Perspectives and Future Directions in Control Configuration Selection (PiCCS)

Workshop Notes

Wolfgang Birk
Miguel Castaño Arranz
Bijan Moaveni
Perspectives and Future Directions in Control Configuration Selection (PiCCS)

Workshop Report

Wolfgang Birk
Miguel Castaño Arranz
Bijan Moaveni
Summary

The PiCCS workshop took place at Luleå University of Technology on 16th and 17th of August 2017. In total 20 researcher and engineers from industry participated in the event.

The main aim of the workshop was to bring together expert in the field of Control Configuration Selection (CCS), which is a sub-field in the research area Automatic Control, to discuss the current state of the art and identify remaining challenges in the field. The identified challenges were formulated as future directions and are summarized in this report, together with an account of the discussion during these two days.

The workshop explored the following topics Implementing optimal operation using simple control elements, Real time optimisation approach in control structure design and benchmarking, Data driven control configuration selection, and Reconfiguration of control structures. Based on the outcome of the discussion, a group of participants proposed an invited session for the 2018 IFAC AdChem Symposium, which has been accepted at the time of the publication of this report and consists of 6 papers addressing challenges discussed during the workshop.
## Contents

1. Background .................................................. 6
2. A note on the terminology .................................. 6
3. Discussion and perspectives ............................... 7
   3.1 Topic 1: Implementing optimal operation using simple control elements ....... 7
   3.2 Topic 2: Real time optimisation approach in control structure design and benchmarking. 8
   3.3 Topic 3: Data driven control configuration selection .......................... 10
   3.4 Topic 4: Reconfiguration of control structures ............................... 11
4. Future research directions ................................... 12
5. Conclusions .................................................. 13
6. Acknowledgements .......................................... 14
A. Workshop program and participants ...................... 18
B. Presentations ................................................. 20
   B.1 Topic 1: Krister Forsman and Sigurd Skogestad ......................... 20
   B.2 Topic 2: Martin Guay and Fredrik Bengtsson ............................ 42
   B.3 Topic 3: André Carvalho Bittencourt and Cristian Rojas .............. 63
   B.4 Topic 4: Yie Cao and Natalia Dudarenko ............................... 76
1 Background

Control configuration Selection (CCS) is a mature field of research in the areas of control engineering, process control and chemical engineering. It has essentially been a field of investigation since the 1960’s, initiated by the pioneering work of Rijnsdorp and Bristol.

The general goal of methodologies in Control Configuration Selection is to determine a configuration of a control system prior to designing and evaluating the control system. Initially, the idea was to select pairs of controlled and manipulated variables in a large scale system which are appropriate for the design of multi-loop single input and single output controllers. Such thinking renders a fully decentralized control system. In later years, the methodologies were broadened to consider sparse control configurations, which enables a controller for a manipulated variable to make use of more than one controlled variable as well as other exogenous variables such as measured process disturbances.

The currently available plethora of methods enables engineers to select control configuration for various kinds of systems, both linear and nonlinear, as well as considering characteristics like uncertainty, delays, and unstable modes, only to mention some. Nevertheless, new methods are suggested and promoted on a regular basis by scientists and engineers. All these new assets to the methodology portfolio leads to the debate on what are the remaining questions in the area and which directions are important to be investigated.

A more problematic issue, constituted by the large portfolio of methodologies, is the fact that it leaves the practitioner often without guidance in the actual applicability of a certain method. It remains often unclear, in which contexts and for which problems a methodology is most appropriate and even more importantly, when a method should not be used. Systematic benchmarking of methods could be a solution to this issue, as long as there is no evaluation scheme that would indicate the applicability.

The authors therefore decided to arrange a workshop with expert researchers and practitioners in the field to discuss and identify needs of future research and which directions are most promising. In order to structure the discussion, the following four topics were selected:

- Implementing optimal operation using simple control elements.
- Real time optimisation approach in control structure design and benchmarking.
- Data driven control configuration selection.
- Reconfiguration of control structures.

For each of the topics two speakers were invited to introduce the topic and ongoing research, which would initiate the discussion on the topics and the related research.

It is assumed that the reader of this report is familiar with some CCS methodologies, otherwise a comprehensive summary can be found in the recent survey by Castaño et. al. (see [1]).

2 A note on the terminology

Both in the literature and also during the discussions of the workshop, the terminology varied. For example the terms control configuration and control structure and control strategy have been used interchangeably.
The term *control configuration* in the context of the workshop was representing the combination of manipulated variables (MVs) and controlled variables (CVs) that would be used for the design of a controller. There, controller can be multivariable and single variable.

When it comes to the realisation of control configuration a number of elements can be used, like feed forward, feed back, as well as switching. Quite often the term *control architecture* is used here.

In the end, no matter which terminology is used, a control law has to be constituted based on characteristics of operation, performance and disturbance scenarios.

### 3 Discussion and perspectives

During the topic sessions numerous questions were posed and rendered a discussion. The discussion was led by the topic leaders. In many ways the discussions were moving around the understanding of the presented ideas.

#### 3.1 Topic 1: Implementing optimal operation using simple control elements

There is a general agreement that the optimal solution for the control structure in terms of sensitivity function performance is always a centralized controller, which is one large optimizing controller. It is also well known that operation of processes usually involves the management of constraints, and that economical operation often lays at the limit of different process constraints.

These constraints could also be seen as an enabling factor instead of a hinder. In this context, a first desired step is the determination of the so-called throughput manipulators (TPM), since in many cases, prices and market conditions are such that optimal operation is the same as maximizing plant throughput (see [2]). In this case, the optimum lies at constraints, in order to maximize throughput (see [3]). The activation of different constraints leads to different operating regions where fairly simple control structures have often been proven to be efficient (see [4]). Switching elements would then be used to adapt the structure for the different regions. Depending on the current operating conditions, which relate to e.g. production cases, and the current disturbance scenario, constraints can be active or not. Hence, the current region would need to be derived.

Simple control structures could then be determined by typical control configuration selection methods for the regulatory layer, while the active constraint analysis will aid in determining the switching elements on a higher layers.

A question that came up was if topology theory could be helpful in identifying these regions in an automated way. A practical challenge in this context is that plant owners are not always aware of all the constraints which are present in their processes.

In addition the time scales at which controlled variables (CV) and manipulated variable (MV) would be acting will also enable a structuring. This is usually done by experience and process know-how. Here, it was also argued that economic MPC could be used to automate this structuring. It is though unclear how.

Thus a hierarchy could be determined through analysis of constraints and time scales.

It was also concluded that the active constraints can be used to derive diagrams that have large similarities with phase diagrams, see for example the distillation example on the slides or in [4]. There the active constraints regions are depicted. In the discussion, Gustafsson inquired about which ones are the
difficulties to create these active region diagrams. Skogestad clarified that the disturbance scenarios affect the regions, and obtaining an appropriate disturbance model makes the derivation difficult and time consuming. Additionally, sampling the process might lead to samples which are only in one region. The variation of the maps due to the aging of the process is normally not a problem, since this effect is usually well compensated by feedback control laws. It should also be noted that the diagrams are derived from static process models. From this perspective Cao promoted the idea of creating at least preliminary phase diagrams from operational data, where the situations with the reached constraints are written in a table representing boundary points in the diagram.

Cao and Skogestad also discussed that adjacent regions might have similar process characteristics but have different degrees of freedom. Moving between regions could then also be used to increase the degrees of freedom on purpose. Gustafsson proposed then that control allocation methodologies could be used in that context to identify which MVs are optimal to be used, when there is over actuation. It remained unclear how the problem can be stated.

Forsman also showed an example, where split range elements could be used as switching elements and that different operating condition would automatically lead to different configurations. The problem here is that there is currently not a straight forward way to design the switching elements, beside the deep understanding of the process by an engineer. On the other hand the solution is then not made in a systematic manner and may render unanticipated issues.

A way to circumvent this could be to avoid moving between different regions by enforcing a supervisory control scheme. Such a solution would be practical and efficient, but sub-optimal, as Cao and Skogestad agreed.

It was also argued by Rönnbäck that the development and commissioning time is usually not considered in the choice of a control strategy, which should be considered as an important factor in the selection. Thereby, the trade-off between gained performance through the use of a complex control strategy, and increased cost for the development, commissioning and maintenance of the control strategy should be investigated. An additional aspect is the acceptance of the advanced control strategy by the practitioners.

In this context the realization of the control strategy would involve the use of feedback and feedforward components. Birk also pointed out that from an understanding of the important MVs and CVs and the interconnection matrix, the translation into feedforward and feedback is not solved. It is usually up to the control engineer to take these decisions.

Finally, Skogestad also reflected on a discussion with Morari about structuring versus MPC. It is the opinion that structuring and understanding operating regions will be a more popular technology in the future than MPC. This is mainly motivated by the fact that design and tuning complexity of an MPC controller is very high. Skogestad illustrated this with the help of an example.

3.2 Topic 2: Real time optimisation approach in control structure design and benchmarking.

Model-free techniques (e.g. Extremum Seeking Control (ESC)) are often sufficient for control design, since feedback is very “forgiving”. RTO (Real Time Optimization) focuses on using steady state models to derive optimal operating conditions. The motivation is that often the manual selection of setpoints leads to poor process conditions, even if the controller is very successful in tracking those setpoints. It should also be noted that the realization of an RTO could be an MPC.

ESC focuses on being a RTO and data-driven technique, requiring measurements of the objective func-
tion and of the constraints. One needs to estimate the gradient of a model which should be locally convex. Even if this is not a new area and has been in practice for a while, the recent academic results are now formally proving the stability of the method.

In the traditional CCS problem using gramian-based IMs, the result is a binary matrix which determines the interconnections which should be considered in the control system. The posterior step of how to synthesize a controller with such a structure is unclear, which is a problem also during benchmarking due to the difficulty of calculating the achievable performance of a selected structure.

Therefore Guay proposes to use a distributed ESC scheme to formulate decentralized (or block decentralized) controllers where the off-diagonal elements in the gramian-based IM could be considered as the information links, like in distributed control. The ESC would then be used to converge to a connectivity matrix. The starting point would then be an established decentralized controller that would be determined based on classical methodologies.

Obviously, there is a need to define a performance metrics for the process in order to run the ESC. This metrics need to be defined in terms of CVs. It was also discussed in what way this approach could have similarities to the economic MPC approaches, which would also converge to a matrix that makes use of different MVs in combination with CVs.

