Application

2015-03-31

2015-05285	Hjalmarsson, Håkan	NT-14

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Project site: Avdelningen för Reglerteknik

Information about application

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Descriptive data

Project info

Project title (Swedish)*

Systemidentifiering: Algoritmer för autonoma system

Project title (English)*

System identification: Unleashing the algorithms

Abstract (English)*

Technical devices integrating physical systems with sensing, actuation, computation and communication, offers fantastic opportunities for society. Challenges in this context are robustness and adaptability.

Estimating models of dynamic systems from observed data is known as system identification. The area is highly interdisciplinary, incorporating theory from many areas, and a wide spectrum of applications. The many facets of system identification necessitate expert intervention. This bottleneck threatens the development outlined above.

With a team of internationally leading researchers from KTH and LiU, we target two of the core areas of the field from the perspective that algorithms should produce reliable models without human intervention. The overarching aim is thus to ``unleash the algorithms". More specifically we target structured systems and address: i) Convex algorithms for parameter estimation, based on an idea of how to link iterative, prediction error and subspace methods together such that favorable properties are inherited from all domains. ii) Analysis tools, allowing explicit insights into how sensors and excitation properties influence estimation accuracy.

Popular scientific description (Swedish)*

Tekniska system i vårt samhälle blir mer och mer avancerade. Genom att integrera fysikaliska (t.ex. mekaniska eller biotekniska) system med billiga (mikro- eller nano-) sensorer och aktuatorer, kraftfulla processorer och snabba kommunikationslänkar kan man uppnå funktionalitet som för bara några år sedan var en utopi. Denna utveckling sker på många fronter. Inom robotik närmar man sig möjligheten att robotar ska kunna vistas och utföra sysslor på ett effektivt och säkert sätt i en hemmiljö. Inom processindustrin går utvecklingen mot anpassningsbara processer som tillåter flexibelt användande av förnyelsebar råvara. Ett annat område är smarta kraftnät som anpassar sig till de energikällor och de laster som finns inkopplade för ögonblicket. Detta krävs för att småskaliga förnyelsebara energikällor ska kunna kopplas in på kommersiella kraftnät. I smarta byggnader så används temperatur- och fuktighetssensorer för att känna av tillståndet i och utanför ett byggnadskomplex för att anpassa t.ex. värmetillförseln på ett komfort- och energioptimalt sätt. Även yttre information som väderutsikter kan användas. Man tittar också på system som kan detektera att det sker förändringar i byggnaden, t.ex. fönster som öppnas eller att personer anländer eller lämnar byggnaden, allt för att optimera driften.

En karaktäristisk egenskap hos alla dessa system är att de yttre betingelserna ändrar sig utom systemets kontroll. När en robot lyfter ett tungt föremål så förändras dess rörelseegenskaper, t.ex. så kommer en viss kraft genererad i en motor i en knäled i roboten att ge en långsammare rörelse än tidigare på grund av att trögheten i kroppen ökat i och med föremålet den bär på. Man brukar säga att systemets dynamik har ändrat sig. På samma sätt förändras dynamiken i ett kraftnät när olika energikällor kopplas in eller ur. Samma gäller en byggnads temperaturdynamik när ett fönster öppnas.

Eftersom det är omöjligt att förutse vilka förändringar som kommer att ske i framtiden måste dessa tekniska system vara anpassningsbara. När de yttre betingelserna förändras måste de själva upptäcka och ta hänsyn till detta. Systemen måste alltså kunna upptäcka och bestämma förändringar i dynamiken i den omgivning de arbetar.

Systemidentifering behandlar hur man med hjälp av sensorinformation konstruerar dynamiska modeller. Området är multidisciplinärt då teorin kommer från matematisk statistik, systemteori och reglerteknik, medans tillämpningarna kommer från alla tänkbara områden: mekanik, bioteknik, elektroteknik, ja listan kan göras hur lång som helst. Även om teorin för denna typ av modellering är välutvecklad, och kraftfull programvara finns tillgänglig, så ställs höga krav på kunskap hos användaren. Den dominerande reglermetoden inom processindustrin utnyttjar denna typ av dynamiska modeller, men processernas egenskaper ändras med tiden och industrin har svårt att hålla modellerna uppdaterade, dels på grund av bristande kompetens, dels på grund av kostnaden. För de system vi tar upp ovan så finns samma typ av problematik.

Syftet med detta projekt är att utveckla algoritmer för systemidentifiering som kan integreras i allehanda tekniska system och ge pålitliga resultat utan behov av mänsklig expertis. Fokus är på fysikaliska system som har någon form av struktur, t.ex. det består av ett antal sammankopplade komponenter. Vi har strukturerat projektet så att det täcker två områden väsentliga för systemidentifiering: i) Algoritmer som ger pålitliga resultat för fysikaliska systemet med struktur. ii) Analysverktyg som kan användas för att bestämma vilka sensorer och aktuatorer i en viss struktur som bör användas om man vill bestämma en viss egenskap hos det fysikaliska systemet med en viss noggrannhet.

Ett spännande tillämpningsområde är system som består av geografiskt utspridda delsystem som sammankopplas antingen fysiskt (jfr kraftnät) eller via kommunikationslänkar, sensorer och aktuatorer.

Project period

Number of project years*

4

Calculated project time*

2016-01-01 - 2019-12-31

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

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

Keyword 1*

systemidentifiering

Keyword 2*

estimering

Keyword 3*

strukturerade modeller

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*

Inga etiska överväganden aktuella.

