Self-calibrating, event-driven flow control and measurement

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Abstract: This paper introduces a simple self-calibrating liquid flow rate control system. A level glass containing discrete optical level sensors is connected on the flow line upstream of the pump. The optical sensors in the level glass provide level-event information and define volumes that can be used to calibrate and control the pump. The system is continuous and is observed by a quantiser, making it overall a discrete-event dynamic system to be controlled by a corresponding controller.

The set-up was installed as a reflux system on a set of distillation columns where the distillate is condensed below the top of the column, providing a industrial-like physical arrangement of the different components. The control system is low-cost and therefore provides a reasonable alternative for flow control and flow measurement.

1. INTRODUCTION

Flow control is a common process operation. It normally involves a flow measurement which is used to control a pump of one or the other kind. The alternative is a metering pump, which is an accurate volume transport device. A metering pump requires a construction that makes the flow rate nearly independent of the pressures before and after the pump. This makes it possible to calibrate the pump accurately, thereby relating the control input to the pumping rate.

In this project we were seeking a cheap and simple alternative for both components namely the measurement and the controlled pump. The flow measurement should not only be simple but also robust and the pump should have the basic properties of a metering pump. The result was a self-calibrating liquid flow control system that uses a level glass for observing the condition of having the outflow of the pump to match the inflow. The level glass also serves as the volume standard used for the on-line auto-calibration of the pump. We utilise the arrangement as a reflux pump and reflux measurement system on distillation columns.

2. PHYSICAL ARRANGEMENT

The physical arrangement consists of two main components: a level glass and a pump. The level glass is connected to the flow line before the pump via a generously wide connection so as to not delay the level change in the level glass. The pump then is put into the flow line moving the fluid. The level glass is equipped with six discrete level detectors, which provide an event-signal whenever the level passes an optical sensor. The dimension of the level glass and the location of the sensors provides a set of known volumes, which can be used for the calibration and control of the pump. The physical dimension of the level glass are chosen to be in a reasonable relation to the expected range of flow rates in the line. Secondarily the geometry must be such that the sensors can be mounted easily. In addition, a solenoid tab is put into the line before the level glass connection so as to interrupt the supply flow, enabling the on-line calibration of the pump.
The peristaltic pump provides the volume transport over a reasonable range of inflow/outflow pressures of the pump and generates a head that is suitable for our application, namely pumping the distillate that we condense on the side of the column, back to the top, thus providing the necessary reflux. Volume transporters are usually moving small constant volumes generated in the pump by toothed wheels or other mechanisms. This makes the flow pulsating, which has a negative effect on the accuracy of the flow rate estimates.

3. DISCRETE-EVENT DYNAMIC CONTROLLER

The overall system is a hybrid of a continuous system and a discrete-event observed system. With the measurement being event-based, the controller is event-based. The task is to design a Discrete-Event Dynamic controller, a DED controller. For the design of the DED controller, we use the techniques discussed in Preisig [1996], Philips [2001], Philips et al. [2003]. The one-dimensional state space, being the level in the level glass, is quantised. The number and location of the discrete sensors determine the discretisation of the state space, dividing it into seven discrete states. Five of those states corresponds to the volume space between two sensors. In addition there are the two additional volume spaces, one above the top sensor and one below the bottom sensor. The sensors report via a process interface (digital input) an event of passing a sensor to the computing device and thus to the control algorithm.

3.1 Time event

The DED controller is designed to keep the level within the middle domain. If the supply flow increases, the level will increase and eventually when the level reaches the upper boarder of the middle domain a state event will be reported. At this point the pump rate will be increased. The aim is to bring the process back to the intermediate domain. If the increase of the pump rate was too small and it happens that the level settles somewhere in the current upper domain, no level event will occur.

To get insight into the problem consider the difference between sampled systems and event-driven systems: In the sampled system, the signal value is read every sampling time instance. So, sampling is driven by a clock. In the case of an event-driven system, the 'reading' is done in the opposite direction, namely the value (state-boundary) is given and if the process passes it an event signal is dispatched. This makes the process being the 'clock'. If for one or the other reason, a state event is not directly observable, one may generate a virtual event by using a prediction in which one replaces the process with a stop watch. The state event is then replaced by a time event, which is the time when the unobservable event is expected to occur. Thus one can view this mechanism as substituting an unobservable event with a stop-watch event, de facto a time event.

This is the mechanism we use in our implementation: The unobservable event that takes place when the level does not change over a specified time, is replaced by a time event. For certain levels, here the events g, h, i and j in Figure 3, a time event is triggered if a level change event does not occur within 50 seconds, with the action of altering the pump flow rate. At the same time, a new timer is started. If this new timer again expires, the flow rate is again adjusted. This procedure is repeated until a level event occurs. The time it takes for the time event to trigger depends on the ratio between level volume and flow rate. For a big level glass with large level volumes and with a low flow rate, the time event should not be triggered until a sufficient time has passed, as a level change event gives flow rate information and is therefore more valuable.