The discussion between Guay and Birk was reflecting on if the Laplacian of the communication graph would actually relate to a Gramian-based interaction measure. Since the approach is running in closed loop, it would be important to understand if the interaction measure has to be stated for a closed loop system. A solution to this is currently not known.

In this context a number of important questions came up, which did not lead to any conclusion:

- How to evaluate achievable performance of a configuration?
- How to quantify complexity of the control system?

Those two questions are related as the performance metrics will also contains a combination of CVs which in turn relate to the complexity of the control system.

The performance metrics is also an important factor in the benchmarking of the adequacy of an interaction measure. Gramian-based interaction measures do have a weak relationship to the performance of the closed loop system, although they are quantifying observability and controllability. It was discussed if a relationsship to the Youla parameterization through the Riccati equation could be found. Thereby, a relationship to the closed loop performance could be found.

Benchmarking is seen as a valuable tool, but it is virtually unclear how it could be conducted so that it provides good indications. The benchmarking methodology would need to be validated and trust by the engineers and scientists need to be created.

Benchmarking also requires the availability of a large collection of multivariable process models for real-life processes with different properties which can be used by researchers to verify their methods but also in education for the training of experts. Rönnbäck brought to discussion the utility of the model library in [5] published in 1990. There was a consensus in the difficulty of finding models for benchmarking multivariable control strategies, and a new model library with special focus on CCS is desirable. Such a model library should not only be supported by text material with discussions but also with scripts with the implemented models, and additional resources like viable decentralized/sparse controllers. Two large scale benchmark models with software resources are available online and have been widely used by the scientific community: The Tennessee Eastman Process (see [6, 7, 8, 9]) and the Pulp Mill Bench-
mark. Whilst these two processes provide a challenge to ultimately test well-established techniques in large scale processes, their large complexity does not make them suitable for neither developing work in progress, illustration nor application of methods for small scales. Some simpler processes which have been discussed during the workshop are: 1) the stock preparation plant, which presents simple dynamics and highly decentralized properties (see [10, 11]), 2) the bark boiler, which presents with the challenge of significantly different time scales and delays in different input-output channels [12, 13, 14], 3) the secondary heating system, which presents pure integrators and it can be controlled with a pure decentralized controller with significant performance increase of simple sparse controllers ([15, 16]), 4) the coal injection vessel, which presents a different decentralized pairing at low and high frequencies, 5) distillation columns, which are described by well-known differential equations which can be linearized for a variety of conditions, like number of trays, reactants or feed rates.

An alternative for obtaining models for benchmarking has been presented by Bengtsson (see slides and [17]), where a library of mathematical models can be randomly generated whilst choosing intervals for certain model properties.

3.3 Topic 3: Data driven control configuration selection

Data driven methods for the configuration selection aim at directly identifying an Interaction Measure (IM) from experimental data, instead of first identifying a process model which then would be used to calculate the interaction measure. Pioneer work on the estimation of IMs in 2007 includes the estimation of PM in [18] and the estimation of RGA in [19]. Continuation of these studies have been performed by Castaño, Birk and Kadhim (see [12, 20, 21, 22, 23, 24, 25, 26, 27]) in order to 1) calculate uncertainty bounds on the estimation of PM or RGA, 2) make use of time-domain or frequency-domain information, or 3) study the effect of weak nonlinearities, 4) create algorithms which automatically select configurations from the estimated IMs. However, these publications form rather a proof of concept more than a final solution, since e.g. they are limited to use open-loop process data obtained with tailored experiments.

Recent results presented by Carvalho in this workshop topic target the use of historic process data under closed loop control (see [14] and slides).

The second presentation on this topic was performed by Rojas, who discussed the opportunities that application-oriented input design could bring to the data-driven control configuration selection. Application-oriented input design keeps a holistic view of the whole control design and aims at making choices in the system identification procedures with focus on the end control goals. Input design can emphasize system properties of interest, while properties of little or no interest can be ‘hidden’ (see [28]). For details on application-oriented input design, the reader can refer to the tutorial in [29]. Rojas suggested that data-driven control configuration selection could be addressed in a sample efficient way via an iterative identification scheme with the use of a performance degradation cost which relates to the CCS problem. As example, the cost could be used to place emphasis on the estimation of the Markov parameters, which quantify important structural properties. It would be important to understand in what way the input design could be applied in the estimation of interaction measures and in what way it improves the experiment which have been currently designed.

Clearly, a difference between Carvalho’s approach of using history data and Roja’s proposition of using tailored excitations signals is that there will be a trade-off between fulfilling excitation properties by the experiment or operational data versus the cost for the experimentation.

A discussion of the benefits of data-driven CCS approaches was initiated by pinpointing the advan-
tage over model-based CCS techniques which is that the most important process interconnections can be determined from process data, and subsequent modeling efforts can be focused on only those interconnections which will be exploited by the controller structure. The modeling effort would thereby be immensely reduced.

During the discussion of the methodology for the estimation of interaction measures the complexity of the procedure was seen as a hinder of application, which lead some of the scholars to be skeptic about the possibility of ever having a fully automated data-driven CCS method. Some of the difficulties are: 1) scaling, 2) experimentation in large scale systems is not feasible to be performed on longer time scale, 3) the possible switching between active constraint regions in the logged data, 4) possible safety issues that would need to be considered during the experimentation, 5) time-scale separation, or 5) the difficulty of automatically designing a control configuration from the obtained IMs. Additionally, it is perceived that as soon as experimentation has to be done, the advantage of the method is reduced.

On the other hand, some of the participants from process industry see a large benefit of the data-driven CCS e.g. when commissioning a new control project. In order to budget the project, it is very useful to be able to use process data to obtain a first (even if incomplete or inaccurate) measure of the structural complexity of the process and the expected modeling efforts and controller complexity.

A common consensus was reached in the fact that real-life case studies for data-driven CCS are needed in order to evaluate the feasibility of the approach and identify challenges to be addressed, but also to understand the potential benefits of the approach.

Subsequent discussions focused on the difficulty (and perhaps impossibility) of automating the decision making, since CCS can be aided by IMS, but is the practitioner who ultimately interprets the IMs and incorporates his own know-how during the decision making (see e.g. the design of a decentralized controller for a heavy oil fractionator in [30]). A consensus was reached in the need of introducing guidelines for practitioners to aid in the decision making. A good step in this direction is the recent introduction of guidelines for CCS in [22], which are illustrated on a real-life system in [16]. These publications also describe the possibility of partially automating the decision making in order to provide with additional support to the practitioners.

It was also argued that a major benefit would be to identify new ways to control a process, as gramian-based methods are not limited to the use of decentralized control. The gramian-based CCS methods select a binary matrix representing the most important input-output channels of the plant and suggest to use a structure of the controller based on the transpose of this binary matrix. This is justified by the fact that achieving a diagonal sensitivity function, the structure of the controller has to be the inverse of the structure of the plant, and therefore we simplify the structure of the model in hope to be sufficiently close to achieve a diagonal sensitivity function. However, the structure of the inverse of a matrix is not necessarily the same as its transpose. Therefore, it was argued by Castaño, that perhaps a more adequate approach is to calculate the gramian-based IMs using the inverse of the model instead and select the most important elements of the inverse of the model. Rojas pointed out that there are many new advances in the estimation of the plant inverse which could help to extend such inverse-based CCS methods to be data driven.

3.4 Topic 4: Reconfiguration of control structures

Reconfiguration is a broad topic and could be understood as changing any element in the control system. These changes could for example be the change of MVs and CVs or the change of a controller type from e.g. PID to MPC. Such a reconfiguration may be done manually or automatically.
A reason for reconfiguration is that performance during operation may be degraded due to changes of operating conditions and operating objectives. The obvious question is what is the performance criteria that would initiate the reconfiguration.

Performing a reconfiguration on the low level, like the regulatory layer is difficult and requires care. Automated solutions might not be adopted easily by the industry. Acting on a higher level, like the supervisory control or planning of operation. On these levels steady-state models might be sufficient and self-reconfigurable control can be stated as an optimization problem.

Applying response surface methods can be used to find new sets of setpoints, but it has to be ensured that the low level control can actually track the new set points in an unconstrained way. The promoted approach does not consider the low level at all for the time being.

It was also discussed to what degree SOC and ESC could be used in this context, but no conclusion could be drawn.

Reconfiguration could be an application of experiment design, e.g. to analyze product samples from different setpoints. Process engineers and researchers who want to create this kind of experiments often lack control engineering knowledge and are afraid of changing the setpoints to conditions where the plant would fail. An automatic retrofit schedule could add additional robustness to this change of setpoints.

Also, it was noted that development of online self-reconfigurable control methods could be very useful. Among of large number of methods for the control reconfiguration it is still necessary to have a guidebook with the clear description of motivation for the usage of any of the methods, their limitations and interpretation of their indications.

4 Future research directions

After the discussion on the specific topics the notes from the discussion were used to condense the ideas into topics of interest. The following topics were understood as important and interesting to conduct further work on:

1. As presented by the example of Forsman, different operating conditions may lead to different configurations. After an explanation for the examples, these configurations were sensible solutions. The problem is that coming up with these solutions is more an art based on know-how than on a specific methodology. As long as methodology based solutions are inferior to engineering understanding, practitioners will not fully trust and make use of methodologies.

The idea is to make use of the active constraint regions to identify the different operating conditions and feasible configurations. A question is which kind of data is needed to determine these regions, but presumably process data, process topology, flow sheets and economic constraints are important pieces of information.

2. Guidelines on how and if certain methods for control configuration selection should be used. Here, prerequisites like availability of models and degree of details represented by the models are important aspects. There is an interdependence between the degree of details that are reflected by the model and the performance requirements on the process itself.

3. There is a trend of developing advanced simulators for training purposes and what-if analysis. Such simulators contain complex models reflecting process behavior which are beneficial for fault-detection and control design (including structure selection).
This leads to the following questions: How well do these models need to reflect reality? How to extract low complexity models which are feasible for the context of control configuration selection? Is it sufficient to have a structural model, or we need gains or even dynamic relationships?