The project includes handling of personal data

No

The project includes animal experiments

No

Account of experiments on humans

No

Research plan

1 Purpose and aims

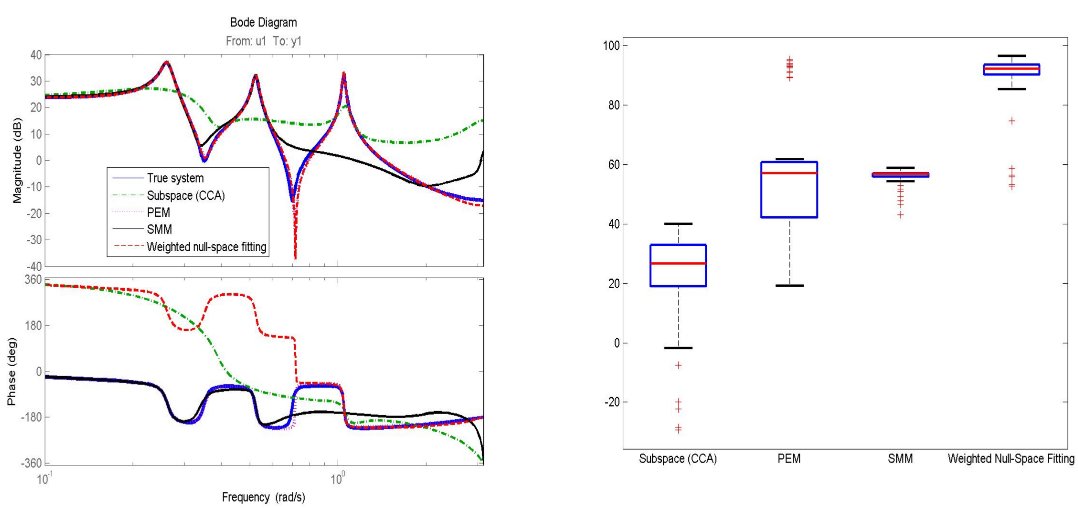
PI Background and Potential. Two questions are essential when judging a research proposal: (1) What is the standing in the field of the applicants? and (2) What new exciting ideas and promising results are envisioned in the proposed research? We start right away by addressing these questions:

(1) It is fair to say that the team is very well recognized internationally. It is evidenced by plenaries (e.g. ECC 2009 [8], IFAC World Congress 2008 [15], IFAC SYSID 2003 [7], Bode Lecture IEEE CDC 2003), prizes and awards (e.g. IEEE Control Systems Award, IFAC Quazza Medal, both applicants are IEEE Fellows). The textbook [14] is the key reference to the field with more than 20000 citations - altogether the applicants have more than 53000 citations (Google Scholar) - and [16] is the leading commercial software platform in the field (in 2007 it was cited to exist to the order of 10^5 licenses).

The applicants are the PI and co-PI of the ERC-Advanced Grant "LEARN-Limitations, Estimation, Adaptivity, Reinforcement and Networks in System Identification" which started in 2011 with maximum score (8.0 out of 8) in the evaluation. Through LEARN the partners have established a fertile research environment, including joint work, e.g. the 2011 IEEE CDC/ECC plenary [17] and supervision. We now have an exceptionally strong background for the research effort we intend to undertake. The proposed project is a follow up of this successful ERC-Advanced Grant which will finish Dec 31 2015.

(2) Accurate and reliable estimation algorithms are essential to understand complex systems.To illustrate the potential of the proposed research, the figure below presents results of a Monte-Carlo study where one of the methods we intend to study (Weighted Null Space Fitting - WNSF) is benchmarked against state-of-the art commercially available algorithms (CCA subspace identification [14], the prediction-error method (PEM) and the Steiglitz-McBride method (SMM)). To the left are Bode diagrams of estimated models from one realization, together with the true system. The box-plots on the right, based on 100 simulations, show that WNSF outperforms the other methods[1] by margin.

We think it is truly remarkable that in 2015 it is possible to devise algorithms that so clearly outperform the state-of-the art that has been established over the past 50 years.



Left: Bode plots. Right: Box plots. Model fit in % (100%= perfect fit). Red bar=Median.

[1]PEM finds the global minimum only in a few cases (red crosses above the box), but suffers otherwise from local minima. SSID and SMM are clearly not statistically efficient.

Project Background. For an engineer, we are living in an exciting time full of fantastic opportunities. Communication and computational resources are cheap and powerful, advances in micro-electronics and nano-technology open up for new inexpensive sensors and actuators, and in all disciplines of natural science there is rapid progress in model based understanding of physical phenomena. This fast-paced development has opened up the possibility to construct "intelligent" machines that are able to perform complex tasks in a physical environment by integrating the dynamics of physical systems with sensing, actuation and information processing, and the interconnection of such devices. Dynamical models of the environment are used internally to compute appropriate actions, e.g. a robot uses a dynamical model of its body to control the motors in its joints. These models have to adapt to changes in the environment, and also reflect the structure of the systems they represent. Estimating models of dynamic systems from observed data is known as *system identification* (SI). Our research agenda aims to develop system identification algorithms that easily can be incorporated into such devices. These problems lie at the intersection between engineered systems (which we can design) and the real world (to which we have to adapt). It is evident that the complexity of real world behavior has to be dealt with in a robust and largely autonomous way. A typical

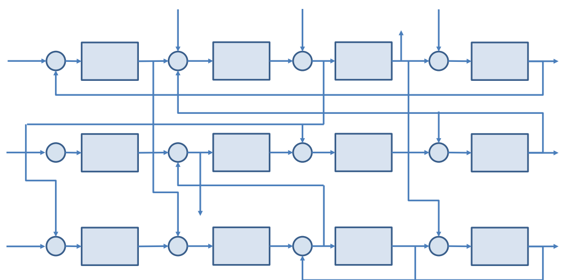


Figure 1: A system consisting of interconnected modules.

system may be represented as in Figure 1. It is highly structured, consisting of simpler interconnected modules. Typically the application requires that the identified model reflects the internal structure of the system.

Project Aims. Our contributions target core areas of system identification, profiled to contribute to the overarching objective of being able to *let the algorithms loose on their own* in systems of the type above:

I) *Convex algorithms for parameter estimation.* Reliable parameter estimation methods are critical in autonomous systems. Even if considerable progress has been made in this area, significant issues remain when structural information is to be accounted for. Methods able to cope with such problems in a statistically efficient way are typically based on local non-linear optimization, thus requiring accurate initial estimates and having issues with local minima. Also, the standard method of generating an initial estimate by a subspace identification method is of limited use since it is difficult to incorporate structure in such methods.

In this context we aim to develop systematic methods for obtaining asymptotically efficient parameter estimators for interconnected models, not suffering from problems with local minima and the issue of finding good initial estimates.

II) *Accuracy analysis.* Conceptually, a structured system can be seen as a (big) multi-input multi-output (MIMO) system, but where the interconnections between different inputs and outputs have a given structure. From an information point of view, it is optimal to identify such a system using all inputs and outputs. However, there are many reasons for why this may not be possible or desirable in practice: For example, the size of the model may become un-manageable from an estimation (optimization) point of view, the system may be spatially distributed so that all sensors are not available at one location, or we may only be interested in certain blocks. It is important to understand the implications of such information constraints.