In our case we implement this behaviour for the main reason that we do not want to change the speed of the pump abruptly, but smoothly. Once a level event occurs we adjust the speed slowly consequently allowing for an over or under shoot of the level. This chosen behaviour is aiming at increasing the accuracy of the flow information extracted from the pump calibration. As an example, when the liquid level changes from "Level 3" to "Level 4", the level change event c causes the pump speed to be set to equal its current speed plus the estimated liquid flow in the level glass. If the estimate is accurate, the action will only stop the rising of liquid in the glass, and not lower it. The time event h will then increase the pump speed by 2.5% so that it reaches "Level 3" again.

3.2 Control automaton

Figure 3 shows the state diagram of the resulting flow control system. Events that are highlighted in red illustrate when pump flow rate adjustment actions are being taken. These highlighted events occur after a change in liquid level, or when a time-event occurs. The ideal state for the controller is the state labelled "Level 3", which is in the middle of the domains bounded by the six sensors.

Fig. 3. State diagram

Figure 5 shows the events that are triggered by a change in level and also the events triggered when there is no change in level for a given time, which is relative to the normal process dynamics rather substantial. The four sensors in the middle acts as soft constraints and the top and bottom sensors acts as hard constraints. On hard constraints the
controller shifts to maximum action, which is full speed on
the top and zero on the bottom.

\[ \dot{V}_{\text{tr}} \quad \text{Flow rate going in to flow control system} \]

\[ \dot{V}_p \quad \text{Flow rate produced by pump} \]

Fig. 4. Symbol definition for Figure 5.

<table>
<thead>
<tr>
<th>Letter</th>
<th>Event</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Level 5 \rightarrow Level 6 \quad \dot{V}_b = \text{auto}</td>
<td>Set PFR to maximal allowed value</td>
</tr>
<tr>
<td>b</td>
<td>Level 4 \rightarrow Level 5 \quad \dot{V}_b = \dot{V}_a + 1.10</td>
<td>Set PFR to 10% above flow rate</td>
</tr>
<tr>
<td>c</td>
<td>Level 3 \rightarrow Level 4 \quad \dot{V}_b = \dot{V}_a</td>
<td>Set PFR equal to flow rate</td>
</tr>
<tr>
<td>d</td>
<td>Level 2 \rightarrow Level 3 \quad \dot{V}_b = \dot{V}_a</td>
<td>Set PFR equal to flow rate</td>
</tr>
<tr>
<td>e</td>
<td>Level 1 \rightarrow Level 2 \quad \dot{V}_b = \dot{V}_a \times 0.90</td>
<td>Set PFR to 10% below flow rate</td>
</tr>
<tr>
<td>f</td>
<td>Level 0 \rightarrow Level 1 \quad \dot{V}_b = 0</td>
<td>Set PFR to zero</td>
</tr>
<tr>
<td>g</td>
<td>dt=+50k,300k,150k \quad \dot{V}_b = \dot{V}_a + 1.05 \quad \text{Increase PFR by 5%}</td>
<td></td>
</tr>
<tr>
<td>h</td>
<td>dt=+50k,100k,150k \quad \dot{V}_b = \dot{V}_a + 1.025 \quad \text{Increase PFR by 2.5%}</td>
<td></td>
</tr>
<tr>
<td>i</td>
<td>dt=+50k,100k,150k \quad \dot{V}_b = \dot{V}_a \times 0.975 \quad \text{Decrease PFR by 2.5%}</td>
<td></td>
</tr>
<tr>
<td>j</td>
<td>dt=+50k,100k,150k \quad \dot{V}_b = \dot{V}_a \times 0.95 \quad \text{Decrease PFR by 5%}</td>
<td></td>
</tr>
<tr>
<td>m</td>
<td>Start \rightarrow Level 0 \quad \dot{V}_b = 0</td>
<td>Set PFR to zero</td>
</tr>
<tr>
<td>k</td>
<td>Start \rightarrow Level 6 \quad \dot{V}_b = \text{auto}</td>
<td>Set PFR to maximal allowed value</td>
</tr>
<tr>
<td>n</td>
<td>Start lvl 1 \rightarrow Level 0 \quad \dot{V}_b = 0</td>
<td>Set PFR to zero</td>
</tr>
<tr>
<td>l</td>
<td>Start lvl 3 \rightarrow Level 6 \quad \dot{V}_b = \text{auto}</td>
<td>Set PFR to maximal allowed value</td>
</tr>
<tr>
<td>→</td>
<td>All other events</td>
<td>Event is ignored</td>
</tr>
</tbody>
</table>

Fig. 5. Time and level change events.