4. Increasing the performance of a simulator relates to the increase of complexity and details of the underlying models. This increase in complexity should go hand-in-hand with design tools for control configuration selection and controller design. If this hypothesis is true, then the selection of the appropriate methodologies should align with the properties of models.

5. Instead of extracting low complexity models from a simulator, RTO could be used on simulators to identify CVs or combination of CVs to improve (reconfigure) a process. In this direction it was argued that the resulting Laplacian in ESC should have a relationship to the gramian-based IMs.

6. Could the RTO approach provide indication on the changes in a configuration that need to be made when moving from the current configuration to the next? This could provide an incremental approach to the reconfiguration problem.

7. Even if CCS methods might not provide the final optimal answer to the control configuration problem, the indications point engineers in the right direction. Data-driven CCS may help engineers to obtain a quick best guess based on the preliminary nature of the analysis of the process. This could aid engineers in evaluating the potential benefits of a development project and its associated costs. Important challenges that need to be addressed are large scale character of processes and their decomposition, as well as how IMs should be interpreted.

8. Collection of benchmark examples and guidelines. A centralized repository for accessing benchmark examples would be needed where also benchmark results are reported back to. A publication to initiate the benchmark repository with an initial set of examples could be created.

9. Providing tools and guidelines to practitioners to use control structure selection methods. Practitioners and researchers would have to work jointly to create a bi-directional knowledge exchanges and safeguard applicability.

10. It is important to understand the root cause for the performance deficiencies in a control system. Especially, if the cause is poor tuning or poor structure. How to distinguish one from the other?

11. There is a lack of defined characteristics of a closed loop system that could be evaluated and subsequently initiate a retrofit or reconfiguration of the closed loop system. How to identify the events which should trigger a retrofit?

12. Providing online automatic reconfiguration is also an unsolved challenge and an important direction of research, which relates to the RTO approach from above.

5 Conclusions

The two day workshop generated a large number of discussions by the participants during the workshop, which also showed that despite the large amounts of research efforts that have been put into control configuration selection, there are several remaining research challenges but also a number of hinders that prevent the methods from being applied in a real-life context.
Especially the hinders and ideas that could increase usefulness are topics that should be further investigated. It cannot be stressed enough, that application of the methods will provide both practitioners and researchers with new insights and needs for further research.

Moreover, there are a number of new ideas which would address some of the shortcomings that are identified with the existing methodologies.

Overall, it can be concluded that the workshop was a success and valuable for all participants. One of the direct results was that a group of participants joined forces and proposed an invited session for the IFAC 2018 AdChem Symposium, which is an flagship conference for the area of process control. The invited session has been accepted and includes 6 papers which are aligned with the workshop sessions and the future research directions (see [31, 32, 33, 34, 35, 36]). This includes: 1) the use of industry examples of how different operating conditions require different configurations in [31], 2) a real-life case study for control reconfiguration of the hydrolealkylation of toluene (HDA) in [32], 3) the optimal operation when changing active constraint regions in [33], 4) the introduction in [34] of a new (non)linear Interaction which can potentially be estimated using the existing theory for estimating Volterra series, 5) the extension of a gramian-based Interaction Measure by considering closed loop performance aspects in [35], 6) the extension of self-optimizing control for sparse measurement selection in [36].

6 Acknowledgements

The PiCCS workshop was made possible by the financial support of several funding bodies. First of all, the STINT financial support received from STINT through the project iLIST under the initiation grant IB 2016-6549 is hereby gratefully acknowledged.

Moreover, the organizers of the workshop want to thank for the support by grants from European Commission within the H2020 Framework program through the OPTi project (Grant Agreement No. 649796) and from the VINNOVA SIP-PiiA PostDoc program through the WARP project.

The workshop dinner was financially supported by the strategic research and innovation area Intelligent Industrial Processes which the organizers are very thankful for.

References


2018–02–19
A Workshop program and participants

The workshop was organized as a 2 day event, where the focus was on the discussion of a number of topics. Discussion and brainstorming around certain topics was highly encouraged. The number of participants was also kept rather small to enable a high level of interaction between the participants.

Day 1 (16th August) - Room A3024

<table>
<thead>
<tr>
<th>Time</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>08:00</td>
<td>Coffee &amp; Tea</td>
</tr>
<tr>
<td>08:20</td>
<td>Welcome and Introduction</td>
</tr>
<tr>
<td>08:30 - 10:30</td>
<td>Topic 1: Implementing optimal operation using simple control elements.</td>
</tr>
<tr>
<td></td>
<td>Topic leaders: Sigurd Skogstad &amp; Krister Forsman</td>
</tr>
<tr>
<td>30 min break</td>
<td>(Coffee room at the department)</td>
</tr>
<tr>
<td>11:00 - 13:00</td>
<td>Topic 2: Real-time optimisation approaches in Control Structure Design and Benchmarking.</td>
</tr>
<tr>
<td></td>
<td>Topic leaders: Martin Guay &amp; Fredrik Bengtsson</td>
</tr>
<tr>
<td>14:00 - 16:00</td>
<td>Topic 3: Data-driven Control Configuration Selection.</td>
</tr>
<tr>
<td></td>
<td>Topic leaders: André Carvalho &amp; Cristian Rojas.</td>
</tr>
<tr>
<td>16:30 - 18:00</td>
<td>Reflections and changes for next day</td>
</tr>
<tr>
<td>19:00 -</td>
<td>Joint dinner at Bistro Norrland, <a href="http://www.bistronorrland.se">www.bistronorrland.se</a></td>
</tr>
</tbody>
</table>

Day 2 (17th August) - Room A3011

<table>
<thead>
<tr>
<th>Time</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>08:00</td>
<td>Coffee &amp; Tea</td>
</tr>
<tr>
<td>08:20</td>
<td>Brief summary of the first day</td>
</tr>
<tr>
<td>08:30 - 10:30</td>
<td>Topic 4: Reconfiguration of control structures.</td>
</tr>
<tr>
<td></td>
<td>Topic leaders: Yi Cao &amp; Natalia Dudarenko.</td>
</tr>
<tr>
<td>30 min break</td>
<td>(Coffee room at the department)</td>
</tr>
<tr>
<td>11:00 - 12:30</td>
<td>Prioritized directions</td>
</tr>
<tr>
<td>1h lunch</td>
<td>Restaurant U:nik (5 minutes from the venue)</td>
</tr>
<tr>
<td>13:30 - 14:30</td>
<td>Reflections &amp; Closing remarks</td>
</tr>
<tr>
<td>Name</td>
<td>Affiliation</td>
</tr>
<tr>
<td>--------------------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>Mohammed Adlouni</td>
<td>Perstorp AB</td>
</tr>
<tr>
<td>Cristian Rojas</td>
<td>KTH</td>
</tr>
<tr>
<td>Sigurd Skogestad</td>
<td>NTNU</td>
</tr>
<tr>
<td>Krister Forsman</td>
<td>Perstorp AB</td>
</tr>
<tr>
<td>Fredrik Bengtsson</td>
<td>Chalmers</td>
</tr>
<tr>
<td>Yi Cao</td>
<td>CRanfield</td>
</tr>
<tr>
<td>Natalia Dudarenko</td>
<td>ITMO</td>
</tr>
<tr>
<td>Martin Guay</td>
<td>Queens University</td>
</tr>
<tr>
<td>Stefan Rönningen</td>
<td>Optimization AB</td>
</tr>
<tr>
<td>Joakim Wallbing</td>
<td>Optimization AB</td>
</tr>
<tr>
<td>Peter Lingman</td>
<td>Optimization AB</td>
</tr>
<tr>
<td>André Carvalho Bittencourt</td>
<td>LIU</td>
</tr>
<tr>
<td>Miguel Castaño Arranz</td>
<td>LTU</td>
</tr>
<tr>
<td>Wolfgang Birk</td>
<td>LTU</td>
</tr>
<tr>
<td>Khalid Atta</td>
<td>LTU</td>
</tr>
<tr>
<td>Ali Kadhim</td>
<td>LTU</td>
</tr>
<tr>
<td>Bijan Moaveni</td>
<td>IUST</td>
</tr>
<tr>
<td>Erik Vanhatalo</td>
<td>LTU</td>
</tr>
<tr>
<td>Bjarne Bergquist</td>
<td>LTU</td>
</tr>
<tr>
<td>Andreas Johansson</td>
<td>LTU</td>
</tr>
</tbody>
</table>
B Presentations

B.1 Topic 1: Krister Forsman and Sigurd Skogestad

Krister Forsman and Sigurd Skogestad introduced the topic Implementing optimal operation using simple control elements, and also led the discussion on the topic.

The presentation slides are appended on the following pages.
Control structure selection:  
a simple example

Krister Forsman
Perstorp AB and NTNU
2017-08-16

Heat exchanger as a simple illustration

- Process: A heat exchanger (cooler), where the product stream should be cooled down to a given temperature, by manipulating the cooling water flow.

- We assume that this cooler is a bottle neck in the overall process, so we wish to maximize the flow through the cooler.
**Process: heat exchanger / cooler**

The temperature must be kept at a given setpoint, e.g., 45 degrees.

**Traditional control structure**

![Diagram of traditional control structure](image)
Various specifications

• We never compromise with the temperature in the product stream.

• We study different scenarios:
  – Maximize flow, cooling water is the active constraint
  – Maximize flow, product flow is the active constraint
  – Maximize flow, either cooling water or product flow is the active constraint, and that could vary over time
  – Give setpoint for flow, but back-off if cooling water valve saturates

• In all cases there is a temperature controller, with an operator setpoint.