In this context we aim to develop analysis tools for how the accuracy of an estimate of a certain block is affected by the use of sensors and actuators at different locations. In particular, we are interested in how spatial correlation in inputs and noise influence the model quality.

We believe we are bringing in fresh ideas to these classical problems that can bring the field close to the point where SI algorithms can be reliably deployed in autonomous systems on a massive scale.

2 Survey of the field

2.1 Convex algorithms for estimation

In order to be specific, we will use the following simple example, where we start with an impulse response estimate as 'data'.

Example 1 *Consider the stable rational transfer function*[2]

$$G(q) = \sum_{k=1}^{\infty} g_k q^{-k} = \frac{B(q)}{A(q)} = \frac{bq^{-1}}{a_0 + a_1 q^{-1}}, \; a_0 = 1.$$

The problem is to estimate $\theta = \begin{bmatrix} a^T & b \end{bmatrix}^T$, *where* $a = \begin{bmatrix} a_1 & a_0 \end{bmatrix}^T$, *using a finite impulse response estimate* $\hat{G}(q) = \sum_{k=1}^{n} \hat{g}_k q^{-k}$ *as 'data', by minimizing the* H_2*-norm*

$$\|\Delta(\cdot, \hat{g}, \theta)\|_2 = \frac{1}{2\pi} \int_{-\pi}^{\pi} |\Delta(e^{i\omega}, \hat{g}, \theta)|^2 d\omega$$

of the difference

$$\Delta(q, \hat{g}, \theta) = \sum_{k=1}^{\infty} \delta_k(\hat{g}, \theta) q^{-k} := \hat{G}(q) - B(q)/A(q).$$

Introduce

$$Z(q, \hat{g}, \theta) = \sum_{k=1}^{\infty} z_k(\hat{g}, \theta) q^{-k} := \hat{G}(q)A(q) - B(q),$$

then $A(q)\Delta(q, \hat{g}, \theta) = Z(q, \hat{g}, \theta)$, *and in terms of impulse response coefficients we have*

$$\underbrace{\begin{bmatrix} z_1(\hat{g},\theta) \\ z_2(\hat{g},\theta) \\ \vdots \\ z_n(\hat{g},\theta) \end{bmatrix}}_{z(\hat{g},\theta)} := \underbrace{\begin{bmatrix} 0 & \hat{g}_1 \\ \hat{g}_1 & \hat{g}_2 \\ \hat{g}_2 & \hat{g}_3 \\ \vdots & \vdots \\ \hat{g}_{n-1} & \hat{g}_n \end{bmatrix}}_{H(\hat{g})} \underbrace{\begin{bmatrix} a_1 \\ a_0 \end{bmatrix}}_{a} - \underbrace{\begin{bmatrix} 1 \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix}}_{e} b = \underbrace{\begin{bmatrix} a_0 & 0 & \dots & 0 \\ a_1 & a_0 & \dots & 0 \\ \vdots & \vdots & \dots & \vdots \\ 0 & 0 & \dots & a_0 \end{bmatrix}}_{T(a)} \underbrace{\begin{bmatrix} \delta_1(\hat{g},\theta) \\ \vdots \\ \delta_n(\hat{g},\theta) \end{bmatrix}}_{\delta(\hat{g},\theta)} \Leftrightarrow \begin{aligned} z(\hat{g},\theta) &:= H(\hat{g})a - eb \\ &= T(a)\delta(\hat{g},\theta) \end{aligned} \quad (1)$$

[2] q^{-1} is the time-shift operator: $q^{-1}u(t) = u(t-1)$.

With n large enough, Parseval's formula gives that the problem is

$$\arg\min_{\theta, a_0=1} \|\Delta(\cdot, \hat{g}, \theta)\|_2^2 = \|\delta(\hat{g}, \theta)\|_2^2 = \|T^{-1}(a)(H(\hat{g})a - eb)\|_2^2 \tag{2}$$

The factor $T^{-1}(a)$ renders the problem (2) non-convex. This means that local optimization methods may encounter problems with local minima and finding good initial values for the search becomes critical. The prediction error method (PEM) and the maximum likelihood (ML) method inherit this problem.

Approaches to cope with this problem can roughly be split into four different classes: Instrumental variable (IV) methods, iterative least-squares like methods, subspace identification (SSID) methods and, most recently, convex relaxations. IV methods solve a linear system of equations and by iterating on the choice of instruments, asymptotic efficiency can be obtained for certain families of model structures [14]. The Steiglitz-McBride Method (SMM) [25] falls into the second class. SMM adapted to the problem in Example 1 can be expressed in the following way: Suppose that an estimate $\hat{\theta}^{k-1} = \begin{bmatrix} (\hat{a}^{k-1})^T & \hat{b}^{k-1} \end{bmatrix}^T$ of θ is available. Then instead of (2), solve

$$\hat{\theta}^k = \arg\min_{\theta, a_0=1} \|T^{-1}(\hat{a}^{k-1})(H(\hat{g})a - eb)\|_2^2 \tag{3}$$

iteratively ($k \to k+1$). It is well known that SMM is not asymptotically efficient [27]. For the above problem, SMM is known to be equivalent to Iterative Quadratic Maximum Likelihood (IQML) (originally presented in [3]), see [19]. IQML applied to impulse response estimation has appeared in [23].

Adding columns to (1) consisting of shifts of the first column gives the matrix equation

$$\begin{bmatrix} z_2 & z_3 & \dots & z_m \\ \vdots & \vdots & \dots & \vdots \\ z_{n-m+2} & z_{n-m+3} & \dots & z_n \end{bmatrix} = \underbrace{\begin{bmatrix} \hat{g}_1 & \hat{g}_2 & \hat{g}_3 & \dots & \hat{g}_m \\ \hat{g}_2 & \hat{g}_3 & \hat{g}_4 & \dots & \hat{g}_{m+1} \\ \hat{g}_3 & \hat{g}_4 & \hat{g}_5 & \dots & \hat{g}_{m+2} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \hat{g}_{n-m+1} & \hat{g}_{n-m+2} & \hat{g}_{n-m+3} & \dots & \hat{g}_n \end{bmatrix}}_{=:\bar{H}(\hat{g})} \underbrace{\begin{bmatrix} a_1 & 0 & 0 & \dots & 0 \\ a_0 & a_1 & 0 & \dots & 0 \\ 0 & a_0 & a_1 & \dots & 0 \\ \vdots & \vdots & \dots & \vdots & \\ 0 & 0 & 0 & \dots & a_0 \end{bmatrix}}_{=:T(a)\in\mathbb{R}^{m\times m-1}} \tag{4}$$

