

# On the actuation of process systems

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**Abstract:** This paper argues that actuation is overlooked in the process systems area. In the future this situation may well lead to control limitations. It is explained that actuation relies on driving forces which links it to irreversible thermodynamics. The importance and potential of actuation is shown in an (optimal) control setting by examples taken from crystallization, reaction and distillation. Exploiting the potential of actuation implies interaction between the various design stages (operation mode, process and control design). Therefore exploitation is better accommodated by process intensification than by traditional process design. Furthermore process intensification offers new possibilities and challenges for actuation.

*Keywords:* Actuation, process systems, inputs, actuators, degrees of freedom, irreversible thermodynamics, optimal control, dynamic optimization, process intensification.

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## 1. INTRODUCTION

It is well known that the presence of inputs, actuators, operational Degrees Of Freedom (DOF) or simply actuation is an essential condition to be able to apply control. Therefore one expects that actuation as a subject would have received a fair amount of attention in the literature. There are however only a handful of related contributions like for example Ponton (1994), Pham (1994) and Luyben (1996), and all them have to do with counting the number of DOF. In other words they provide alternatives for “the variables minus equations” approach which is rather sensitive for error since the number of DOF can easily be orders of magnitude smaller than the number of variables or equations. It can be concluded that the literature does not say much about actuation itself.

A possible explanation for the absence of the subject is that the control community considers actuation to be the outcome of process design while on the other hand the process community is unaware of the issue or believes that actuation is fixed for a particular unit operation. For instance a heat exchanger has one DOF and a two-cut splitter five DOF. Although these viewpoints are not (completely) correct they do reveal that actuation is an aspect of the interaction between process design and control. Furthermore there are indications that the oversight of actuation limits the advancement of the research related to this interaction. For example Meeuse (2002) states that: “One of the main limitations is that all available methods can only analyse the controllability of given process alternatives. No clues are given on how to generate alternatives with improved controllability.” It is easy to see that the neglect of actuation as a part of overall process systems design exactly leads to the situation that Meeuse sketches.

Over the last three decades process control has made considerable progress with the introduction of Model Predictive Control (MPC), Real Time Optimization (RTO) and more recently Non-linear MPC (NMPC). However all this progress boils down to better utilization of the available DOF. So it is only a matter of time that process control will find itself in the situation that little progress can be made as the available actuation has become the limiting factor. In other areas like aerospace and automotive engineering the importance and potential of actuation has already been identified, see table 1. In this context it seems only fitting to point out that the invention of the airplane is normally contributed to the Wright brothers in the year 1903 simply because they designed, constructed and operated the first fully actuated airplane. The main contribution is to show the importance and potential of exploiting the actuation of process systems.

Table 1. The number of hits for various combinations of keywords.

Keywords in title	Scopus hits
“process system” actuator OR actuation	1
“process system” sensor OR sensing	7
aerospace actuator OR actuation	26
automotive actuator OR actuation	44

The rest of this paper is organized as follows. In section 2 actuation is discussed and this establishes an insightful relationship with irreversible thermodynamics. The next section illustrates by three examples the importance and potential of exploiting actuation. Section 4 explains the consequences of such exploitation for process design and process intensification. The last section summarizes the conclusions and does suggestions for further work.

## 2. ACTUATION

What is actuation? Before answering that question lets answer another but related question: What is sensing? Sensing is the conversion of the value of a process variable (pressure, temperature etc.) into the value of another but nowadays typically electric variable (voltage, current etc.); a signal. It is tempting to simply invert this answer for actuation: Actuation is the conversion of the value of a signal into the value of a process variable. But why would such a conversion be possible? A signal represents virtually no material and/or energy while a process variable does. Such a conversion would be possible because of the presence of a driving force or in the terms of irreversible thermodynamics; driving forces result in fluxes. The relation between a driving force  $X$  and a flux  $J$  is typically described by:

$$J = f(L, X) \quad (1)$$

Here  $L$  stands for the phenomenological constant. The conversion of the flux into the related flow  $F$  is given by:

$$F = G_v J = G_v f(L, X) \quad (2)$$

With  $G_v$  being the relevant geometric variable (area or volume). Equation 2 actually explains the mechanism of actuation. The actuation signal influences the phenomenological constant and/or the relevant geometric variable and as a result the flow changes. The mechanism does not require material and/or energy; this is supplied by the driving force. This important insight can be used to explain existing actuation but also to exploit actuation. For example in the case of flow control the driving force is a pressure difference while the actuation signal influences the phenomenological constant and/or the area of the control valve changing the material flow. In the case of temperature control the driving force is a temperature difference that is also determined by a hot or cold utility flow which itself is actuated in the same way as flow control. Concerning the exploitation of actuation the link with thermodynamics clarifies how to extend actuation. Examples will be given in the next section.