Scenario: Maximize flow through cooler

If the flow control valve is the limiting factor, then use this structure:

If the cooling water control valve is limiting, then use this structure:
Globally maximizing structure

- The temperature controller does the following:
  - In first hand: keep production valve fully open and manipulate the cooling water valve to control the temperature
  - In second hand: keep cooling water valve fully open and manipulate the production valve to control the temperature

Flow setpoint; sacrifice flow

This structure allows the operator to give a setpoint for the flow. If the flow setpoint cannot be reached without violating the temperature constraint, then give up flow control.
Basic constraints, on manipulated variables

Scenario 1: Cooling water temperature is low
Scenario 2: Cooling water temperature is high

Same constraints, but SP for flow

Scenario 3: CW temp low, SP for flow
(In practice the valve position is given by the flow controller)
Perspectives and future directions in control structure selection

Sigurd Skogestad
NTNU
Trondheim

16 Aug. 2017

Control structure selection

- Optimal: minimize cost $J$ subject to constraints (for varying disturbances)
- Cost $J$: Should include both economics and robustness
- Optimal solution is centralized
  - «One big optimizing controller» (economic MPC)
- So: Control structures selection arises because we want to use non-optimal hierarchical (vertical) and/or decentralized (horizontal) decomposition

\[
\text{RTO / Extremum seeking / Manual} \\
\text{MPC / «advanced control»} \\
\text{PID}
\]
Control structure decisions

- Basic control layer (single-loop decentralized control)
  - Selection of stabilizing CVs (CV2)
  - Selection of MV2
  - Pairing of CV2 with MV2
    - Usually fairly obvious once TPM has been located

- Advanced control layer (decentralized or MPC)
  - Selection of «economic» CVs (CV1) (also when we use MPC)
    1. Active constraints
    2. Self-optimizing variables \( c = Hy \) (which require infrequent update of setpoints)
      - Control structure decision: Structure of \( H \) (which measurements \( y \)?)
  - Selection of MV1 to control CV1:
    - CV2s / unused MV (also when we use MPC)
  - Feedforward control
  - Pairing of CV1 and MV1 (if decentralized control)
    - Classical: «pair close» and avoid pairing on negative RGA-elements (integrity)
    - New issue: Prepare for constraint switching

- Supervisory control: Switching between active constraint regions
  - Alternative: Single control structure in several regions (with acceptable loss)?

TPM = throughput manipulator (traditionally the feed rate)

Switching between active constraint regions
(Supervisory control)

Reach new constraint (because of disturbance or setpoint change):

- CV constraint
  - Give up another less important CV (max/min selector)

- MV constraint (the MV is used for control of a CV, otherwise it would not saturate)
  1. Low-priority CV (e.g., self-optimizing variable or throughput): No special action needed; Give up CV («let CV float»)
  2. Important CV (active constraint): Must find another MV
    - Split range control (SRC) or some other logic
    - Suboptimal (avoid switching): Use the other MV for valve position control (= Input resetting = Midranging)

Notes.
- Case 1: This case is preferable so get pairing rule:
  - «MV that may saturate should be paired with CV that may be given up»
  - Alternative interpretation: «Avoid using MV that may optimally saturate (steady-state) to control important CV»
- Case 2: Unless there is an «unused» MV, we must find another MV that is controlling a CV which can be given up, e.g., using a selector
Switching between active constraint regions (Supervisory control)....

- Designing a supervisory control system in a systematic manner requires precomputing and analyzing all possible future scenarios (caused by disturbances and price changes)

- Relevant issue also for MPC
  - MPC can handle some switches but not all (must anyway define priority for MPC)

- Graphical can be useful
  - Optimal constraint regions as function of disturbances (max- two disturbances)
  - CV values / cost as function of MVs (max two MVs)

Implementation of optimal operation using simple control elements

Sigurd Skogestad and Krister Forsman
Basis. Want (close-to) Optimal Operation

**MV**s should always contribute to optimizing operation (minimize cost $J$)
- Control active constraints
- For remaining unconstrained degrees of freedom: Control self-optimizing variables (so that setpoints only need infrequent updates)

**Disturbances** are the main problem:
- Optimal constraint variables may change!
- Optimal setpoints change

**Question:**
- How can we implement optimal operation in a simple manner?
- Using feedback as our smart tool/trick!

Rules

- Control active constraints
- **MV** that may saturate should be paired with CV that may be given up
  - Alternative interpretation of rule: Avoid using MV that may optimally saturate (steady-state) to control important CV (active constraint)
- TPM should be located close to bottleneck
  - Reason: Avoid «long loop» (and resulting backoff) when we have max. throughput
  - Bottleneck: Last constraint to be reached as we increase throughput
- **Arrange the inventory control loops (for level, pressures, etc.) around the TPM location according to the radiation rule** (Georgakis)
- **Select “sensitive/drifting” variables as controlled variables CV$_2$ for regulatory control.**
More rules

- Never control the cost function J (at fixed value)
  - May give infeasibility and certainly non-optimal operation
- Never do inventory control across TPM-location
  - Corresponds to pairing on zero

Example: Maximize flow through a cooler

The temperature must be kept at a given setpoint, e.g. 45 degrees.

“Traditional” structure:

Weakness of this structure: there is no automatic mechanism that guarantees maximum flow.
2 MVs: \( q, q_{cw} \) (both have max-constraints; \( q < q_{\text{max}}, q_{cw} < q_{cw_{\text{max}}} \))

2 CVs (at constraints): \( T = 45^\circ \text{C} \) (always),
\[ q = q_s \] (can be given up if infeasible)

Cost \( J = ? \) (not needed, because solution always at constraints)

**Active constraint regions**

Three active constraints regions (in all regions \( T = 45^\circ \text{C} \)):
1. \( q = q_s \)
2. \( q_{cw} = \text{max} \) (CW valve is bottleneck)
3. \( q = \text{max} \) (product valve is bottleneck)

Need control structure that can handle all these regions.
Three active constraints regions (in all regions $T=45\degree C$):

1. Given setpoint for flow: $q = q_s$
2. Bottleneck 1: $q_{cw} = \max (CW \text{ valve})$ \ SRC + min.select
3. Bottleneck 2: $q = \max (product \text{ valve})$ \ No action needed, just give up $q$

**Distillation example**

- Separate components A (light) and B (heavy)
- Cost $(J) = - \text{Profit} = p_F + p_V V - p_D D - p_B B$
- Prices: $p_F=p_D=1 \$/mol, p_B=2 \$/mol, Energy $p_V=0-0.2 \$/mol (varies)$
- With given feed and pressures: 2 steady-state DOFs.
- 3 constraints
  - Product purities (D,B) > 95%
  - capacity constraint on V

$\begin{align*}
x_A &> 95\% \\
V &< 4 \text{ mol/s} \\
x_B &> 95\% \\
\end{align*}$

«Avoid product give-away» -> Valueable product constraint always active -> $x_B=95\%$

**DOF = Degree Of Freedom**
Three active constraint regions (+ bottleneck):

Region 1
Region 2

Bottleneck!
3 active constraints:
$x_A$, $x_B$ and $V$ (bottleneck)

Region 1
Region 2

Bottleneck!
3 active constraints:
$x_A$, $x_B$ and $V$ (bottleneck)

Region 1
Region 2

Regulatory control of levels and pressure

TPM
PC
LC
FC
$x_A$=99.1% (self-optimizing; can give up)
$x_{B*}=95\%$ (always active!)
Three active constraint regions (+ bottleneck):

Region 1: $x_A$ and $x_B$
Region 2: $x_B$ and $V$
Infeasible region

Bottleneck! 3 active constraints: $x_A$, $x_B$, and $V$ (bottleneck)

Region 2

TPM

Column 1

$\min u$

 SRC

$\min L$

$\min V$

3 active constraints:

Region 1: $x_A$ and $x_B$
Region 2: $x_B$ and $V$
Infeasible region

Bottleneck! 3 active constraints: $x_A$, $x_B$, and $V$ (bottleneck)

Region 2

TPM

Column 1

$\min u$

 SRC

$\min L$

$\min V$
Operation of Distillation columns in series

- Cost \( (J) = \) Profit \( = p_F F + p_D (V_1 + V_2) - p_D1 D_1 - p_D2 D_2 - p_B2 B_2 \)
- Prices: \( p_F = p_D1 = p_B2 = 1 \) $/mol, \( p_D2 = 2 \) $/mol, Energy \( p_v = 0-0.2 \) $/mol (varies)
- With given feed and pressures: 4 steady-state DOFs.
- Here: 5 constraints (3 products > 95% + 2 capacity constraints on V)

\[
\begin{align*}
\text{QUIZ: What are the expected active constraints?} \\
1. \text{Always.} \quad 2. \text{For low energy prices.}
\end{align*}
\]

Example:

Control of Distillation columns. Cheap energy

Given

Overpurified: To avoid loss of valuable product B
Control of Distillation columns. Cheap energy

What happens if we increase the federate?

Is this control structure still OK??
Given (TPM)

Increase federate: Reach $x_A$-constraint

Increase federate further: Reach also $x_C$-constraint (Bottleneck)

TPM used as MV
Move TPM to F2 (closer to bottleneck) and rearrange level loop.

Active constraint regions for two distillation columns in series

Distillation example: Not so simple

Mode 1, Cheap energy: 3 active constraints -> 1 remaining unconstrained DOF (L₁) -> Need to find 1 additional CVs (“self-optimizing”)

More expensive energy: Only 1 active constraint (xB) -> 3 remaining unconstrained DOFs -> Need to find 3 additional CVs (“self-optimizing”)

Energy price [$/mol]

CV = Controlled Variable
How many active constraints regions?

- Maximum: \( 2^{n_c} \)
  \( n_c = \) number of constraints

  BUT there are usually fewer in practice
  - Certain constraints are always active (reduces effective \( n_c \))
  - Only \( n_u \) can be active at a given time
    \( n_u = \) number of MVs (inputs)
  - Certain constraints combinations are not possible
    - For example, max and min on the same variable (e.g. flow)
  - Certain regions are not reached by the assumed disturbance set

- Distillation
  \( n_c = 5 \)
  \( 2^5 = 32 \)
  \( x_B \) always active
  \( 2^4 = 16 \)
  \(-1 = 15 \)

In practice = 8

MV 1 2 3 4 Bottleneck

<table>
<thead>
<tr>
<th>MV</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>Bottleneck</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>F</td>
<td>«</td>
<td>«</td>
<td>«</td>
<td>xC=0.95</td>
</tr>
<tr>
<td>L1</td>
<td>xA=0.991</td>
<td>XAb=0.023</td>
<td>SRC+min.select*</td>
<td>xA=0.95</td>
<td>max.select</td>
</tr>
<tr>
<td>V1</td>
<td>XAb=0.023</td>
<td>V1=max</td>
<td>«</td>
<td>«</td>
<td>«</td>
</tr>
<tr>
<td>L2</td>
<td>xB=0.95</td>
<td>«</td>
<td>«</td>
<td>«</td>
<td>«</td>
</tr>
<tr>
<td>V2</td>
<td>xC=0.993</td>
<td>«</td>
<td>V2=max</td>
<td>«</td>
<td>«</td>
</tr>
</tbody>
</table>

Blue: unconstrained optimal values (depend on energy price)
*Could avoid with reverse pairing in region 1 (pair on negative RGA)
Solution for low federate

Solution for higher feedrate
Solution for all regions

Solution for all regions

Solution for all regions

Solution for all regions

Solution for all regions

Solution for all regions

Solution for all regions

Solution for all regions

Solution for all regions

Solution for all regions

Solution for all regions

Solution for all regions
B.2 Topic 2: Martin Guay and Fredrik Bengtsson

Martin Guay and Fredrik Bengtsson introduced the topic *Real time optimisation approach in control structure design and benchmarking*, and also led the discussion on the topic.