if the first row is omitted. With the estimate $\hat{g}$ replaced by g the left hand side is zero, and since by contruction $T(a)$ has full rank it must hold that the Hankel matrix $\bar{H}(g)$ has rank 1 (the order of the system). SSID methods are based on this and the additional observation that the range space of $\bar{H}(g)$ is spanned by the columns of the extended observability matrix. In this rank-1 example, the left singular vector corresponding to the largest singular value of $\bar{H}(\hat{g})$ gives an estimate of this range space, from which state-space matrices can be estimated. A drawback with this type of method is that it is not easy to incorporate structural information, see [6]. Furthermore, although considerable effort has been devoted to analyzing the asymptotic accuracy, e.g. [1, 4], a complete picture is missing, but it is generally conjectured that SSID mehods are asymptotically efficient only for certain experimental conditions.

One can also eliminate a and b from the problem and directly try to estimate an impulse response g which corresponds to a low order model. Using $\hat{g}$ as 'data', conceptually one should then for our example solve

$$\min_g \|g - \hat{g}\|_W^2, \text{ s.t. rank } \bar{H}(g) = 1$$

for some appropriate weighting matrix W. Recently, there has been contributions where the non-convex rank constraint has been relaxed to a convex problem using nuclear norm regularization, e.g. [13], and [11].

2.2 Accuracy analysis

In [2] systems composed of cascade, feed-forward, feedback and multiplicative connections of linear dynamic and zero memory nonlinear elements are considered. It is showed that such systems can be identified in terms of the individual component subsystems from measurements of the system input and output only. More recent work on identification of structured models can be found in [12]. A network structure with process disturbances is considered in [28] and conditions for when direct PEM, two-stage and joint input-output methods give consistent estimates of a block are derived.

3 Project description

3.1 Convex algorithms for estimation

We will consider two classes of algorithms, weighted null-space fitting, and convex relaxations, details of which are provided below.

Weighted null-space fitting. While most SSID methods have focused on estimating the range space of $\bar{H}(g)$ (from which a state-space model can be recovered), notice that $z(g,\theta) = 0$ when g and θ correspond to the same model and that then (4) gives $0 = \bar{H}(g)T(a)$ and hence knowing the null-space of $\bar{H}(g)$ will give us the denominator polynomial $a_0 + a_1 q^{-1}$ (which then can be used to recover the numerator b). This path has been pursued in [30] where an estimate of the null-space is derived from the singular value decomposition (SVD) of $\bar{H}(\hat{g})$. We intend to pursue this approach with two important contributions:

i) *Incorporating structure.* It does not seem to be widely recognized that considering a suitable null-space allows structure to be easily incorporated. Consider the cascade system

$$y_1(t) = \frac{B_1(q)}{A_1(q)}u(t) + e_1(t), \quad y_2(t) = \frac{B_2(q)}{A_2(q)}\frac{B_1(q)}{A_1(q)}u(t) + e_2(t)$$

By first estimating high order finite impulse response (FIR) models $\hat{G}_1(q)$ and $\hat{G}_{12}(q)$, using the model

$$y_1(t) = G_1(q)u(t) + e_1(t),\ y_2(t) = G_{12}(q)u(t) + e_2(t),$$

by least-squares, the polynomials A_1, B_1, A_2 and B_2 can be estimated from the relations

$$A_1(q)G_1(q) - B_1(q) = 0,\ A_2(q)G_{12}(q) - B_2(q)G_1(q) = 0$$

which, following the derivations above that lead to $0 = \bar{H}(g)T(a)$, can be expressed in terms of a null-space relation (where the polynomial coefficients appear linearly) from which the sought polynomials can be recovered.

In summary, with $\mathcal{S}$ denoting the true system, our approach consists of two steps: 1) Lifting (by way of overparametrization) the structured estimation problem to a simpler unstructured problem which can be easily solved (e.g. by least-squares), giving an estimate $\hat{\mathcal{S}}$. Then, 2) recovery of the structured estimate, represented by parameters θ, by solving

$$\mathbf{D}(\hat{\mathcal{S}})M(\theta) \approx 0 \tag{5}$$

for θ, where $\mathbf{D}$ is a suitably chosen matrix such that the null-space of $\mathbf{D}(\mathcal{S})$ is linear in θ, i.e., $\mathbf{D}(\mathcal{S})M(\theta) = 0$ where M is linear in θ.

As a wide range of parameter estimation problems can be formulated as low-rank estimation problems [18], and any such problem can be reformulated as a null-space estimation problem problem, a wide variety of estimation problems fit into this framework.

ii) *Vectorization.* So far we have not been specific in how the null-space should be estimated from (5). For range-space based SSID methods based on (4), the statistical properties can be influenced by weightings. This is achieved by left and right multiplications of the estimated Hankel matrix with weighting matrices W_1 and W_2 [14]: $W_1\bar{H}(\hat{g})W_2$, before taking the SVD. However, notice that this does not allow us to shape the correlation structure between all the elements of $\bar{H}(\hat{g})$ in an arbitrary way – we are constrained by that it is a matrix multiplication. *We believe that this is the reason why it does not seem possible to make SSID methods asymptotically efficent in a universal setting.* Next, we make an important observation, namely that, unlike in range space estimation, we can *vectorize our null-space matrix equation.* For example, vectorizing (4) will give us back (1) (with a number of replicas). Suppose that $\hat{g} \in \mathcal{N}(g, P)$ and notice that[3] $\Delta(q, \hat{g}, \theta)) = \hat{G}(q) - B(q)/A(q) = \hat{G}(q) - G(q)$ so that $\delta_k(\hat{g}, \theta) = \hat{g}_k - g_k$. Thus (1) gives

$$H(\hat{g})a - eb = T(a)(\hat{g} - g) \in \mathcal{N}(0, T(a)PT^T(a))$$

and an optimal estimate of a and b is obtained by solving

$$\min_{a,b,a_0=1} \|H(\hat{g})a - eb\|_W^2, \; W = (T(a)PT^T(a))^{-1}$$

Unfortunately, the optimal weighting W depends on a, but this can be handled by a two step procedure with $W = I$ in a first least-squares step (which can be shown to give a consistent estimate) and then using the estimate of a from the first step in W, which gives a weighted least-squares (WLS) problem. If the unstructured estimate $\hat{g}$ is a sufficient statistic, this will result in an asymptotically efficient estimate. Notice that we achieve this since, thanks to the vectorization, we can take the entire correlation structure of $\hat{g}$ into account in our weighting. Notice also that instead of using SVD we use the computationally much cheaper WLS, which also opens up for recursive estimation.

