been analyzed [J18,J25]. Finally, it has been found that, depending the final application of the model to be estimated, not only the input signal, but also the estimators can be fined tuned for improved performance [J20,J28,J30].

As a result of the outcomes of the aforementioned VR project, the applicant has noticed that, in order to overcome the standing difficulties with the application of system identification to real-world applications, as in process control, the scope of his research has to be extended to the entire control commissioning process, which needs to be re-conceived as a multi-stage decision process. Two aspects of such long term goal are considered in the current proposal: how to properly take into account the effects of uncertainties in the commissioning process (using risk-coherent measures), and how to release the model from its role as an approximation to reality and turn it into an expert/advisor directly linked to the final control objective (using the prediction with expert advice framework). This means that the current proposal shares a similar goal as the previous VR project, namely, to overcome some limitations of current system identification practice (due, for example, to undermodelling), but the tools envisioned for this new proposal are entirely new (even to the system identification community).

In addition to the aforementioned VR grant, the applicant has also been partially funded by an ACCESS Linnaeus Centre grant for 1.000.000 SEK over the period 2013-2014 for the coordination of a seed project on "Sparse Estimation in Signal Processing and System Identification". However, the goals of this project did not overlap with the aforementioned VR grant nor with the current proposal.

Budget and research resources

Project staff

Describe the staff that will be working in the project and the salary that is applied for in the project budget. Enter the full amount, not in thousands SEK.

Participating researchers that accept an invitation to participate in the application will be displayed automatically under Dedicated time for this project. Note that it will take a few minutes before the information is updated, and that it might be necessary for the project leader to close and reopen the form.

Dedicated time for this project*

	Role in the project	Name	Percent of full time
1	Applicant	Cristian Rojas	45

Salaries including social fees

	Role in the project	Name	Percent of salary	2016	2017	2018	2019	Total
1	Applicant	Cristian Rojas	45	443,091	456,384	470,075	484,178	1,853,728
2	Other personnel without doctoral degree	PhD student	80	416,581	429,079	441,951	455,210	1,742,821
	Total			859,672	885,463	912,026	939,388	3,596,549

Other costs

Describe the other project costs for which you apply from the Swedish Research Council. Enter the full amount, not in thousands SEK.

Premises

	Type of premises	2016	2017	2018	2019	Total
1	Office space	76,511	78,806	81,170	83,605	320,092
	Total	76,511	78,806	81,170	83,605	320,092

Running Costs

	Running Cost	Description	2016	2017	2018	2019	Total
1	Travel	Travel costs	120,000	120,000	120,000	120,000	480,000
2	Equipment	Computer costs	40,000	40,000	40,000	40,000	160,000
	Total		160,000	160,000	160,000	160,000	640,000

Depreciation costs

Depreciation cost	Description	2016	2017	2018	2019

Total project cost

Below you can see a summary of the costs in your budget, which are the costs that you apply for from the Swedish Research Council. Indirect costs are entered separately into the table.

Under Other costs you can enter which costs, aside from the ones you apply for from the Swedish Research Council, that the project includes. Add the full amounts, not in thousands of SEK.

The subtotal plus indirect costs are the total per year that you apply for.

Total budget

Specified costs	2016	2017	2018	2019	Total, applied	Other costs	Total cost
Salaries including social fees	859,672	885,463	912,026	939,388	3,596,549		3,596,549
Running costs	160,000	160,000	160,000	160,000	640,000		640,000
Depreciation costs					0		0
Premises	76,511	78,806	81,170	83,605	320,092		320,092
Subtotal	1,096,183	1,124,269	1,153,196	1,182,993	4,556,641	0	4,556,641
Indirect costs	315,062	324,514	334,249	344,277	1,318,102		1,318,102
Total project cost	1,411,245	1,448,783	1,487,445	1,527,270	5,874,743	0	5,874,743

Explanation of the proposed budget

Briefly justify each proposed cost in the stated budget.

Explanation of the proposed budget*

The salary of the applicant is considered as equal to 52 000 SEK / month in 2015, and subject to a 3% increase per year. He expects to spend 45%
of his time on the project.

The salary of a Ph.D. Student, the premise costs and the indirect costs are based on standard amounts from the Department of Automatic Control at KTH.

The indirect costs, due to the common expenses at KTH, the School of Electrical Engineering and the Department of Automatic Control, are associated with the salaries of the applicant and the Ph.D. student.

The travel expenses have been calculated considering the possibility to attend two conferences and one workshop per year, and two trips for the Ph.D. student per year.

The computer expenses should cover for computer hardware, software and support for the applicant and the Ph.D. student.