The presentation slides are appended on the following pages.
The application of model free and data-driven real-time optimization for controller structure selection

M. Guay

August 16, 2017, Lulea, Sweden

Controller Structure Selection

- Controller Structure Selection focusses on a number steps:
  - Decentralized or Distributed Structure
  - Network Structure
  - Input-output pairings
  - Controller design technique
  - Performance metric
  - Robustness to uncertainties
  - Failure mitigation strategy
  - Computation platform
  - Data collection and monitoring
  - etc...

- In this presentation, we focus here on elements 1-3.
- We favor a model free distributed RTO framework: Extremum seeking control (ESC).
Outline

- Brief Introduction of ESC.
- Distributed Control using ESC.
- Optimal network structure for Control Structure Selection.
- Simulation study.
- Conclusions and Outlook.

Introduction

- Extremum seeking is a real-time optimization technique.

Figure: Basic RTO loop.

- RTO is a supervisory system designed to monitor and improve process performance.
- It uses process data to move the process to operating points that are optimal wrt a meaningful user-defined metric.
Introduction

Extremum Seeking Control (ESC) is a model free technique that relies on minimal assumptions concerning:
- the process model
- the objective function
- the constraints

ESC only requires the measurement of the objective function and the constraints.

Considerable appeal in practice:
- Achieves RTO objectives without the need for complex model-based formulations.
- Recent developments also provide strong evidence of a reliable model-free control technique.
- It is a prime candidate for the design of flexible, reliable and sustainable control architecture.

Basic ESC objectives:
- Given an (unknown) nonlinear dynamical system and (unknown) measured cost function:
  \[ \dot{x} = f(x, u) \quad (1) \]
  \[ y = h(x) \quad (2) \]

- The objective is to steer the system to the equilibrium \( x^* \) and \( u^* \) that achieves the minimum value of \( y = h(x^*) \).
Basic ESC Loop

The stability analysis relies on two components:
- an averaging analysis of the persistently perturbed ESC loop
- a time-scale separation of ESC closed-loop dynamics between the system dynamics and the quasi steady-state extremum-seeking task.

This analysis shows that the tuning parameters of the ESC must be chosen very carefully to guarantee convergence to a neighbourhood of the unknown optimum.

Standard perturbation based approaches can be difficult to tune and usually leads to slow convergence.
Problem Definition

- The objective is to steer the system to the equilibrium \( x^* \) and \( u^* \) that achieves the minimum value of \( y(= h(x^*)) \).
  - The equilibrium (or steady-state) map is the \( n \) dimensional vector \( \pi(u) \) which is such that:
    \[
    f(\pi(u), u) = 0.
    \]
  - The equilibrium cost function is given by:
    \[
    y = h(\pi(u)) = \ell(u) \tag{3}
    \]
  - The problem is to find the minimizer \( u^* \) of \( y = \ell(u^*) \).

Figure: ESC Basic Assumptions.
Proportional Integral ESC

- Performance improvement achieved using a dual mode ESC

\[ \dot{x} = f(x, u) \]
\[ y = h(x) \]

Analysis demonstrates that:
- the proportional action minimizes the impact of the time scale separation
- the integral action acts as a standard perturbation based ESC
- Combined action guarantees stabilization of the unknown equilibrium
- With fast convergence

- Impact of dither signal is inversely proportional to the frequency
- Size of ROA is proportional to \( \frac{a}{k} \).
- **PIESC is a robust nonlinear PI controller.**
Example 1

We consider the following dynamical system taken from earlier work:

\[
\dot{x}_1 = x_2^2 + x_2 + u \\
\dot{x}_2 = -x_2 + x_1^2
\]

The cost function to be minimized is given by:

\[y = -1 - x_1 + x_2^2.\]

- The optimum cost is \(y^* = -1.25\) and occurs at \(u^* = -0.5, x_1^* = 0.5, x_2^* = 0.25\).
- The tuning parameters are chosen as: \(k = 10, \tau_I = 0.1, a = 10, \omega = 100\) with \(\omega_h = 1000\).
- Outperforms the model-based approaches.
Controller Structure Selection

- The PIESC provides a versatile building block for controller structure selection.
  - Given a suitable input-output pairing the controller provides a robust, flexible and high performance building block.
  - Control systems can be implemented as networks of these model free mechanisms.
- The dual mode approach has been applied in a variety of mechanisms:
  - Estimation based techniques (RLS, Phasor ESC)
  - Geometric averaging (Lie Bracket)
  - Continuous-time & Discrete-time

Discrete-time Proportional Integral ESC

- The cost function dynamics are parameterized as follows:
  \[ y_{k+1} = y_k + \theta_{0,k} + \theta_{1,k}^T (u_k - \hat{u}_k) \]
  where \( \theta_{0,k} \) and \( \theta_{1,k} \) are the time-varying parameters, \( \theta_{0,k} = \Psi_{0,k} \) and \( \theta_{1,k} = \Psi_{1,k}^T \).
- Proposed PI-ESC given by:
  \[
  u_k = -k_g \hat{\theta}_{1,k} + \hat{u}_k + d_k \\
  \hat{u}_{k+1} = \hat{u}_k - \frac{1}{\tau_I} \hat{\theta}_{1,k}
  \]
  where
  - \( \hat{\theta}_{1,k} \) is the estimation of \( \theta_{1,k} \).
  - \( k_g \) is the proportional gain
  - \( \tau_I \) is the integral time constant.
  - \( d_k \) is the dither signal.
Proportional Integral ESC

Consider a simple, 1st order, dynamical system:

\[ x_{k+1} = 0.8 x_k + u_k \]
\[ y_k = (x_k - 3)^2 + 1 \]

The steady-state optimum occurs at

\[ u^* = 0.6 \]
\[ y^* = 1. \]
Distributed Extremum seeking control

- The discrete-time ESC approach can be generalized for the design of distributed optimization and control of complex unknown networks
- Dual mode ESC can adjust local actions in the absence of any knowledge about the underlying dynamics and network interactions

Basic Distributed Optimization Problem

- Consider a network of local performance objectives (denoted but $y_i$) and controllers or agents (with input $u_i$).
- Objective is optimize the sum of all performance objectives ($J = \sum_{i=1}^{n} y_i$).
Controller design

Distributed architecture

Distributed Optimization and Control

- Controller structure implies local input-output pairings \((u_i - y_i)\).
- Local controllers can share local measurements with neighbours to achieve consensus.

Consensus estimation

Each agent (controller) measures \(y_i\) and estimates \(\frac{1}{p} J\) by a consensus algorithm

\[
\begin{bmatrix}
\tilde{J}[k+1] - \tilde{J}[k] \\
\rho[k+1] - \rho[k]
\end{bmatrix} = 
\begin{bmatrix}
-\kappa_P I - \kappa_I L & -I \\
\kappa_P \kappa_I L & 0
\end{bmatrix}
\begin{bmatrix}
\tilde{J}[k] \\
\rho[k]
\end{bmatrix} \Delta t 
+ \begin{bmatrix}
\kappa_P I \\
0
\end{bmatrix} y[k] \Delta t + \begin{bmatrix}
I \\
0
\end{bmatrix} \Delta y[k]
\]

Example (Laplacian matrix)

\[
L = \\
\begin{bmatrix}
3 & -1 & 0 & -1 & -1 \\
0 & 1 & 0 & 0 & -1 \\
-1 & -1 & 4 & -1 & -1 \\
-1 & 0 & 0 & 2 & -1 \\
0 & -1 & 0 & 0 & 1
\end{bmatrix}
\]
Controller Structure Selection

Local Parameterization of Total Cost

- The total cost dynamics can be parameterized as:
  \[
  \frac{1}{p} \Delta J[k + 1] = \theta_{0,i}[k] + \theta_{1,i}[k]u_i[k] = \theta_i^T[k] \phi_i[k]
  \]  
  (5)

- Using consensus, each agent estimates a pair of parameters, a bias term, \(\theta_{0,i}[k]\) and a local gradient of the \(\hat{J}_i\) with respect to \(u_i, \theta_{1,i}[k]\)

- The bias term \(\theta_{0,i}[k]\) estimates the contribution of other agents dynamics.

- This provides an effective decentralization mechanism for each agent.

