Closed-Loop Multi-Input/Output System Identification amidst Noise and Unmeasured Disturbances using Ultra-Short Duration Data based on the “SLIC-ID (Step-Less Closed-Loop) Identification” Algorithm

Steve Howes and Janarde LePore
*PiControl Solutions LLC, Houston, TX, USA*

ABSTRACT
System identification is an important area in process control and statistics. Identification of transfer function parameters provides significant benefits for research and in the design of closed-loop control systems. Despite over six decades of research and applications of system identification, only a handful of methods are currently available. Most current methods are somewhat complex and their results often uncertain or inconclusive when processing industrial data superimposed with noise and complex unmeasured disturbances. This paper illustrates the successful identification of transfer function parameters for multi-input/output systems amidst disturbance, noise with ultra-short duration data. This new method can easily be used in the control room environments, academic colleges and for research.
KEYWORDS
Closed-loop system identification, transfer function identification, multi-input dynamic identification, control system design.

1. Evolution of System Identification

Since the mid-1950s, only a handful of system identification algorithms have been invented and put to practical use. The most widely known include Box and Jenkins (1, 2), ARMAX (auto regressive moving average models with exogenous inputs) (3, 4) and step-response vector coefficient models (5). These methods require extensive skill and training in order to use them correctly for the design of control systems. Industrial data is often superimposed with random noise, complex unmeasured disturbances and nonlinearities. These menaces make the system identification process more challenging and result in potentially uncertain or inaccurate results. In other cases, the need for intrusive tests, longer duration tests and tests calling for bigger than possible bumps in the process make the system identification process difficult, delayed or even impossible. Some of the existing methods work on SISO (single-input/single-output) (6) processes only. Other MIMO (multiple-input/multiple-output) (6) methods are rather complex and require extensive training, time and experience in order to work correctly. Several decades after the original invention of the Box and Jenkins system identification method, and despite the knowledge of other system identification methods, a very small number of control engineers and other personnel currently use system identification tools on a regular basis. Academic schools and colleges typically do not cover system identification in undergraduate level courses as this is perceived to be an advanced, graduate level topic. A majority of the time inside industrial control rooms- PID tuning parameters, feedforward parameters and many APC-related control
parameters are purely guessed or estimated using the old-fashioned trial-and-error methods. Furthermore, there is an excessive focus on academic topics like Laplace transforms (7) and frequency domain analysis (8). Practical tools and methods catering to the control room environment are not available easily and even if they are available, they are complex, expensive, bulky, and often produce uncertain results.

2. **SLIC-ID (Step-Less Closed-Loop) Identification**

   A brand-new method called “**SLIC-ID (Step-Less Closed-Loop) Identification**” aims at both SISO and small to medium scale MIMO problems. DSI performs calculations internally in the Laplace (S) and the discrete (Z) domains (9) but all user-interface is presented in the more easy-to-understand time domain. DSI works remarkably well even with very short data sets (typically one-half to one-tenth of the data set required by other known methods). DSI does not need open-loop step tests in manual mode; it can process complete closed-loop data without steps on the setpoint in auto mode. DSI can use data in complete cascade mode, with setpoint changes made from a multivariable supervisory advanced control scheme. Another strength of DSI is in its relatively low sensitivity to large levels of random noise (white noise) in the system. While other techniques can generate errors and uncertainties on data superimposed with significant unmeasured disturbances and drifts, DSI is able to isolate both the noise and disturbances and produce accurate system identification results.

3. **Characterization of Dynamic Systems**

   System identification can be defined as determining the dynamic relationship between a controlled variable and a manipulated variable. A controlled variable (abbreviated as CV) is the
variable that must be controlled at some target, often called the setpoint. The manipulated variable (abbreviated as MV) is the variable that is manipulated (adjusted) in order to move the CV near its target. The CV is the dependent variable and the MV is the independent variable. The relationship between a MV and CV can be characterized using a transfer function. See Fig. 1.