Other funding

Describe your other project funding for the project period (applied for or granted) aside from that which you apply for from the Swedish Research Council. Write the whole sum, not thousands of SEK.

Other funding for this project

	Funder	Applicant/project leader	Type of grant	Reg no or equiv.	2016	2017	2018	2019	Total
1	ERC	Cristian Rojas	ERC Starting Grant	Submitted, but not granted	1,503,302	2,998,194	3,096,207	3,194,219	10,791,922
	Total				1,503,302	2,998,194	3,096,207	3,194,219	10,791,922

CV and publications

CV

Curriculum Vitae

Name	Cristian Ricardo Rojas
Born	September 5, 1980, in Manchester, England
Citizenship	Chilean and British
E-mail	cristian.rojas@ee.kth.se
ORCID	0000-0003-0355-2663
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Address	Department of Automatic Control, School of Electrical Engineering Royal Institute of Technology (KTH) Osquldas väg 10 SE-100 44 Stockholm, Sweden

1 Ph.D. Degree

Doctor of Philosophy (Ph.D.) in Electrical Engineering, School of Electrical Engineering and Computer Science, The University of Newcastle, Newcastle, Australia. The Thesis was submitted in June 20, 2008, and the degree was obtained in October 23, 2008. Supervisors: Prof. Graham C. Goodwin and Dr. James S. Welsh. Title of the Thesis: "Robust Experiment Design".

2 Postdoctoral Positions

2008-2010 Postdoctoral Scholar, ACCESS Linnaeus Center, KTH, Stockholm, Sweden.

2008 Research Assistant, School of Electrical Engineering and Computer Science, The University of Newcastle, Newcastle, Australia.

3 Present Position

2014- Associate Professor, School of Electrical Engineering, KTH, Stockholm, Sweden.

4 Previous Positions

2011-2014 Assistant Professor in Automatic Control, School of Electrical Engineering, KTH, Sweden.

2010-2011 Researcher, School of Electrical Engineering, KTH, Sweden.

5 Supervision of graduate students and postdoctoral fellows

2012- Main Supervisor of 1 PhD student, School of Electrical Engineering, KTH, Sweden.

2011- Co-supervisor of 5 PhD students, School of Electrical Engineering, KTH, Sweden.

2013 Supervisor of 1 Postdoctoral researcher, School of Electrical Engineering, KTH, Sweden.

6 Honors and Awards

2013 Docent in Automatic Control, School of Electrical Engineering, KTH, Sweden.

2012 ACCESS Seed Project Grant, "Sparsity in Signal Processing and System Identification", KTH, Sweden.

2012 VR Junior Researcher Grant, "Robust Modelling of High Order Systems", Swedish Research Council (VR), Sweden.

2009 Award for Research Higher Degree Excellence (given to the best PhD thesis of the Faculty of Engineering and Build Environment in 2008), The University of Newcastle, Australia.

2008-2010 KTH ACCESS Linnaeus Centre Postdoc Scholarship, KTH, Sweden.

2006-2008 University of Newcastle Postgraduate Research Scholarship (UNRS Central) and the Endeavour International Postgraduate Research Scholarship (EIPRS), The University of Newcastle, Australia.

2004 Awards "Distinción Académica Federico Santa María" and AEXA-USM (given to the best student of Electronics Engineering and to the best student of the UTFSM graduated in 2004, respectively), Universidad Técnica Federico Santa María (UTFSM), Chile.

2003-2004 Federico Santa María University Postgraduate Research Scholarship, UTFSM, Chile.

1999 Federico Santa María Scholarship (given to the student with the highest entrance grade to the university in 1999), UTFSM, Chile.

7 Institutional Responsibilities

2012- Coordinator of PhD courses, Department of Automatic Control, KTH, Sweden.

2012- Assistant Director of the Strategic Research Area (SRA) ICT The Next Generation (ICT-TNG), KTH, Sweden.

8 Membership of scientific societies

2008- Member, Research Network "European Research Network on System Identification" (ERNSI).

2011- Faculty member of the ACCESS Linnaeus Centre, KTH, Sweden.

2013- IEEE Member, belonging to the IEEE Technical Committee on System Identification and Adaptive Control.

2014- Member of the IFAC Technical Committee TC 1.1 on Modelling, Identification and Signal Processing.

9 Publications

31 journal papers (published or to appear + 10 under revision), 64 conference papers (published or to appear + 6 under revision), 3 book chapters (published).