Controller design

Extremum seeking control (ESC)

- The objective of ESC is to minimize a measured cost

- Consider a PI form of ESC:
  \[
  u_i[k] = -K_g \hat{\theta}_{1,i}[k] + \hat{u}_i[k] + d_i[k]
  \]  
  (6)

  \[
  \hat{u}_i[k + 1] = \hat{u}_i[k] - \frac{1}{\tau_L} \hat{\theta}_{1,i}[k]
  \]  
  (7)

- \(\hat{\theta}_{1,i}\) is the gradient estimate, \(K_g\) and \(\tau_L\) are tuning parameters, and \(d_i\) is a dither signal

- Dither signals must all have different frequencies
Controller design

Dither signal $\rightarrow$ Extremum seeking controller $\rightarrow$ Process Dynamics $\rightarrow$ Agent $i$’s input $u_i$ $\rightarrow$ Agent $i$’s local cost $y_i$ $\rightarrow$ Dynamic consensus

Other agents’ average cost estimates

Input reference $\rightarrow$ Gradient estimate $\rightarrow$ Average cost estimate

Parameter estimation

Proportional component $K_p$ $\rightarrow$ Integral component $\frac{1}{\tau_i}$

Controller Structure Selection

Distributed framework
- The distributed structure is very general and provides additional degrees of freedom for controller structure selection.
- If pairings $u_i - y_i$ and $u_j - y_j$ are not suitable then the exchange of information between agents $i$ and $j$ can resolve the loss of performance.
- Adjustments of pairings can be achieved by:
  - The weights of the graph (of diagonal elements of the Laplacian) $L$.
  - Partial consensus can be sufficient (partial decentralization)
  - All local controllers implement a model free (ESC) mechanism.
Simulation Case Study

Consider the MIMO system:

\[
\begin{bmatrix}
\dot{x}_1 \\
\dot{x}_2 \\
\dot{x}_3
\end{bmatrix}
= \begin{bmatrix}
0 & 1 & 0 \\
2 & -1 & 2 \\
-2 & 0 & 2
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2 \\
x_3
\end{bmatrix}
+ \begin{bmatrix}
0 & 0 \\
1 & 0 \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
u_1 \\
u_2
\end{bmatrix}
\]

with local costs:

\[ y_1 = (x_1 + x_3 - 3)^2, \quad y_2 = (x_1 + x_2 - 2)^2 + x_2^2. \]

- Two agents (Controllers 1 and 2) can exchange information to drive to a consensus value.
- The decision variable becomes the weight of the exchange

Simulation Case Study

- Consider the communication described by
  \[ L = \begin{bmatrix}
  \theta & -\theta \\
  -\theta & \theta
  \end{bmatrix} \]
  for \( \theta \geq 0 \).
- The best achievable total cost \( J = y_1 + y_2 \) is a function of \( \theta \).
- We let \( \theta = 1 \).
Simulation Case Study

- We let $\theta = 0.5$.

Control Structure Selection

- The communication weights can be used to identify the most appropriate controller structure:
  - Each agent implements a PI-ESC (for example)
  - Completely model free (no knowledge of dynamics)
  - Poor input-output pairings can be identified by introducing weights as decision variables
- Adaptation of weights can be done in real-time to achieve best overall performance
- Example demonstrates network communication structure is crucial for stability and performance
- Active communication can overcome poor designs in real-time and identify important system interactions.
Concluding Remarks

- ESC can be used to solve a number of problems where:
  - Exact mathematical nature of the input-output dynamics are unknown
  - Cost function can be measured or inferred
- Useful for the development of a wealth of new tools in PSE
- This presentation highlights the interaction of communication protocols, control and identification of system interactions
- We are dealing with large systems with unknown dynamics ⇒ Input-output pairings are key decision variables

Outlook

- Beyond existing techniques there are a wealth of new tools that are emerging:
  - Machine Learning
  - Optimization on clouds, etc...
- Identification of local performance objectives is key
  - Here we used e.g. squared deviations to desired setpoints
  - ESC based reinforcement learning can be used to synthesize local performance objectives in real-time.
- Data-driven control and data-analytics are providing a very comprehensive set of tools.
- This requires a closer-look by process and control engineers.
Deployment and Evaluation of Control Structures and their relation to Benchmarking

Control of multiple input multiple output (MIMO) systems

- Numerous possible control structures can be used:
  - Decentralized control
    - Each output is controlled by one input
    - Different input output pairings
  - Sparse control
    - Control expanded to include
      - MIMO subsystems
      - Feedforward
  - Full MIMO control
    - Design a single control structure which controls all the outputs.
Determining control structures

- Multiple ways to find control structures
  - Input-output pairing
    - RGA, DRGA, RIA, HIIA and many more
  - Some methods can only be used to find decentralized controllers, while others can be used to produce sparse controllers as well.

Evaluating control configurations

- Often done by simulation, implementing the configuration and comparing it to other configurations
- This requires
  - Controller design
    - Different controller design methods may give different results
  - Series of test to evaluate performance
Evaluating methods for determining control structure

- Generally when a method for determining control structure is presented it is demonstrated on one or a few systems.
- Its success on these systems forms the basis of evaluating the method.

Benchmarking

- Given a free choice of system, controller design and performance test, nearly any controller configuration can be shown to be preferable.
- With multiple methods to solve the control configuration problem, there is a need to compare different methods to evaluate in which context they are preferable.
- This in turn creates the need to be able to evaluate different control configurations for a system.
How to best evaluate the performance of control structures?

- Impact of control design on the results
- Types of test to evaluate performance.

How to evaluate methods for designing control structures

- Testing methods on one or a few systems produces mainly anecdotal results
- Ways to ensure that general conclusions can be drawn?
- Establishing benchmarks to which existing and new methods can be compared against.
  - Based on real industrial applications or large numbers of randomly generated systems?
- How to quantify the advantages/disadvantages of simple decentralized control techniques over more complex structures
B.3 Topic 3: André Carvalho Bittencourt and Cristian Rojas

André Carvalho Bittencourt and Cristian Rojas introduced the topic *Data driven control configuration selection*, who also led the discussion on the topic.

The presentation slides are appended on the following pages.
Data-driven Gramian based CSS

André Carvalho Bittencourt

Automatic Control, Linköping University

August 16, 2017

Data-driven control configuration selection

Known model (Gramian) -> Uncertain Model (Robust) -> Data-driven

Why data-driven CSS?

- too complex to model
- time-varying
- reconfigure after deployment
- costly to experiment

Challenges

- data quality
- complex MIMO interactions
- nonlinearities
- open, closed, cascade loops
Gramian based CSS

Interaction measures
\[ \Sigma_p^p = \sum_{G_{ij}}^p \sum_{k,l} G_{kl} \]

\( \{G_{ij}\}_P \propto \text{interaction } u_j \rightarrow y_i \)

\( \Sigma_P^p \) is normalized to 1

Gramian-based (squared) measures

HIIA: \( \{G_{ij}\}_H \triangleq \|G_{ij}\|_H^2 = \rho(P_j Q_i) \)

PM: \( \{G_{ij}\}_{PM} \triangleq \|G_{ij}\|_{H_{SH}}^2 = \text{tr}(P_j Q_i) \)

H2: \( \{G_{ij}\}_2 \triangleq \|G_{ij}\|_2^2 = \text{tr}(b_j^T Q_i b_j + D_{ij}^2) \)

Simple guidelines for CSS

- try to consider most of the interactions, e.g. \( \sum_{ij} \Sigma_p^p > \hbar \)
- remove small contributions, e.g. \( \Sigma_{ij} < 1/(n_u n_y) \)
- put more effort on larger values of \( \Sigma_{ij} \) and try simple structures first

Three computational paths

Based on SS matrices

HIIA: \( \|G_{ij}\|_H^2 = \rho(P_j Q_i) = \max_l |\lambda_l(R_{ij})| \)

PM: \( \|G_{ij}\|_{PM}^2 = \rho(P_j Q_i) = \text{tr}(R_{ij}^2) \)

H2: \( \|G_{ij}\|_2^2 = \text{tr}(b_j^T Q_i b_j + D_{ij}^2) \)

Based on the frequency response funcns (FRF)

PM: \( \|G_{ij}\|_H^2 = \frac{1}{2\pi} \int_0^{2\pi} |G_i(e^{j\nu})|^2 \text{ arg } G(e^{j\nu}) d\nu \)

H2: \( \|G_{ij}\|_2^2 = \frac{1}{2\pi} \int_0^{2\pi} |G_i(e^{j\nu})|^2 d\nu \)

Based on Markov parameters (MP)

HIIA: \( \|G_{ij}\|_H^2 = \rho(H_j^T H_{ij}) \)

PM: \( \|G_{ij}\|_{PM}^2 = \text{tr}(H_j^T H_{ij}) = \sum_{k=1}^\infty k g_j(k)^2 \)

H2: \( \|G_{ij}\|_2^2 = \sum_{k=0}^\infty \theta_j^2(k) \)

SS: mainly model-based
- from \( A, B, C, D \) or estimates
- with +\( \Delta \) uncertainty
- solve 2 Lyap 1 Sylv. eq

FRF: mainly data-driven
- from \( \hat{G} \)
- with multi/stoch uncertainty
- special inputs, open-loop

MP: mainly data-driven
- from \( \hat{g}_{ij} \)
- with stoch uncertainty
- special inputs, open-loop
Three computational paths

Based on SS matrices

\[ HIIA : \|G_{ij}\|_H^2 = \rho(P_j Q_i) = \max |\lambda_i(R_{ij})| \]
\[ PM : \|G_{ij}\|_H^2 = \rho(P_j Q_i) = \text{tr}(R_{ij}^2) \]
\[ H2 : \|G_{ij}\|_2^2 = \text{tr}(b_j^T Q_j b_j + D_j^2) \]

Based on the frequency response funcs (FRF)

\[ PM : \|G_{ij}\|_H^2 = \frac{1}{\pi} \int_0^{2\pi} |G_{ij}(e^{j\omega})|^2 \frac{d \arg G(e^{j\omega})}{d\omega} \]
\[ H2 : \|G_{ij}\|_2^2 = \frac{1}{2\pi} \int_{-\pi}^{\pi} |G_{ij}(e^{j\omega})|^2 d\omega \]

Based on Markov parameters (MP)

\[ HIIA : \|G_{ij}\|_H^2 = \rho(H^T J H) \]
\[ PM : \|G_{ij}\|_H^2 = \text{tr}(H^T J H) = \sum_{k=1}^{\infty} k g_j(k)^2 \]
\[ H2 : \|G_{ij}\|_2^2 = \sum_{k=0}^{\infty} g_j^2(k) \]

SS: mainly model-based
- from A, B, C, D or estimates
- with +\Delta uncertainty
- solve 2 Lyap 1 Sylv. eq

FRF: mainly data-driven
- from \( \hat{G} \)
- with mult/stoch uncertainty
- special inputs, open-loop

MP: mainly data-driven
- from \( \hat{G}_j \)
- with stoch uncertainty
- special inputs, open-loop

Three computational paths

Based on SS matrices

\[ HIIA : \|G_{ij}\|_H^2 = \rho(P_j Q_i) = \max |\lambda_i(R_{ij})| \]
\[ PM : \|G_{ij}\|_H^2 = \rho(P_j Q_i) = \text{tr}(R_{ij}^2) \]
\[ H2 : \|G_{ij}\|_2^2 = \text{tr}(b_j^T Q_j b_j + D_j^2) \]