The level change events b, c, d and e trigger an action
that sets \( \dot{V}_b \) (pump flow rate) equal or close to \( \dot{V}_{\text{tr}} \) (flow rate coming in). In order for this to happen, \( \dot{V}_{\text{tr}} \) must be determinable. If the level rises from "Level 3" to "Level 4", it must before that have risen from "Level 2" to "Level 3" in order for \( \dot{V}_{\text{tr}} \) to be known. As an example of the opposite, if the level were to oscillate between "Level 3" and "Level 4", the level change event c will not be triggered at the change from "Level 3" to "Level 4".

4. PUMP CALIBRATION

The solenoid valve introduced into the line enables the isolation of the level glass and the pump from the supply. Since the volumes in the level glass are known, one can use the fluid in the level glass for the calibration of the pump. The procedure is controlled by a calibration automaton. It implements a sequence of operations:

- a: open valve
- b: close valve
- c: start pump
- d: stop pump
- e: start control mode
- f: start x seconds countdown
- g: compute flow rates
- h: change pump speed parameter
- i: increase counter by 1
- j: start time
- k: note time

Table 1. Calibration actions

Calibration procedures (i), (ii) and (iii) are done in succession, one time after assembly of the system is finished:

(i) **Find correlation between one pump input and flow rate.** This is done by specifying an input signal to the pump and collecting the output flow into a container with a known volume. The flow rate, \( \dot{V} \), for the given input, \( u \), is found by measuring the time, \( \Delta t \) required to fill the volume-calibrated container to volume \( V \):

\[
\dot{V}(u) = \frac{V}{\Delta t(u)} \quad (1)
\]

(ii) **Find volume between sensors** using flow rate from the previous volume calibration (i). As one flow rate is known, this is used to calculate the relevant volumes. Figure 6 shows the state-flow diagram for the calibration automaton: The level glass is filled to and beyond the top sensor by opening the valve and stopping the pump. When the liquid level is sufficiently above the top sensor (which is determined by a timer of a few seconds), the valve closes and the pump is started at a given rpm corresponding to input used in (i), thus starting the emptying of the level glass. When the liquid level passes through the top sensor, i.e. enters "Level 5", a timer starts. For each new level entered, the time is noted. When the liquid level reaches "Level 0", the pump is stopped and the valve opens, allowing the liquid to fill the level glass again. This experiment is repeated a given number of times in order to also get statistical information. Once the last experiment is completed, the automaton algorithm switches back to control mode.

The volume of "Level n" is calculated as:

\[
V(n) = \dot{V}(u) \ast (t_n(u) - t_{n-1}(u)) \quad (2)
\]

The results are used by the control algorithm. The last calibration procedure uses the volume from top sensor to bottom sensor, \( \sum v(i) \).

(iii) **Find correlation between pump inputs and flow rates for entire input span**, using the equation:

\[
\dot{V}(u) = \frac{V}{t_5(u) - t_0(u)} \quad (3)
\]

\( t_5(u) - t_0(u) \) is the time it takes to the level to drop from "Level 5" to "Level 0", corresponding to the volume between the top and bottom level sensor. This is the same equation as the first calibration procedure, but since the volume of the level glass is now known, is can be used as fixed volume container. The procedure is shown in Figure 7. The level glass is filled and emptied, similar to the procedure explained in (ii), but the algorithm cycles through an array of specified pump speeds instead of using the same speed for all the calibration cycles. It also does not note the time when the liquid level enters the intermediate levels, but the time is taken only when entering "Level 5" and "Level 0".
5. PRACTICALITIES

5.1 Static volume

Operating at steady flow, the controller keeps the liquid within “Level 3”, between the two middle sensors. This effectively traps the liquid in the level glass for an extended periods of time. If the properties of the fluid in the line change with time, then the liquid in the glass will be different. As the flow decreases in the line, fluid from the level glass will come back into the line thus changing temporarily the properties of the pumped fluid. In case of our distillation column, this can potentially affect the composition in the column. Whilst the volume in the level glass is small this behaviour should be kept in mind and if it is potentially disturbing the operation of the plant, the control automaton must be modified so as to exchange the fluid in the level glass periodically by taking the necessary control actions. In our current application, the level glass holds \( \approx 50 \text{ ml} \) maximum, which under normal operation will not cause any problems.

5.2 Handling overflow

The level glass may overflow under certain operating conditions, for example if the line flow exceeds the maximal pump ratio. It may also be caused by a malfunction of a sensor or the pump or some air bubbles. The likelihood of overflow can be reduced by having a large volume reservoir above the top sensor and having a time event for “Level 6” that stops or reduces the flow into the level glass. This has the potential downside of larger static volume, which was discussed in the previous subsection. There are multiple ways of handling overflow situations. There is no single optimal solution, and one should choose the one most fitting to the specific application. The following are some suggestions:

- Overflow can be directed by a hose into the waste reservoir. This has the added benefit of preventing overpressure.
- Overflow can be redirected into another stream.
- A one-way output valve could be used for letting air pass freely through without letting liquid pass through the top. The pipe will in this case lose the ability to overflow, creating the possibility of a pressure build-up.