![Transfer Function Diagram]

Fig. 1 Input and Output Signals in a Transfer Function

### 3.1 Industrial Transfer Functions

In most real-life industrial processes, the time factor is involved. In other words, if an independent variable is stepped (bumped), the dependent variable does not instantaneously reach a new value, but takes a finite amount of time to start changing and then eventually reach a new steady state. This relationship between an independent variable and the dependent variable can be characterized using a transfer function, as shown in Fig. 2. Almost all real-life transfer functions can be characterized by four types of transfer functions as shown in Fig. 3. Transfer functions shown in Fig. 3a to 3d are very common in any manufacturing process. The transfer function shown in Fig. 3e is commonly encountered on exothermic chemical process reactions, particularly those for manufacturing polymers. Almost 95-98% of all industrial process dynamics can be defined using these five types of process transfer functions shown in Fig. 3a to
3e. Fig. 4 shows less common types of industrial transfer functions. Fig. 4a shows a relatively small initial inverse response. Fig. 4b shows a significant inverse response followed by complex dynamics. Fig. 4c shows rather rare and abnormally complex dynamics that are better off characterized using step response coefficient dynamic models (5) instead of transfer function models.

Based on analysis of industrial processes, it is known that the transfer functions shown in Fig. 3 (a-e) and 4a account for about 98% of all industrial process dynamics.

Modern plants are often very highly interactive because of heat balance and mass balance integration which maximizes thermodynamic efficiencies. Modern industrial processes are often run close to constraint limits and shutdown limits for maximizing production rates and operating
efficiencies. These modern operating modes often make traditional step tests (on the setpoints or outputs of manipulated variables) required for system identification difficult.

Fig. 3. Various types of typical industrial transfer functions

Application of current system identification methods like Box-Jenkins, ARMAX and step response coefficient models used by research and academic professionals has been somewhat too complex and cumbersome for the industrial control room environments. Only a very small number of control-room personnel in manufacturing plants either have skills, time or access to simple and robust system identification tools and technology. Knowledge of system identification is very useful in the design of control system in manufacturing processes and in statistical research. Simpler technology and less complex software product aimed at reading process data from a DCS, PLC or a computer and identifying transfer functions would be very valuable in the current modern control room environment. This could also improve the quality and practicality of the process control semester education at the graduate, under-graduate and community-college level.
3.2 Uniqueness and Power of SLIC-ID Algorithm

This paper illustrates the results from a brand-new invention of an algorithm that can identify transfer function dynamics far more quickly and easily compared to current methods. The new algorithm named “SLIC-ID (Step-Less Closed-Loop) Identification” has the following functions and capabilities:

- Can be used on multiple-input and multiple-output systems (not restricted to single-input and single-output).
- Requires much shorter duration data (about one-half to one-tenth) compared to current methods.
- Can use closed-loop, open-loop data or a mixture of both. Closed-loop data are data with the control loop in closed-loop (automatic or cascade) mode. Unlike existing technologies, the closed-loop data need not contain clean steps on the setpoint of the

Fig. 4 Additional varieties of industrial transfer functions
controller(s) but, could be ramping or any complex closed-loop setpoint trajectory imposed by the existing supervisory advanced control system.

- Can identify process dead time (dead time does not need to be specified by the user).
- Relatively less sensitive to fast/high frequency noise or random noise compared to current methods.
- Possesses the capability of isolating and determining unmeasured disturbances and drifts.
- Data does not need to be stationary.
- Data pre-conditioning and pre-processing as required by other methods are not required.
- Though internal calculations use the Laplace (s) domain and the discrete (z) domain, all user-interface is presented in the simpler time domain. The simplicity makes the approach usable by technicians and engineers alike. It can be also used in undergraduate semester to teach system identification as a new major topic.
- The process of learning and using the algorithm and applying to control-room industrial problems or in class-room semester projects takes just a few hours - even for a new student, technician or a novice process control engineer.

The new algorithm was tested and proven using both known transfer functions based on simulations and also based on real industrial process data.

### 3.3 Practical Illustration

Fig. 5 shows a triple cascade PID control scheme used to demonstrate the identification of closed-loop transfer functions using the SLIC-ID method. The cascade PID is an AC (online analyzer controller). The slave PID is a TC (temperature controller). The slave PID TC
dynamics include a FC (flow controller). The slave transfer function is between the FC’s setpoint and the slave’s temperature PV signal. The cascade PID is active (in automatic mode). The slave PID is also active (in cascade mode). Most current closed-loop system identification research defines closed-loop identification as identification of dynamics amidst step changes on the setpoint of a controller in automatic (active) mode. The controller could be a PID, MPC (model predictive controller), fuzzy logic, and rule-based or any other closed-loop controllers. The system could be single-input/single-output (SISO), multiple-input/single-output (MISO) or multiple-input/multiple-output (MIMO).