Based on the frequency response funcs (FRF)

\[ PM : \|G_{ij}\|_H^2 = \frac{1}{\pi} \int_0^{2\pi} |G_{ij}(e^{j\omega})|^2 \frac{d \arg G(e^{j\omega})}{d\omega} \]
\[ H2 : \|G_{ij}\|_2^2 = \frac{1}{2\pi} \int_{-\pi}^{\pi} |G_{ij}(e^{j\omega})|^2 d\omega \]

Based on Markov parameters (MP)

\[ HIIA : \|G_{ij}\|_H^2 = \rho(H^T J H) \]
\[ PM : \|G_{ij}\|_H^2 = \text{tr}(H^T J H) = \sum_{k=1}^{\infty} k g_j(k)^2 \]
\[ H2 : \|G_{ij}\|_2^2 = \sum_{k=0}^{\infty} g_j^2(k) \]
Three computational paths

Based on SS matrices

\[ \text{HIIA}: \| G_{ij} \|^2_H = \rho(P_j Q_i) = \max |\lambda_i(R_{ij})| \]
\[ \text{PM}: \| G_{ij} \|^2_H = \rho(P_j Q_i) = \text{tr}(R_{ij}) \]
\[ \text{H2}: \| G_{ij} \|^2_H = \text{tr}(b_i^T Q_i b_i + D_{ij}^2) \]

Based on the frequency response funcs (FRF)

\[ \text{PM}: \| G_{ij} \|^2_H = \frac{1}{\pi} \int_{-\pi}^{\pi} \| G_{ij}(e^{jv}) \|^2 d\arg G(e^{jv}) dv \]
\[ \text{H2}: \| G_{ij} \|^2_H = \frac{1}{2\pi} \int_{-\pi}^{\pi} \| G_{ij}(e^{jv}) \|^2 dv \]

Based on Markov parameters (MP)

\[ \text{HIIA}: \| G_{ij} \|^2_H = \rho(H_{ij}^T H_{ij}) \]
\[ \text{PM}: \| G_{ij} \|^2_H = \text{tr}(H_{ij}^T H_{ij}) = \sum_{k=1}^\infty k g_{ij}(k)^2 \]
\[ \text{H2}: \| G_{ij} \|^2_H = \sum_{k=0}^\infty g_{ij}^2(k) \]

SS: mainly model-based
- from \( A, B, C, D \) or estimates
- with +\( \Delta \) uncertainty
- solve 2 Lyap 1 Sylv. eq

FRF: mainly data-driven
- from \( \hat{G} \)
- with mult/stoch uncertainty
- special inputs, open-loop

MP: our approach
- from \( \hat{g}_{ij} \)
- with stoch uncertainty
- any inputs, open/closed-loop

Identification of Markov parameters

Predictor model

\[ \hat{x}_{k+1} = \hat{A} \hat{x}_k + \hat{B} u_k + K y_k \]
\[ y_k = C \hat{x}_k + D u_k + \epsilon_k \]
\[ \hat{A} = A - K C, \hat{B} = B - K D, \]
- \( G(q) \equiv \hat{G}(q) \)
- stable model
- white innovation even in CL

Markov parameters given by

\[ \tilde{g}_k = \begin{cases} D, & \text{if } k=0 \\
C \hat{A}^{k-1} \hat{B} + \sum_{i=1}^k C \hat{A}^{i-1} K \tilde{g}_{k-i}, & \text{otherwise} \end{cases} \]

Input-output description

\[ y_{k+p} = \epsilon_{k+p} + C \hat{A}^p \hat{x}_k + Du_{k+p} + \sum_{i=1}^p C \hat{A}^{p-i}[\hat{B} \hat{K}] \begin{bmatrix} u_{k+i-1} \\ y_{k+i-1} \end{bmatrix} \]
\[ \hat{A} = A - K C, \text{ is stable, } \hat{A}^p \to 0 \text{ for large } p \]
\[ y_{k+p} = \Theta[u_{k+p} \cdots u_k y_{k+p-1} \cdots y_k] + \epsilon_{k+p} \]

Our approach

1. Find \( \Theta \) from data with RQ-RLS,
2. including uncertainty estimates.
3. Compute predictor \( \text{MPs}, \tilde{g}_k \),
4. and propagate uncertainty.
5. Find \( \Sigma \) from \( \tilde{g}_k \).
A 4 × 4 system with known control issues

\[ \Sigma^2 \quad \Sigma^{PM} \quad \Sigma^H \]

\begin{align*}
&y_1 \quad y_2 \\
&y_3 \quad y_4 \\
&u_1 \quad u_2 \\
&u_3 \quad u_4
\end{align*}

\[ 0.4 \quad 0.2 \quad 0 \]

---


Closed-loop for loops 1 and 2, open for 3 and 4

\begin{align*}
&F_{11} \\
&F_{22} \\
&G
\end{align*}

\begin{align*}
r_1 \quad r_2 \\
&\quad u_1 \\
&\quad u_2 \\
&\quad y_1 \\
&\quad y_2 \\
&\quad y_3 \\
&\quad y_4 \\
u_3 \quad u_4
\end{align*}
Bark boiler (sim)

Stepwise excitation

Results of identification ($\rho = 8$)

- $|\Delta^2_M P|$
- $|\Delta^PM_M|$
- $|\Delta^H_M P|$

Var{$\Sigma^2_M P$}$^{1/2}$

Var{$\Sigma^PM_M$}$^{1/2}$
Bark boiler (sim)

Comparison with a subspace approach (PBSID)

MC comparison, average absolute error

Consistently larger errors
PBSID requires additional computation of a LS and a SVD
Conclusions

Summary
- works with both open or closed loop data
- can handle large datasets (RQ-RLS)
- all three Σ found using the same method
- provides an estimate of uncertainty (robust CSS)

Extensions
- empirical Gramians
- frequency selective filtering
- use orthonormal polynomials

Future work
- devise of algorithm for operational data
- model consistency check
- data and model quality check for each subsystem
Some thoughts on
Data-Driven Control Configuration Selection

Cristian R. Rojas

KTH Royal Institute of Technology, Sweden

Luleå, August 16, 2017

About myself

- BSc and MSc in Electronic Engineering from UTFSM, Chile
- PhD in Automatic Control from U. Newcastle, Australia
- Postdoc at KTH, Stockholm
- Currently: Assoc. Prof. in Automatic Control at KTH
- Research interests: System identification, signal processing, ...

http://people.kth.se/~crro/index.html

Disclaimer: Not done research on control configuration selection (yet...)
Identification as an iterative procedure

User choices

- **Experimental condition**
  input, sampling freq, open/closed loop, ...

- **Model structure**
  linear/nonlinear, parametric/nonparametric, ...

- **Identification method**
  least squares, PEM, ...

A more holistic view...

Make choices in identification procedure with focus on the end goal

For example, [Input design can emphasize system properties of interest, while properties of little or no interest can be ‘hidden’.](Rojas, Barenthin, Welsh and Hjalmarsson, 2008)
Application-oriented input design

Define $V_{app}(\theta, \theta_o)$ as a performance degradation cost of designing a controller based on $\theta$, and also

$$E_{app}(\gamma) := \{ \theta : V_{app}(\theta) \leq \frac{1}{\gamma} \}$$

$$E_{id}(\alpha) := \text{confidence region for } \theta, \text{ of significance level } \alpha$$

$\Rightarrow$ Pose input design as an convex optimization problem:
find an input of minimum power such that $V_{app}(\hat{\theta}_N) \leq 1/\gamma$ with probability at least $\alpha$. We can guarantee this by

$$E_{id}(\alpha) \subseteq E_{app}(\gamma)$$

A chicken vs egg dilemma

- Typically, optimal input depends on the very thing we want to estimate: the true system!

- In application-oriented input design, this is because both $E_{app}(\gamma)$ and $E_{id}(\alpha)$ depend on $\theta_o$

- Three approaches to solve this problem:
  - Bayesian: assume prior on $\theta_o$
  - Robust: optimize for worst case over $\theta_o \in \Theta$
  - Adaptive: re-design input based on recursive estimate of $\theta_o$
A solution: iterative identification

- Adaptive schemes may be prone to instability, and are difficult to analyze

- Instead try *poor man's* version: iterative identification, i.e., work on batches, where the input is designed based on data from previous batches

- Recent ideas from machine learning, namely, on *Multi-Armed Bandits*, provide asymptotically optimal adaptive strategies that could be applied to our problem (current research topic; preliminary findings in CDC'17)

Summary

- Data-driven control configuration selection could be addressed in sample efficient way via an *iterative identification* scheme

- Promising ongoing research on optimal schemes for this class of problems
B.4 Topic 4: Yie Cao and Natalia Dudarenko

Yie Cao and Natalia Dudarenko introduced the topic *Reconfiguration of control structures*, and also led the discussion on the topic.

The presentation slides are appended on the following pages.
Outline

- What is control system reconfiguration?
- Why do we need to reconfigure a control system?
- How can we reconfigure control systems?
- Control system retrofit example
- Self-reconfigurable control?
Elements of control systems

What does a control system consist?
- Manipulated variables / actuators
- Controlled variables / measurements
- Pairing for decentralised control systems
- Controllers, types, parameters and setpoints

What is control system reconfiguration?
- Reconfiguration: change one or more elements of a control system
- Manually offline
- Automatically online
Safe operation under faulty conditions

- Faulty conditions such as actuator and sensor faults
- Maintain minimum performance without shut down
  - Fault tolerant control
  - Reconfigurable control
- Mainly in safety critical systems, such as flight control systems.
- Rely on actuator and measurement redundancy

Regain optimality

- Operation optimality may be lost due to changes of operating conditions and operating objectives
- Traditional approaches are
  - Adaptive control to alter control parameters online
  - Real-time optimization to adjust set-points online
- Can we change control structure automatically online?
Global self-optimizing control

- SOC: select $c = Hy$ such that when $c$ are controlled at constant setpoints
  the overall operation is optimal or near optimal without RTO
- Local SOC: design $H$ based on linearized models at a nominal point.
- Global SOC: design $H$ based on data from Monte Carlo simulation.
- $\text{Loss}(H, d) = \text{feedback cost}(H, d) - \text{optimal cost}(d)$
- $H$ can be obtained by minimizing average loss over all $d \in D$
- Approach 1: Monte Carlo simulation over $d \in D$, and $u \in U$, evaluate $y$ and $dJ/du$. Regression to find $dJ/du = Hy$
- Approach 2: Monte Carlo simulation over $d \in D$, for each $d$ solve optimization problem to obtain optimal $u^*$ and $y^*$
- CV: $c = Hy = 0$, $c^* = Hy^*$, $dc = c - c^* = -c^*$
- Loss can be approximated as a quadratic function of $dc$.
- Minimizing loss solves $H$.
- Note, $H$ includes setpoints.