5.3 Maintenance

All parts of the flow control set-up are robust, have relatively high standing times, and are easily replaceable if so needed. The liquid level sensors are low price and are simply screwed into the side of the level glass. The level glass is made from one solid piece of see-through plastic material, and is cheap both in material and manufacturing.

5.4 Regular calibration

Peristaltic pumps have a tendency to deform the hose over time, thereby altering the input/flowrate correlation. It is recommended to regularly check the hose for damage and wear. Since the calibration procedure is completely automated, it can be scheduled to regularly be repeated. Deviations may be taken as a sign for the ageing of the hose triggering a replacement. This also provides the control algorithm regularly with updated flow rate values. The calibration can be run manually or automatically, without stopping the overall process, given that the system allows for some accumulation of mass upstream to the valve. For a distillation set-up, accumulation is allowed in the tubing following the condenser or even in the condenser itself. Accumulation depends on how slowly the level glass is emptied, i.e. the minimum pump input that is being tested.

6. EXPERIMENTAL RESULTS

A distillation column is fitted with the discussed flow control scheme, as shown in Figure 8.
process interface that connects directly to the RS 485 instrumentation bus. The level glass is approx 15 cm high and holds \( \approx 50 \text{ ml} \) between the top and bottom sensor.

A calibration program is realised as a separate program, making it possible to run the calibration independent of the control program. The program is also used to determine volumes between the sensors in the level glass.

### 6.1 Calibration results

Figure 9 shows the correlation between pump rpm, being the input to the pump, and the volumetric flow rate. The graph is linear up to \( \approx 90 \text{ rpm} \) at which point linearity is lost. We found that this phenomenon is reproducible. The detailed cause is not known, but it can likely be attributed to some interaction between deformation of the hose and the workings of the peristaltic pump. Under normal operations, the pump does not exceed 90 rpm. Only under extreme conditions and when the system enters the maximum level domain, the pump is operating at high speed up to a maximum 150 rpm.

![Fig. 9. line: Results from calibration procedure 3. Red line: linear regression.](image)

The use of a linear correlation is easy and convenient, but can be inaccurate when getting into the non-linear region. If so necessary one may consider fitting a higher-order polynomial that is capable of capturing the irregularity feature reasonably accurate. Alternatively one may consider fitting piecewise either with linear or non-linear functions.

### 6.2 Dynamic results

A limited number of dynamic experiments were done, mainly to inspect if changes in the speed of rotation has a significant effect on the estimated flow rate compared to the actual flow rate. The experiments were done using an integral volume measurement on the outflow changing the conditions. The speed of rotation was changed repeatedly using different patterns. This provided some insight into the dependency on the dynamics, which was found surprisingly minimal. More precise information would require a precise dynamic volume or mass flow measurement, which was not available at the time.

Dynamic control experiments showed excellent results both off-line as well as implemented on the distillation.

Certainly, a combination of flow measurement and PID controller could be tuned to have a smaller settling time, for example, but at the costs of larger variations and, not at least, having to implement a flow measurement. The here-installed controller is acting in the time-frame dictated by the volume in the measurement device. Adjusting the volume changes the dynamic behaviour, besides the two main parameters in the DEDS controller, which is the time to change the flow rate and the rate with which it is changed.

### CONCLUSION

The event-based, discretised-state flow control system consists of a volume transporter, a cylindrical vertical glass with six discrete level liquid sensors, and a computer interface. The difference between inflow and outflow is estimated from the time taken for a change to occur in the liquid height in the level glass detected by the discrete level sensors. The control algorithm adjusts the pump speed and thus the pumping ratio accordingly. The fully automated calibration procedure interferes minimally with the operation of the assembly and can thus be periodically repeated, thereby maintaining a high accuracy of the estimated flow rate through regular re-calibration.

The self-calibrating flow rate control structure is low-cost, robust and easily implemented and maintained. The realisation of the automaton algorithm is extremely simple and consists of a recursive two-table look-up procedure. The first table provides the next state given the current state and current event whilst the second gives the set of actions given the current state and the current event. It thus requires only memory for the automata tables and the few lines of code. The assembly can be used to manually or automatically calibrate both on and off-line. Its use has been demonstrated on a set of lab-scale distillation columns, where it acts as reflux measurement and pump system.

In addition, if one does not require flow information, the metering pump can be replaced by a generic cheap pump and calibration can be abandoned.

### REFERENCES