Fig. 5 Configuration for system identification using known transfer functions
### Table I- Known values of transfer function parameters used in the illustrations

<table>
<thead>
<tr>
<th>Transfer Function</th>
<th>Delay (minutes)</th>
<th>Process Gain</th>
<th>Time Constant (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
<td>8.0</td>
<td>6.5</td>
<td>25.0</td>
</tr>
<tr>
<td>Disturbance</td>
<td>0.0</td>
<td>-1.0</td>
<td>15.0</td>
</tr>
</tbody>
</table>

One of the notable achievements of the SLIC-ID method is that it does not require any step changes on the setpoint in automatic mode. In Fig. 5, the system identification envelope comprises of four inputs:

- The first input is the signal labeled MV1 in Fig. 5, the slave PID’s OP. This signal has absolutely no step changes as this is the OP from the slave PID in cascade mode. The cascade PID in auto mode is manipulating the slave PID’s SP and based on the slave and cascade PID’s controller tuning parameters, the MV1 input signal is a complex signal that does not possess any step changes at all. The MV1 signal feeds the slave PID controller loop’s transfer function.

- The second input is the signal labeled DV1 which comprises of a superimposed pulse and ramp signal that feeds a disturbance transfer function.

- The third input, labeled DV2 is a purely random signal (random noise) which, in varying degrees is very common in most process signals.

- The fourth input, labeled DV3 comprises of a disturbance signal comprising of both fast disturbances and slow drift superimposed to look similar to disturbances encountered in many manufacturing processes.
The outputs from these four transfer functions are then added to generate the composite signal labeled CV in Fig. 5. The known transfer function parameters for the slave transfer function and the disturbance transfer function used in the process control schematic are shown in Table I.

3.4 Closed-Loop System Identification with Two Inputs

Fig. 6 shows the successful transfer function identification of a closed-loop data set. The cascade and slave PID are both active (cascade PID is in auto mode and the slave PID is in cascade mode). The measured disturbance (DV1) signal and the high frequency random noise signal (DV2) as shown in Fig. 5 are both active but the unmeasured disturbance signal (DV3) is not present (DV3 signal in this case is zero). The CV (output) signal shown in Fig. 6 (the jagged/spiky trend line) is the CV signal marked in Fig. 5. The second trend line in the top window in Fig. 6 (the non-spiky trend line) is the transfer function model prediction based on the identified transfer functions based on the SLIC-ID algorithm. The transfer function parameters identified by the SLIC-ID algorithm are shown in Table II. Notice the close match between the true (actual) transfer function parameters shown in Fig. 5 and the identified parameters shown in Fig. 6.
Fig. 6- Closed-loop transfer function identification with two inputs

<table>
<thead>
<tr>
<th>Transfer Function</th>
<th>Delay (minutes)</th>
<th>Process Gain</th>
<th>Time Constant (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
<td>8.47</td>
<td>6.73</td>
<td>25.0</td>
</tr>
<tr>
<td>Disturbance</td>
<td>0.63</td>
<td>-1.04</td>
<td>16.8</td>
</tr>
</tbody>
</table>

Table II. Transfer Functions Identified by DSI Algorithm with Two Measured Inputs

### 3.5 Closed-Loop System Identification with Two Inputs and Unmeasured Disturbance

Fig. 7 shows the successful determination of transfer function parameters also for a closed-loop case. In this case, the slave and cascade PID are both active. The MV1 moves in closed-loop mode (manipulated by the slave PID) in order to maintain the CV at its setpoint. DV1 (measured disturbance) and DV2 (fast random noise) are both active. DV3 is also active and impacts the CV. DV3 is deliberately treated as an unknown disturbance in order to challenge the capability of the SLIC-ID algorithm. DV3 impacts the CV and forces a mismatch in the transfer
function model prediction. Notice the significant deviation in the CV (output) and the Transfer Function Model trends (top trend plot in Fig. 7). Despite this significant deliberate injection of the unmeasured disturbance signal (DV3), the transfer function parameters identified by the SLIC-ID algorithm as shown in Table III, closely match the true transfer function parameters shown in Table I. This illustrates the ability of the SLIC-ID algorithm to identify transfer functions using short duration closed-loop data with multiple inputs and with both measured and unmeasured disturbances.