For the general expression (5) we have $(I \otimes \mathbf{D}(\hat{\mathcal{S}}))\text{vec}(M(\theta)) \approx 0$ and again it will be appropriate with a two-step WLS procedure taking the statistics of $\hat{\mathcal{S}}$ into account.

[3] Recall that Δ was defined in Example 1.

While the approach is rooted in IQML, prior works in this direction, such as [25, 23], have not taken the statistics of the unstructured estimate into account and we believe that it is precisely due to this reason that SMM is not asymptotically efficient. We strongly believe that when the optimal weighting is used, asymptotic efficiency can be achieved. The null-space approach is discussed in [21], but without recognizing the importance of using statistically optimal weighting and without exploring its applicability to structured systems. The contribution [26] takes the statistics into account for MIMO transfer function estimation but is based on an instrumental variable approach and does not appear to give efficient estimates. Our approach can be seen as a link between PEM, SSID and iterative methods, inheriting favorable properties from all domains. We also point to the connection between WNSF and the indirect prediction error method [24].

Convex relaxations. Being fashioned from SSID, present nuclear norm relaxation techniques have difficulties in incorporating structure. Also here a null-space embedding seems fruitful. Returning to (1), when the impulse response g exactly corresponds to a and b, we have $H(g)a - eb$ which can be expressed as

$$Q(g,a,b)\begin{bmatrix}-1\\ a\\ 1\end{bmatrix} = 0, \quad Q(g,a,b) := \begin{bmatrix}1 & a & b & 0 & 0 & \dots\\ 0 & 1 & 0 & g_1 & g_2 & \dots\\ 1 & 0 & g_1 & g_2 & g_3 & \dots\end{bmatrix}^T$$

and thus $Q(g,a,b)$ should be rank deficient. Thus by using the unstructured impulse response model g and the structured model $\{a,b\}$ jointly, and using nuclear norm regularization to relax the rank constraint on $Q(g,a,b)$, structure (here the orders of A and B) can be incorporated. We believe it is possible to extend this approach to a wide variety of problems.

To cope with the choice of regularization parameter we intend to pursue the idea in [22] which is based on statistical considerations. This leads to one-shot methods, as opposed to current practice of optimizing the weight by way of computationally costly cross-validation.

Structured identification. We intend to explore the techniques outlined above for a wide variety of structured identification problems, e.g. rational linear and non-linear models, MIMO, block-structured, errors-in-variables (EIV), closed-loop problems and combinations of these. Here, we give a brief glimpse of what can be achieved.

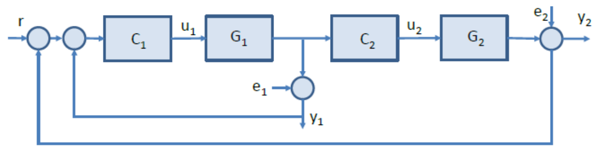
Consider the *cascade feedback system* in the figure below. Here C_1 and C_2 are known linear controllers while G_1 and G_2 represent the unknown system, modeled as rational transfer functions $G_1 = B_1/A_1$ and $G_2 = B_2/A_2$. It is well known that in such a closed loop setting, PEM gives biased estimates if, together with the measured outputs y_1 and y_2, the direct inputs u_1 and u_2 are used, unless also accurate noise models for e_1 and e_2 are used. IV methods can be used to alleviate this problem or, so called, two-stage methods [29, 14]. Using the external excitation r instead, consistent estimates of the closed loop transfer functions $T_1 := C_1G_1/(1 + C_1G_1)$ and $T_2 := T_1C_2G_2/(1 + T_1C_2G_2)$ can be obtained using PEM, as this is an open loop identification problem. But this means that WNSF can easily be applied to estimate G_1 and G_2 as it holds

$$T_1 + T_1C_1G_1 - C_1G_1 = 0 \;\Rightarrow\; A_1T_1 + T_1C_1B_1 - C_1B_1 = 0$$

With C_1 and T_1 given, this is a linear system of equations in the parameters of A_1 and B_1. Thus consistent estimates of these parameters can be obtained by solving a least-squares problem as outlined above. The quality can then be improved by solving a weighted least-squares problem. These estimates can then be used in the relation

$$T_2 + T_1 C_2 G_2 T_2 - T_1 C_2 G_2 = 0$$

to obtain consistent estimates of $G_2 = B_2/A_2$ in the same manner as for A_1 and B_1.



3.2 Accuracy analysis

EIV vs PEM. At present block-structured/network models of the type in Figure 1 have either assumed process disturbances only and no measurement noise, e.g. [28], or vice-versa. However, it seems more realistic that both types of disturbances are present in a real system. Then, while standard PEM can be used if the excitation signals are available, the problem turns into an EIV problem if only measured variables are used and building on [10] we will analyze differences in accuracy between PEM and EIV in a structured system context.

The value of sensors and actuators. We have initiated a study, e.g. [5, 31], of how sensors and actuators influence the model accuracy, using the geometric analysis technique introduced in [9]. Particular to this is that the dynamics of such devices often have to be modelled as well, which deteriorates accuracy. By studying asymptotic situations we have gained insights into the underlying mechanisms. We intend to extend this study to more general block structures, particular interesting cases occur when there are feedback interconnections.

In [20] we have analyzed the model accuracy for multi-input/single-output models for the case that the inputs are spatially correlated. We have found a connection to Bayesian Networks in that the Cholesky factor of the inverse of the correlation matrix for the input plays an important role. Now, noise in spatially distributed sensors may very well be correlated as well, c.f. interference in antenna arrays or ECG sensors on a body. How such correlation influences the estimation accuracy is an interesting problem.

4 Significance

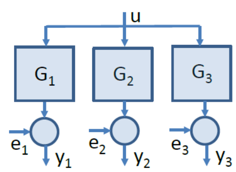
In this proposal we are targeting two of the core areas of system identification and progress in these directions will have a strong impact on the field. As outlined in Section 1 we believe that data-based modeling is highly relevant for model based engineering. This step severely limits the use of modern control technology in process industry, and in future massively deployed applications this issue will become a serious bottleneck. We intend to continue our strategy of spinning-off our theoretical developments into applications, which so far has spanned wireless communication, combustion engine modeling, and process control.