The connection between process control and irreversible thermodynamics at least dates back almost 15 years. For example Ydstie and Viswanath (1994) and Farschman et al. (1998) focused on the stability of process systems while Luyben et al. (1999) and Meeuse (2002) concentrated on their controllability. However the authors of this paper are unaware of any work that connects actuation with irreversible thermodynamics.

## 3. CONTROL

This section illustrates in three examples the importance and potential of actuation for control. The first example deals with crystallization and shows that limited actuation has serious consequences for control. The second and last example are taken from reaction and distillation respectively, these examples show how to exploit the potential of actuation. All examples make use of the link between actuation and irreversible thermodynamics.

### 3.1 Crystallization

The discussion in this subsection is based on Kalbasenka et al. (2005) but the focus is now more on on driving forces and fluxes. Figure 1 shows a typical batch crystallizer with three DOF; seeding, stirrer speed and heat input. Obviously the relevant driving force is supersaturation while the relevant flux is from the liquid solute to the solid crystalline phase. Let's analyze the various DOF with respect to this driving force and flux. Seeding provides the initial condition for the partial differential equation that describes the Crystal Size Distribution (CSD) development. As such it can be considered a discrete DOF. Although seeding is very important is has no relationship with the driving force or flux and therefore seeding can not help to suppress disturbances like secondary nucleation that happen during the batch. The main function of the stirrer is to avoid settling of the crystals. Also this DOF has no influence on the driving force or flux and unfortunately it even causes secondary nucleation. The heat input has a clear influence on the supersaturation and on the flux and this makes it an effective DOF. However it should be noted that it is not possible to direct the flux to a certain part of the CSD. In other words the total crystal mass can be controlled but not the complete CSD.

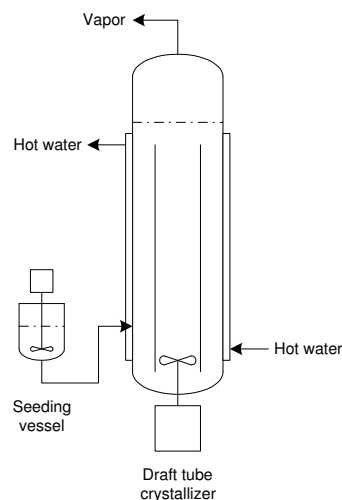


Fig. 1. A batch crystallizer system with normal actuation.

It can be concluded that the actuation of batch crystallizers is quite limited. There are two ways to deal with this. The first possibility is to simply accept the limitation; from a control point of view this implies designing a controller that controls the growth rate rather than the CSD. As a matter a fact this approach has been rather successful, see Mesbah et al. (2008). Of course the other possibility is to extend the actuation such that the flux can be directed to a specific part of the CSD. This is not really straightforward but in a sense this is done in practice by some form of classification (for example fine extraction in an annular zone) followed by dissolution (in fact a negative flux). In the following subsections extension of actuation will receive more attention.

### 3.2 Reaction

In a batch reactor component A is converted in the components B and C;  $A \rightarrow B$  and  $2A \rightarrow C$ . The first reaction is desired while the second one is not. The reaction rates or fluxes are given by:

$$J_B = k_B A = 10^6 e^{\frac{-45000}{RT}} A \quad (3)$$

$$J_C = k_C A^2 = 5.10^{11} e^{\frac{-90000}{RT}} A^2 = 0.5k_B^2 A^2 \quad (4)$$

Here  $k_B$  and  $k_C$  denote the specific rates,  $A$  the concentration of A,  $R$  the universal gas constant and  $T$  the absolute temperature. Suppose that in the normal case the batch reactor is actuated by a transformed temperature  $k_B$  (see figure 2, left). From the fluxes the flows can be derived:

$$F_B = k_B A_R V_R \quad (5)$$

$$F_C = 0.5k_B^2 A_R^2 V_R \quad (6)$$

So it should be possible not only to actuate the system by  $k_B$  but also by the concentration of A in the reactor  $A_R$  and the volume in the reactor  $V_R$ . Both variables can be influenced by an inlet flow of A to the reactor;  $F_1$  (see figure 2, right). Note that an outlet flow from the reactor would only influence  $V_R$ .