Publication list

Publications (during the last eight years)

Citations count from Google Scholar. '*' denotes those publications which are most important to the project. Some of the publications which have only been submitted or that have been accepted for publication are available at:

`http://people.kth.se/~crro/pubs.html`

1 Most Cited Publications

[MC1] C. R. Rojas, J. S. Welsh, G. C. Goodwin, and A. Feuer. "Robust optimal experiment design for system identification". *Automatica*, 43(6): 993-1008, 2007. Number of citations: 119.

[MC2] G. C. Goodwin, J. C. Agüero, J. S. Welsh, J. I. Yuz, G. J. Adams, and C. R. Rojas. "Robust identification of process models from plant data". *Journal of Process Control*, 18(9): 810-820, 2008. Number of citations: 36.

[MC3] C. R. Rojas, J. C. Agüero, J. S. Welsh, and G. C. Goodwin. "On the equivalence of least costly and traditional experiment design for control". *Automatica*, 44(11): 2706-2715, 2008. Number of citations: 25.

[MC4] C. R. Rojas, J. S. Welsh, and G. C. Goodwin. "A receding horizon algorithm to generate binary signals with a prescribed autocovariance". In *Proceedings of the 2007 American Control Conference (ACC)*, pages 122-127, New York, July 2007. Number of citations: 23.

[MC5] C. R. Rojas and H. Hjalmarsson. "Sparse estimation based on a validation criterion". In *Proceedings of the 50th IEEE Conference on Decision and Control and European Control Conference (CDC-ECC11)*, Orlando, USA, 2011. Number of citations: 19.

2 Peer Reviewed Journal Papers

[J1] C. R. Rojas, J. S. Welsh, G. C. Goodwin, and A. Feuer. "Robust optimal experiment design for system identification". *Automatica*, 43(6): 993-1008, 2007. Number of citations: 119.

[J2] G. C. Goodwin, J. C. Agüero, J. S. Welsh, J. I. Yuz, G. J. Adams, and C. R. Rojas. "Robust identification of process models from plant data". *Journal of Process Control*, 18(9): 810-820, 2008. Number of citations: 36.

[J3] C. R. Rojas, J. C. Agüero, J. S. Welsh, and G. C. Goodwin. "On the equivalence of least costly and traditional experiment design for control". *Automatica*, 44(11): 2706-2715, 2008. Number of citations: 25.

[J4] C. R. Rojas, J. S. Welsh, and J. C. Agüero. "Fundamental limitations on the variance of estimated parametric models". *IEEE Transactions on Automatic Control*, 54(5): 1077-1081, 2009. Number of citations: 18.

[J5] C. R. Rojas, M. Barenthin, J. S. Welsh, and H. Hjalmarsson. "The cost of complexity in system identification: Frequency function estimation of Finite Impulse Response systems". *IEEE Transactions on Automatic Control*, 55(10):2298-2309, 2010. Number of citations: 19.

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[C61] C. R. Rojas and B. Wahlberg. "How to monitor and mitigate stair-casing in ℓ_1 trend filtering". In *Proceedings of the 40th International Conference on Acoustics, Speech and Signal Processing (ICASSP)* (accepted for publication), Brisbane, Australia, 2015.

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4 Book Chapters

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[B2] C. R. Rojas, J. Mårtensson, and H. Hjalmarsson. "A tutorial on applications-oriented optimal experiment design". In D. Alberer H. Hjalmarsson, and L. del Re, editors, *Identification for Automotive Systems*, pages 149-164. Springer, 2012.

CV

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Research education

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Dissertation title (en)

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Subject doctors degree	ISSN/ISBN-number	Date doctoral exam
20202. Reglerteknik		2008-10-23

Publications

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Rojas, Cristian has not added any publications to the application.

Register

Terms and conditions

The application must be signed by the applicant as well as the authorised representative of the administrating organisation. The representative is normally the department head of the institution where the research is to be conducted, but may in some instances be e.g. the vice-chancellor. This is specified in the call for proposals.

The signature*from the applicant*confirms that:

- the information in the application is correct and according to the instructions form the Swedish Research Council
- any additional professional activities or commercial ties have been reported to the administrating organisation, and that no conflicts have arisen that would conflict with good research practice
- that the necessary permits and approvals are in place at the start of the project e.g. regarding ethical review.

The signature *from the administrating organisation* confirms that:

- the research, employment and equipment indicated will be accommodated in the institution during the time, and to the extent, described in the application
- the institution approves the cost-estimate in the application
- the research is conducted according to Swedish legislation.

The above-mentioned points must have been discussed between the parties before the representative of the administrating organisation approves and signs the application.

Project out lines are not signed by the administrating organisation. The administrating organisation only sign the application if the project outline is accepted for step two.

Applications with an organisation as applicant is automatically signed when the application is registered.