The PIs have a long tradition of dissemination research results not only in journal publications, but also in textbooks and industrially relevant software, courses for industry and industrial applications. This will of course continue also with the current project: The PI is working with B. Ninness, Newcastle Univ., on a textbook project, and with J. Sjöberg, Chalmers, on a software project; both projects will draw heavily from results in the project.

5 Preliminary results

In regards to *convex algorithms for estimation*, we refer to the example in Section 1.

In regards to *accuracy analysis*, consider the system in the figure below, where $G_1 = g_1$, $G_2 = g_2$ and $G_3 = g_3 + g_4 q^{-1}$ are to be estimated from measurements of $y_1 - y_3$ and u when the input $\{u_t\}$ is white noise. When the measurement errors $e_1 - e_3$ are dependent, the accuracy can be significantly improved. Focusing for simplicity on g_4, the idea is to use y_1 and y_2 to estimate the noise e_3 that perturbs the measurement equation where g_4 is involved. Consider the ideal case when we can measure e_1 and e_2 exactly. Then we can compute an optimal estimate $\hat{e}_3(t)$ from these measurements and form $y_3(t) - \hat{e}_3(t) = g_3 u(t) + g_4 u(t-1) + e_3(t) - \hat{e}_3(t)$ which is less noisy than $y_3(t)$, thus allowing the quality of the g_4-estimate to be improved. Quite surprising, it seems as if the same accuracy for the estimate of g_4 as in this procedure can be achieved using $y_1 - y_3$ and simultaneously estimating $g_1 - g_3$ as well.



6 International collaboration

In recent years we have collaborated with P. Van den Hof, TU Eindhoven, X. Bombois, Ecole Centrale de Lyon, V. Krishnamurthy, UBC, L. Gerencsér, MTA SZTAKI, J. Schoukens, VUB, M. Gevers, UCL, G. Goodwin, B. Ninness and J. Welsh, Newcastle Univ., I. Manchester, Univ. of Sydney, A.Chiuso, G. Pillonetto, Univ of Padova, and A. Bazanella and D. Eckhard, Univ. Federal do Rio Grande do Sul on topics closely related to this project.

7 Other grants

The VR Linneaus Centre ACCESS is a consortium consisting of seventeen founding professors (including Håkan Hjalmarsson), researchers, postdocs and PhD students from seven labs at KTH. The annual budget of the centre is decided by the Centre Board. From a KTH perspective the funding is considered as faculty funding (fakultetsmedel).

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[8] H. Hjalmarsson. System identification of complex and structured systems. *European Journal of Control*, 15(4):275–310, 2009. Plenary address. European Control Conference.

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[10] H. Hjalmarsson, J. Mårtensson, C.R. Rojas, and T. Söderström. On the accuracy in errors-in-variables identification compared to prediction-error identification. *Automatica*, 47(12):2704–2712, Dec 2011.

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[31] B. Wahlberg, H. Hjalmarsson, and J. Mårtensson. Variance results for identification of cascade systems. *Automatica*, 45(6):1443–1448, 2009.

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

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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	Håkan Hjalmarsson	20
2	Participating researcher	Lennart Ljung	40
3	Other personnel without doctoral degree	Miguel Galrinho	80
4	Other personnel without doctoral degree	Niklas Everitt	80
5	Other personnel without doctoral degree	NN	80

Salaries including social fees

	Role in the project	Name	Percent of salary	2016	2017	2018	2019	Total
1	Applicant	Håkan Hjalmarsson	16	250,000	255,000	260,000	265,000	1,030,000
2	Other personnel without doctoral degree	Miguel Galrinho	80	454,000	472,000	524,000	545,000	1,995,000
3	Other personnel without doctoral degree	Niklas Everitt	40	227,000	252,000	0	0	479,000
4	Other personnel without doctoral degree	NN	40	0	0	220,000	229,000	449,000
5	Participating researcher	Lennart Ljung	8	117,000	117,000	117,000	117,000	468,000
	Total			1,048,000	1,096,000	1,121,000	1,156,000	4,421,000

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	Kontor	83,000	87,000	89,000	93,000	352,000
	Total	83,000	87,000	89,000	93,000	352,000

Running Costs

	Running Cost	Description	2016	2017	2018	2019	Total
1	Resor	Konferenser	100,000	100,000	100,000	100,000	400,000
2	Datorer		20,000	20,000	20,000	20,000	80,000
	Total		120,000	120,000	120,000	120,000	480,000

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	1,048,000	1,096,000	1,121,000	1,156,000	4,421,000	2,588,000	7,009,000
Running costs	120,000	120,000	120,000	120,000	480,000	0	480,000
Depreciation costs					0		0
Premises	83,000	87,000	89,000	93,000	352,000	22,000	374,000
Subtotal	1,251,000	1,303,000	1,330,000	1,369,000	5,253,000	2,610,000	7,863,000
Indirect costs	341,000	359,000	368,000	381,000	1,449,000	91,000	1,540,000
Total project cost	1,592,000	1,662,000	1,698,000	1,750,000	6,702,000	2,701,000	9,403,000

Explanation of the proposed budget

Briefly justify each proposed cost in the stated budget.

Explanation of the proposed budget*

Projektledaren verksam 20% i projektet, varav 16% täcks av VR. Resterande del fakultetsmedel (redovisat under Annan kostnad)
Medverkande forskare aktiv 40% i projektet varav 8% av lön samt resekostnader täcks av projektet. Ingen overhead då prof. emeritus. Övrig del av lön täcks också av detta (redovisat under annan kostnad).
1.5 doktorand under projektets löptid.
4 konferensresor/år för att presentera projektresultat, svarar mot 1 konferensresa/projektdeltagare.
1 laptop/år.
Sammantaget beräknas detta täcka projektets omfattning.

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

CV and publications

CV

CURRICULUM VITAE

HÅKAN HJALMARSSON

Address:	Automatic Control/ School of Elec. Eng.	**Phone:**	08–790 8464
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HIGHER EDUCATION QUALIFICATION

August 1988 Master of Science, *Civilingenjör*, Telecommunication, Linköping University, Linköping, Sweden.

DEGREE OF DOCTOR

April 2, 1993 PhD in Engineering (Automatic Control), Linköping University, Linköping, Sweden.