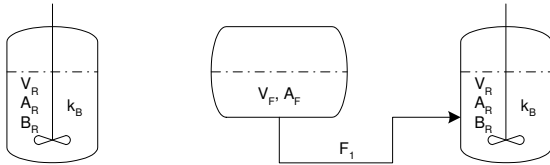


Fig. 2. A reactor system with normal (left) and extended actuation (right).

Therefore the actuation is extended by adding  $F_1$  as a DOF. Both systems were used to solve an optimal control problem. The idea is to determine the value of extended actuation in a framework that supports a realistic objective, non-linear process behaviour and operational constraints. The objective was to maximize  $V_R(t_f) B_R(t_f)$  with  $t_f$  being the time horizon subject to system behavior (mass and component balances) and operational constraints (state and input limitations). The objective reflects the total production of component B. Great care was taken to ensure a fair comparison between the normal and extended case. The optimal control problem was solved using dynamic optimization; the simultaneous approach based on an implicit Euler transcription. The implementation was done in the algebraic language GAMS with the solver CONOPT. The results are shown in figure 3. In the case of normal actuation the objective value was 0.8317 while in the case of extended actuation it increased to 0.8710; an improvement of 7%.

The results can be explained from a process point of view. In the normal case the reaction starts at high values for  $V_R$  and  $A_R$ . In other words initially there is a large flow to C compared to B. In the case of extended actuation first  $A_R$  is lowered after which  $V_R$  is slowly increased.

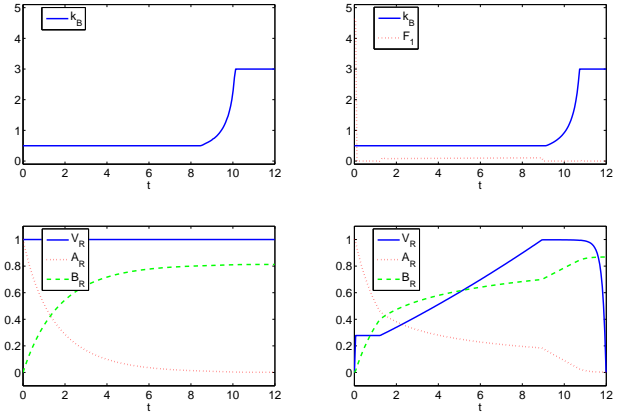


Fig. 3. The reactor system results for normal (left) and extended actuation (right).

### 3.3 Distillation

In a continuous distillation column a mixture of the components A and B is separated and B is stored in a product tank. In the normal case the distillation column is actuated by the feed  $F$ , the boilup  $V$  and the reflux  $L_{10}$  (see figure 4, left). The flows between the liquid and vapor phase depend on the transfer coefficient, the interface area and the distance from equilibrium. The latter is easy to influence by the liquid flow in the downcomers; for example  $L_9$  (see figure 4, right). So the actuation can be extended by adding  $L_2 - L_9$  as DOF. The significant increase in the number of DOF, from three to 11, is a result of the distributed nature of distillation columns.

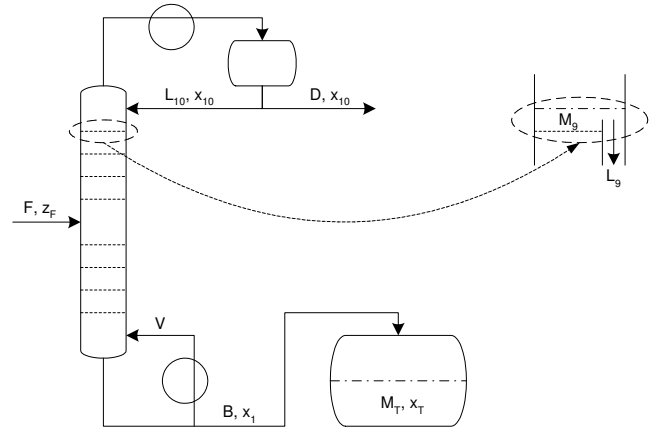


Fig. 4. A distillation system with normal (left) and extended actuation (right).