---

gSOC: retrofit Self Optimizing Control

- Do we need to redesign the entire control system for SOC?
- Retrofit SOC: control CVs selected by adjusting existing setpoints

Advantages:
- Implementation does not need plant shut down
- Dynamic performance and constraints handling inherited
- gSOC to ensure best economic performance
- Subset selection to ensure simplest control structure
- Directly compatible with RTO
- Applicable to IoT
Retrofit SOC: operation optimization

- Economic objective: minimize the cost
  \[ J = (\text{loss of raw materials in purge and products}) + (\text{steam costs}) + (\text{compression costs}) \]

Various Constraints:
1. Product mixup (ratio of G:H), production rate
2. Reactor pressure, temperature
3. Vessel levels
4. MV saturations
5. etc

- Degrees of freedom:
  - 9 active constants: XMEAS(7,8,12,15,17,19,40), XMV(5,9,12)
  - 3 DOF for SOC
  - Retrofit SOC adjust 3 set-points, \( y_A, y_{AC} \) and \( T_{rc} \)
Retrofit SOC: existing optimal control structures

1. Ricker, N. (1996), (CS_Ricker)
   • Nominal optimization + heuristic design
   • Decentralized control structure is available via http://depts.washington.edu/control/LARRY/TE/download.html

2. Larsson et. al. (2001), (CS_Skoge)
   • Individual measurement based SOC

Results and simulations

• 7 Operating conditions considered
  • nominal
  • IDV(1): A/C feed ratio
  • IDV(2): B composition
  • production rate ±15%
  • product mix change: 50 G/50 H to 40 G/60 H
  • step change of reactor pressure set-point to 2645 kPa
Minimal loss against subset size

<table>
<thead>
<tr>
<th>m</th>
<th>XMEAS index</th>
<th>XMV index</th>
<th>average loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>[9, 20, 31]</td>
<td>-</td>
<td>0.7001</td>
</tr>
<tr>
<td></td>
<td>[21, 31, 33]</td>
<td>-</td>
<td>0.7211</td>
</tr>
<tr>
<td></td>
<td>[31, 33, 34]</td>
<td>-</td>
<td>0.7518</td>
</tr>
<tr>
<td></td>
<td>[28, 31, 34]</td>
<td>-</td>
<td>0.7576</td>
</tr>
<tr>
<td>4</td>
<td>[9, 23, 25]</td>
<td>-</td>
<td>1.4615</td>
</tr>
<tr>
<td></td>
<td>[5, 9, 31]</td>
<td>-</td>
<td>0.9083</td>
</tr>
<tr>
<td>5</td>
<td>[25, 29, 34, 38]</td>
<td>-</td>
<td>0.1081</td>
</tr>
<tr>
<td></td>
<td>[23, 25, 34, 38]</td>
<td>-</td>
<td>0.1101</td>
</tr>
<tr>
<td>6</td>
<td>[9, 20, 31, 38]</td>
<td>[6]</td>
<td>0.0328</td>
</tr>
<tr>
<td></td>
<td>[9, 23, 31, 38]</td>
<td>[6]</td>
<td>0.0356</td>
</tr>
<tr>
<td></td>
<td>[9, 10, 29, 31, 38]</td>
<td>-</td>
<td>0.0359</td>
</tr>
<tr>
<td></td>
<td>[4, 18, 20, 30, 31, 34]</td>
<td>-</td>
<td>0.0169</td>
</tr>
<tr>
<td></td>
<td>[4, 18, 20, 24, 31, 34]</td>
<td>-</td>
<td>0.0177</td>
</tr>
<tr>
<td></td>
<td>[4, 18, 20, 28, 30, 31]</td>
<td>-</td>
<td>0.0179</td>
</tr>
</tbody>
</table>

XMEAS(>=23) : compositions

Simulation and Result economic loss

<table>
<thead>
<tr>
<th></th>
<th>CS_Ricker</th>
<th>CS_Skoge</th>
<th>This work (m=3)</th>
<th>This work (m=6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal</td>
<td>0</td>
<td>0</td>
<td>0.1</td>
<td>0.04</td>
</tr>
<tr>
<td>IDV(1)</td>
<td>0</td>
<td>0.03</td>
<td>0.2</td>
<td>0.05</td>
</tr>
<tr>
<td>IDV(2)</td>
<td>2.7</td>
<td>1.7</td>
<td>0.9</td>
<td>0</td>
</tr>
<tr>
<td>throughput +15%</td>
<td>6.1</td>
<td>1.5</td>
<td>2.4</td>
<td>0.05</td>
</tr>
<tr>
<td>throughput -15%</td>
<td>2.6</td>
<td>0.6</td>
<td>0.2</td>
<td>0.02</td>
</tr>
<tr>
<td>40 G/60 H</td>
<td>0.7</td>
<td>0.3</td>
<td>0.5</td>
<td>0.01</td>
</tr>
<tr>
<td>rct press 2645 kPa</td>
<td>0.3</td>
<td>4.5</td>
<td>1.3</td>
<td>0.01</td>
</tr>
<tr>
<td>sum</td>
<td>12.4</td>
<td>8.63</td>
<td>5.6</td>
<td>0.23</td>
</tr>
</tbody>
</table>
Future work: Self-reconfigurable control

• Any scenario requires online self-reconfigurable control
  • Unexpected disturbances
  • Incipient faults
  • Flexible operation conditions

• Criteria to initiate online control system reconfiguration
  • Statistic process monitoring to identify abnormal operation conditions
  • Optimality of operations

• Implementation to make control systems online self-reconfigurable
  • Linear combinations of measurements as controlled variables

• Relevant approach to reconfigure control systems automatically online
  • CV adaptation through just-in-time regression
Topic 4. Reconfiguration of control structures

Natalia Dudarenko

University ITMO
dudarenko@mail.ifmo.ru, dudarenko@yandex.ru

PiCCS – 2017, August 17 (Luleå, Sweden)

Control in practice

Basic principles

Hierarchical control

Decentralized control

Optimization

Supervisory control

Regulatory control
Approaches for controller reconfiguration

Groups of key approaches

- Input-Output pairing analysis
- Selection of controlled variables
- Control degree of freedom analysis
- Usage of a virtual actuator

Control reconfiguration in theory

Typical procedure

1. Define objectives/required indicators.
2. Simulation study and analysis.
3. Analysis of the current control configuration; identification of feasible changes.
4. Control configuration selection.
5. Assessment of the required indicators.
6. Reconfiguration of the current control scheme.
7. Re-evaluation of the new control configuration.
8. Implementation and validation of the new control scheme.
9. Assessment of the required indicators of the improved system.
Can the closed loop performance of the air control system of a bark boiler be improved?

The main problems are:

- The performance of the air control system of a bark boiler deviates from required performance and the complete re-design is not feasible.
- Find a controller based on the current controller which improves the performance of the closed loop system.
- Use the closed loop performance as indicator.
Proposed the control reconfiguration methods

Proposed methods for the reconfiguration of a multivariable controllers:
- the factorization of the closed loop sensitivity function (transfer function approach)
- the degeneration factors of the closed loop system (state space approach)

Sensitivity factorization

A decentralized or block-decentralized controller for the complete process $G$ can be given as

$$K(s) = \begin{bmatrix} K_{11}(s) & 0 & \cdots \\ 0 & \ddots & \ddots \\ \vdots & \ddots & \ddots \end{bmatrix}, \quad \hat{G}(s) = \begin{bmatrix} G_{11}(s) & 0 & \cdots \\ 0 & \ddots & \ddots \\ \vdots & \ddots & \ddots \end{bmatrix}$$

In the controller synthesis the dynamics $\hat{G} = G - \hat{G}$ is neglected
Sensitivity factorization can be

$$S = (I + \Delta)^{-1} \hat{S}$$
$$\Delta = \hat{S} \hat{G} K$$

where $S$ and $T$ are the closed loop sensitivity functions
The performance loss due to the neglected dynamics is
$$\Delta S = \hat{T} - T$$
Degeneration factors

- The degeneration factors $J_{Dj}$ are defined as follows:
  \[ J_{Dj} = \frac{\alpha_j(N)}{\alpha_1(N)}; j = 1, 2 \]
  where $\alpha_j$ is the $j$-singular value of the criterion matrix $N$.
- $N$ is the criterion matrix of the system, which can be the frequency response of the closed loop system or the output spectral density matrix $S_y$.
- The performance loss is deviation of the degeneration factor from its nominal value $\Delta J_D = J_{D0} - J_D$.

Analysis results

- $\Delta$ can also be evaluated using the index array:
  \[ [\Sigma]_{ij} = \frac{\|\Delta_{ij}\|_\infty}{\Sigma_{ij}\|\Delta_{ij}\|_\infty} \]
  and yields:

  \[
  \begin{array}{c|ccc}
  \hat{y}_1 & e_1 & e_2 & e_3 \\
  \hat{y}_2 & 0.2236 & 0 & 0.0566 \\
  \hat{y}_3 & 0.4094 & 0.2871 & 0 \\
  \end{array}
  \]
- Applying the degeneration tool on $S_y$ yields an effect on the outputs from the inputs: $u_1 \rightarrow y_2 (58\%)$;
  $u_2 \rightarrow y_2 (46\%), y_3 (40\%); u_3 \rightarrow y_2 (68\%); u_4 \rightarrow y_2 (40\%), y_3 (49\%)$

**Conclusion:** Use connection $G_{21}$ in the controller design!
Reconfigured the air control system

- A feedforward has been introduced from $e_1$ to $u_2$. For the sake of simplicity a decoupling of the link is introduced.

Performance of the reconfigured closed loop system

- The reconfiguration yields a control system with better performance. The worst case performance loss is reduced by 3%.
Future research

Open questions

- Extension of the control reconfiguration methods for the uncertain systems.
- Extension of the control reconfiguration methods for the systems in the presence of disturbances.
- Extension of the control reconfiguration methods for different type of controllers.

Publication activity within the area of reconfiguration of control structures