Thesis title: Aspects On Incomplete Modeling in System Identification

Supervisor: Lennart Ljung

POSTDOCTORAL POSITIONS

July 1991 – August 1992 Lecturer/Visiting Associate at the Department of Chemical Engineering, California Institute of Technology, Pasadena, USA.

September 1993 – March 1994 Research associate at the Centre for Systems Engineering and Applied Mechanics (CESAME), University of Louvain, Belgium

August 1995 – December 1995 Research fellow at the Dept. of Electrical Engineering and Computer Science, University of Newcastle, Australia.

QUALIFICATION FOR APPOINTMENT AS A DOCENT

February 1997 Docent in Signal Processing, Royal Institute of Technology, Sweden.

PRESENT POSITION

March 2003 – Professor in Signal Processing in the Automatic Control Group, Royal Institute of Technology, Sweden. Currently 60% research, 15% teaching, 25% administration.

February 2007 – Director of Graduate Studies, School of Electrical Engineering, Royal Institute of Technology, Sweden. 20% of full time.

PAST POSITIONS

March 1995 – January 1997 Assistant Professor in Signal Processing at the Dept. of Signals, Sensors and Systems, Royal Institute of Technology, Sweden. Acting Head March 1996 – March 1997.

February 1997 – December 1998 Associate Professor in Signal Processing at the Dept. of Signals, Sensors and Systems, Royal Institute of Technology, Sweden.

January 1999 – 2002 Head of the Automatic Control Group, Department of Signals, Sensors and Systems, Royal Institute of Technology.

December 2002 – June 2003 Visiting professor at the School of Electrical Engineering and Computer Science, University of Newcastle, Australia.

INTERRUPTION IN RESEARCH

September 2003 – January 2004, September 2006 – January 2007. Parental leave. Total 10 months.

PHD AND POSTDOC SUPERVISION

- Ola Markusson (PhD, 2002). Henrik Jansson (PhD, 2004). Jonas Mårtensson (PhD, 2007), Niels Möller (PhD, 2008, co-supervisor). Krister Jacobsson (PhD, 2008). Märta Barenthin (PhD, 2009, co-supervisor), Oscar Flärdh (PhD, 2012), Christian Larsson (PhD, 2014), Cristian Rojas (PostDoc, 2008-2010), Dimitrios Katselis (PostDoc, 2011-2013), Lirong Huang (PostDoc, 2010-2012), Giulio Bottegal (PostDoc, 2013-present).

OTHER APPOINTMENTS

1996 – 2002	Associate Editor for Automatica.
1999 –	Member of the International Program Committee for the triennial IFAC Symposium on System Identification
2000–2002	Guest Editor for special section on *Iterative Feedback Tuning. Theory and Applications.* Control Engineering Practice.
2001–2002	Guest Editor for special issue on *Design and optimisation of restricted complexity controllers.* European Journal of Control.
2003–2006	Program Chair and General Co-Chair for the 14th IFAC Symposium on System Identification, Newcastle, Australia, 2006.
2004 – 2007	Associate Editor for IEEE Transactions on Automatic Control.
2008 – 2010	Chair of IFAC Technical Committee on Modeling, Identification and Signal Processing (TC-MISP) (member since 1996, Co-Chair 2006-2008)
2009	Editor at Large for the 48th IEEE Conference on Decision and Control, Shanghai, China, 2009
2011–2012	Guest Editor for special issue on *A System Identification Benchmark.* Control Engineering Practice.
2011-	Member IFAC Technical Board & Coordinating Chair of Technical Area Signals and Systems
2014–	IPC Co-Chair for European Control Conference 2016

KEYNOTE ADDRESSES

March 31-April 1, 2010	*"System identification of complex and structured systems. Parts I and II"* Plenaries at 29th Benelux meeting on Systems and Control 2010.
August 23-26, 2009	*"System identification of complex and structured systems."* Plenary at European Control Conference 2009, Budapest, Hungary.
August 27, 2003	*"From experiments to closed loop control."* Opening plenary at SYSID 2003, Rotterdam, The Netherlands

AWARDS

2001	The KTH Award for outstanding contribution to the undergraduate education program at the Royal Institute of Technology, Stockholm, Sweden.
2010	Co-recepient of ERC-Advanced Grant "LEARN - Limitations, Estimation, Adaptivity, Reinforcement and Networks in System Identification". 60% of funding. Proposal received maximum score.
2013	IEEE Fellow for contributions to data-based controller design.

PUBLICATIONS

1 book, 12 book chapters, 74 journal papers (published/under review), 176 conference papers (published/under review). 1 ISI highly cited paper. Google Scholar data: 6600 citations.

CV Lennart Ljung (460913-4319)

See http://www.control.isy.liu.se/~ljung for more information.

Degrees

1967 Bachelor of Arts (Russian Language and Mathematics), Lund University
1970 Master of Science (Engineering Physics), Lund Institute of Technology
1974 PhD in Automatic Control, Lund Institute of Technology (supervisor: Karl Johan Åström)

Honorary Degrees

1996 Doctor h.c. at the Baltic State Technical University, S:t Petersburg, Russia
1998 Doctor of Philosophy h.c. Uppsala University, Sweden
2004 Doctor of Philosophy h.c. , Université de Technlogie de Troyes, UTT, France
2004 Doctor of Philosophy h.c. (Ehredoctor) , Katholieke Universiteit Leuven, Belgium
2008 Honorary Doctor, TKK, The Technical University of Hesinki, Finland

Honorary Membership Professional and Academic Societies

1985 Fellow of the Institute of Electrical and Electronic Engineers (IEEE)
1985 Member of the Royal Swedish Academy of Engineering (IVA)
1987 Advisory Professor at the East China Normal University, Shanghai
1993 Advisor to the International Federation of Automatic Control (IFAC)
1995 Member of the Royal Swedish Academy of Science (KVA)
1996 Honorary Professor at the Northeastern University, Shenyang, China
2001 Honorary Member of the Hungarian Academy of Engineering
2004 Foreign Associate of the US National Academy of Engineering, NAE
2010 Honarary Professor of the Academy of Mathematics and Systems Science, Chinese Academy of Sciences

Awards

1979: The IEEE Control Systems Society Outstanding Paper Award
1981: The Automatica Prize Paper Award
1993: The Automatica Prize Paper Award
1993: College of Electrical Engineers' Gold Plaque, The Institute of Engineers, Australia
1996: The Chester Carlsson Research Prize, awarded by IVA
2002: The Quazza Medal, awarded by IFAC
2003: The Hendrik W Bode Lecture Prize, awarded by IEEE Control Systems Society
2007: The IEEE Control Systems Field Award.