Again both systems were used to solve an optimal control problem. The objective was to minimize  $\int_0^{t_f} wF(t) + V(t) dt$  subject to system behavior, operational constraints and the constraints  $M_T(t_f) = 1.1$  and  $x_T(t_f) = 0.2$ . The objective reflects the operational costs; feed plus energy, with  $w$  being the cost of feed over the cost of energy. Again great care was taken to ensure a fair comparison. The optimal control problem was solved in the same way as the batch reactor example. The normal case is described in detail by Huesman et al. (2007). The results are shown in figure 5. In the case of normal actuation the objective value was 7.2327 while in the case of extended actuation it could

at least go as low as 4.6417; this means an improvement of 35%.

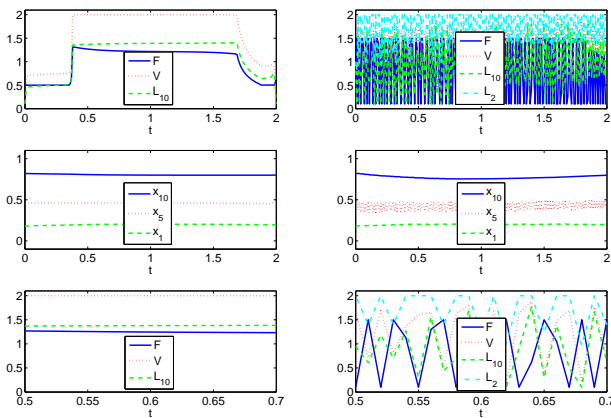


Fig. 5. The distillation system results for normal (left) and extended actuation (right).

Figure 6 presents part of the data in a McCabe-Thiele diagram. Note that on average “the extended or intensified working line” is further away from the equilibrium line than “the normal working line”. So intensified actuation allows for a more favorable positioning of the working line.

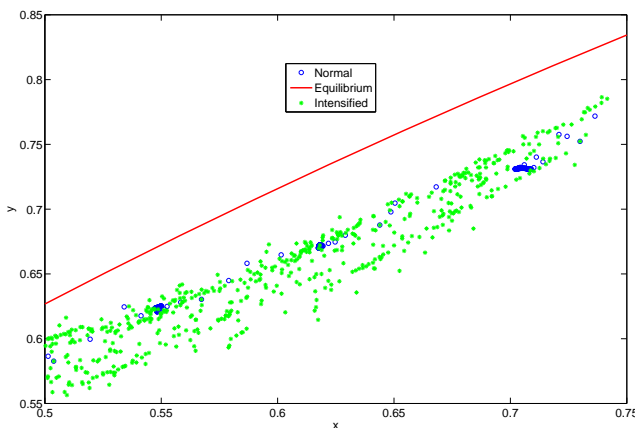


Fig. 6. The distillation system results in a McCabe-Thiele diagram.

#### 4. DESIGN

It is evident that the extension of actuation has consequences for the operation mode as well as the process design. In the reaction example the mode changed from batch to fed-batch and an open-shut valve must be replaced by a flow control loop. In the distillation case there was a shift from continuous to periodic operation and the downcomers, trays etc. must be modified such that all downcomer flows can be manipulated.

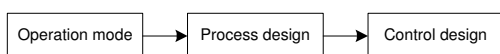


Fig. 7. The three stages of overall process systems design.