Employments

1976 – Present: Professor of the Chair of Automatic Control, Linköping University
1974–1975: Research Associate, ISL, Stanford
1980–1981: Visiting Professor, ISL, Stanford
1985–1986: Visiting Scientist, LIDS, MIT
2005: Russel Severance Springer Fellow, UC Berkeley,

Graduate Supervision

Main supervisor of 32 PhD's (with current affiliation):
Mille Millnert 1982 (VR), Ton van Overbeek 1982 (European Space Agency), Bengt Bengtsson (Sectra, retired), Eva Skarman (Trulsson) 1983 (Saab), Stefan Ljung 1983, (ABB Ludvika), Kjell Nordström 1987, (Consultant), Bo Wahlberg 1985 (KTH), Svante Gunnarsson 1986 (LiTH), Alf Isaksson 1986 (ABB), Mats Viberg 1987 (Chalmers), Inger Erlander Klein 1990 (LiTH), Håkan Hjalmarsson 1993 (KTH), Peter Nagy 1992 (FOI), Fredrik Gustafsson 1992 (LiTH), Jan-Erik Strömberg 1994 (DKR),Thomas McKelvey 1995 (Chalmers), Jonas SJöberg 1995 (Chalmers), Roger Germundsson 1995 (Wolfram Research), Peter Lindskog 1996 (Nira Dynamics), Johan Gunnarsson 1997 (Sörman), Anders Helmersson 1995 (SAAB Sapce) Urban Forssell 1999 (Öhlin's Racing) Magnus Larsson 1999 (ABB), Fredrik Tjärnström 2002 (Autoliv), Jakob Roll 2003 (Autoliv), David Lindgren 2005 (FOI), Martin Enqvist 2005 (LiTH), Ingela Lind 2006 (SAAB), Jonas Gillberg 2006 (IBM), Markus Gerdin 2006 (Quamcom), Henrik Ohlsson 2010 (Berkeley).
Co-supervisor of 20 additional PhD-theses. Also, supervisor of 40 Licentiate theses.

Publications

13 books (Prentice Hall, MIT Press, Springer and Studentlitteratur), 200 journal papers (mostly in IFAC's Automatica and IEEE Transactions and Magazines), and around 300 conference papers (in IEEE and IFAC peer reviewed conferences).

Author of a major Matlab software package: *The System Identification Toolbox*

Publication list

Håkan Hjalmarsson

Citations count from Google Scholar. Total: 6600 citations.

Most cited journal papers

[HH-HC1] J. Sjöberg, Q. Zhang L. Ljung, A. Benveniste, B. Deylon, P-Y. Glorennec, H. Hjalmarsson, and A. Juditsky. Nonlinear black-box models in system identification: a unified overview. *Automatica*, 31:1691–1724, 1995. Number of citations: 1536

[HH-HC2] H. Hjalmarsson, M. Gevers, S. Gunnarsson, and O. Lequin. Iterative Feedback Tuning: theory and applications. *IEEE Control Systems Magazine*, 18(4):26–41, August 1998. Number of citations: 498

[HH-HC3] A. Juditsky, H. Hjalmarsson, A. Benveniste, B. Deylon, L. Ljung, J. Sjöberg, and Q. Zhang. Nonlinear black-box models in system identification: Mathematical foundations. *Automatica*, 31:1725–1750, 1995. Number of citations: 336

[HH-HC4] H. Hjalmarsson. From experiment design to closed loop control. *Automatica*, 41(3):393–438, March 2005. Number of citations: 298

[HH-HC5] H. Hjalmarsson. Iterative Feedback Tuning –An overview. *International Journal on Adaptive Control and Signal Processing*, 16(5):373–395, 2002. Number of citations: 230

Publications 2007-2014

Journal Papers

[HH-J1] M. Barenthin and H. Hjalmarsson. Identication and control: Joint input design and H_∞ state feedback with ellipsoidal parametric uncertainty via LMIs. *Automatica*, 44(2):543–551, 2008. Number of citations: 22

[HH-J2] H. Hjalmarsson and H. Jansson. Closed loop experiment design for linear time invariant dynamical systems via LMIs. *Automatica*, 44(3):623–636, 2008. Number of citations: 36

[HH-J3] M. Barenthin, X. Bombois, H. Hjalmarsson, and G. Scorletti. Identification for control of multivariable systems: Controller validation and experiment design via LMIs. *Automatica*, 44(12):3070–3078, 2008. Number of citations: 29

[HH-J4] L. Gerencsér, H. Hjalmarsson, and J. Mårtensson. Identification of ARX systems with non-stationary inputs - asymptotic analysis with application to adaptive input design. *Automatica*, 45(3):623–633, March 2009. Number of citations: 48

[HH-J5] K. Jacobsson, L. L. H. Andrew, A. K. Tang, S. H. Low, and H. Hjalmarsson. An improved link model for window flow control and its application to FAST TCP. *IEEE Transactions on Automatic Control*, 54(3):551–564, 2009. Number of citations: 36

[HH-J6] J. Mårtensson and H. Hjalmarsson. Variance error quantifications for identified poles and zeros. *Automatica*, 45(11):2512–2525, Nov. 2009. Number of citations: 16

[HH-J7] B. Wahlberg, H. Hjalmarsson, and J. Mårtensson. Variance results for identification of cascade systems. *Automatica*, 45(6):1443–1448, 2009. Number of citations: 25

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Citation count from Google Scholar. Total citations **46817**.

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CV

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Dissertation title (en)

Aspects on Incomplete Modeling in System Identification

Organisation	Unit	Supervisor
Linköpings universitet, Sweden Sweden - Higher education Institutes	Institutionen för systemteknik (ISY)	Lennart Ljung

Subject doctors degree	ISSN/ISBN-number	Date doctoral exam
20202. Reglerteknik	ISSN 0345-7524	1993-04-02

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Konvergens för identierings- och adaptiva reglernings-algoritmer

Dissertation title (en)
Stochastic convergence of algorthms for identification and adaptive control

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Subject doctors degree	ISSN/ISBN-number	Date doctoral exam
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Publications

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Hjalmarsson, Håkan has not added any publications to the application.

Publications

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Ljung, Lennart 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.