According to Douglas (1988) the traditional overall design consists of three stages (see figure 7). These stages are

dealt with in a pure sequential manner. So extension of actuation which implies going back from the control stage to the process and operation mode stage does not go well with traditional design. On the other hand process intensification that aims to improve processes and equipment may consider extension of actuation an opportunity. According to Gerven and Stankiewicz (2009) process intensification is based on four domains. All domains are discussed below including their relationship with actuation and/or control:

- (1) Spatial; the drastic reduction of characteristic dimensions to micrometer up to nanometer scale. However even on the traditional process scale improvements are possible. Worth mentioning is the idea developed at the Delft University of Technology of small sensors and actuators that float in the process medium and communicate via ultra-wideband radio. This enables an innovative form of spatial process control.
- (2) Thermodynamic; the application of alternative driving forces such as gravitational, electromagnetic or acoustic fields. Given the relationship between driving forces and actuation, this opens complete new possibilities for actuation. For instance, the application of microwaves offer a fundamentally different way (faster, more precise etc.) of heating material compared to conventional heating by conduction.
- (3) Functional; the integration of various functions within a single unit operation. A well-known example is reactive distillation. Although this is attractive since it leads to compact designs it may well reduce the possibilities for actuation.
- (4) Temporal; the dramatic shortening of the characteristic times and the use of deliberate non-steady state operation. The last point was clearly illustrated in the distillation example.

So there are new and promising possibilities for process intensification and control to cooperate in which actuation will play a central role.

#### 5. CONCLUSIONS AND FUTURE WORK

The main conclusions of this paper are:

- The subject actuation is overlooked in the process systems area. In the future this may well lead to control limitations.
- Actuation relies on driving forces and therefore actuation is related to irreversible thermodynamics.
- The importance and potential of actuation was shown in examples taken from crystallization, reaction and distillation.
- Exploitation of actuation is best supported by process intensification. The latter also offers new possibilities and challenges for actuation and control.

Future work will focus on:

- Deepen the theoretical relation between irreversible thermodynamics and actuation.
- Application of extended actuation to more process systems; especially those with new driving forces.
- Evaluation of extended actuation in the presence of uncertainty (feedback setting).

## REFERENCES

- Douglas J.M. (1988) *Conceptual Design of Chemical Processes*. McGraw-Hill, New York, pages 406 and 414.
- Farschman C.A., Viswanath K.P. and Ydstie B.E. (1998) Process systems and inventory control. *AIChE Journal*, 44, pages 1841–1857.
- Gerven T. van, Stankiewicz A. (2009) Structure, Energy, Synergy, Time - the Fundamentals of Process Intensification. *Industrial & engineering chemistry research*, 48, accepted.
- Huesman A.E.M. , Bosgra O.H. and Van den Hof P.M.J. (2007) Degrees of freedom analysis of economic dynamic optimal plantwide operation. In Foss B. and Alvarez J., editors, *Prepr. of the 8th IFAC International Symposium on Dynamics and Control of Process Systems*, volume 1, pages 165–170, Cancun Mexico.
- Kalbasenka A., Huesman A., Kramer H. and Bosgra O. (2005) Controllability analysis of industrial crystallizers. In Jones M. and Ulrich J., editors, *Proc. of the 12th International Workshop on Industrial Crystallization*, pages 157–164, Halle Germany.
- Luyben W.L. (1996) Design and control degrees of freedom. *Industrial & engineering chemistry research*, 35, pages 2204–2214.
- Luyben W.L., Tyr eus B.D. and Luyben M.L. (1999) *Plantwide process control*. McGraw-Hill, New York, appendix A.
- Meeuse F.M. (2002) *On the design of chemical processes with improved controllability characteristics*. PhD thesis, Delft University of Technology, Delft, page 25.
- Mesbah A., Kalbasenka A.N., Huesman A.E.M., Kramer H.J.M. and Van den Hof P.M.J. (2008) Real-time dynamic optimization of batch crystallization processes. In *Proc. of the 17th IFAC World Congress*, pages 3246–3251, Seoul Korea.
- Pham Q.T. (1994) Degrees of freedom of equipment and processes. *Chemical Engineering Science*, 49(15), pages 2507–2512.
- Ponton J.W. (1994) Degrees of freedom analysis in process control. *Chemical Engineering Science*, 49(13), pages 2089–2095.
- Ydstie B.E. and Viswanath K.P. (1994) From thermodynamics to a macroscopic theory for process control. In *Proc. of the 5th Int. Symposium on Process Systems Engineering*, pages 781 – 787.