![Transfer Function Model](image)

Fig. 7- Closed-loop transfer function identification with two inputs and amidst strong unmeasured disturbances

<table>
<thead>
<tr>
<th>Transfer Function</th>
<th>Delay (minutes)</th>
<th>Process Gain</th>
<th>Time Constant (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
<td>8.41</td>
<td>6.45</td>
<td>21.2</td>
</tr>
<tr>
<td>Disturbance</td>
<td>0.1</td>
<td>-1.11</td>
<td>18.6</td>
</tr>
</tbody>
</table>
Table III. Transfer Functions Identified by DSI Algorithm with Two Measured Inputs and Unmeasured Disturbances

<table>
<thead>
<tr>
<th>Transfer Function</th>
<th>Delay (minutes)</th>
<th>Process Gain</th>
<th>Time Constant (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
<td>8.19</td>
<td>6.74</td>
<td>25.2</td>
</tr>
<tr>
<td>Disturbance</td>
<td>0.0</td>
<td>-1.04</td>
<td>17.0</td>
</tr>
</tbody>
</table>

Table IV. Transfer Functions Identified by DSI Algorithm with Multiple Measured Inputs
3.6 Closed-Loop System Identification with Multiple Measured Inputs

As a final illustration, Fig. 8 shows the closed-loop determination of transfer function parameters for both the slave and disturbance transfer function parameters by including DV3 as a measured input in addition to all other inputs also as measured inputs (MV1, DV1 and DV2). Now, since DV3 is also a measured input, the match between the CV (output) and the Transfer Function Model are excellent (the CV trend and the transfer function model trends are very nicely superimposed with very little residual error).

The above cases of system identification were performed using closed-loop data generated from a simulation with known transfer function parameters and known disturbances. The close match between the identified transfer function parameters and those used to simulate the closed-loop data proves the success of the SLIC-ID algorithm. The SLIC-ID algorithm has been applied to many closed-loop data sets from several industrial and manufacturing processes in chemical, petrochemical, oil-refining, gas, electric-power, solar, metallurgical and related industries. Two more case studies showing the successful application of the SLIC-ID algorithm using closed-loop data are described below.

3.7 Closed-Loop System Identification with Discontinuity

Fig. 9 shows a temperature controller (TC) in automatic mode. The MV1 (Input 1) trend in the bottom window is the output from the TC. The CV (output) trend in the top window is the process value (PV) of the TC. The controller setpoint is bumped automatically by the sequence. The data is completely closed-loop and there are discontinuities in the data set caused by time
periods when the TC is in manual and offline. The discontinuities can pose serious challenges to other currently practiced system identification methods, if the data set is not sliced or pre-conditioned. The discontinuities do not affect the SLIC-ID algorithm. In fact the discontinuities and nonlinearities (if any) are identified and isolated by the SLIC-ID algorithm while determining the true transfer function process dynamics.

The identified transfer function parameters using this completely closed-loop data are shown in Table V.

![Fig. 9- Closed-loop transfer function identification on a real industrial temperature controller (TC)](image)

<table>
<thead>
<tr>
<th>Transfer Function</th>
<th>Delay (minutes)</th>
<th>Process Gain</th>
<th>Time Constant (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
<td>1.26</td>
<td>1.63</td>
<td>27.6</td>
</tr>
</tbody>
</table>

Table V. Transfer Function Identified by DSI Algorithm with Closed-Loop Data with No Step Tests
3.8 Multi-Input Closed-Loop System Identification with Disturbances and No Step Tests

Fig. 10 shows a three-input system identification case using completely closed-loop data. A commercial MPC (model-predictive controller) was making simultaneous closed-loop setpoint changes on all three MVs (MV1, MV2 and MV3 shown in Fig. 10). There are no step changes on the setpoints and all setpoint changes made by the MPC are completely closed-loop. Second order transfer function parameters have been identified using SLIC-ID algorithm and are shown in Table VI. What is notable about this case is that the total width of the data set used for the closed-loop system identification is only about four times the first-order time constant of the process dynamics. Such ultra-short duration data are inadequate for obtaining successful results from existing system identification methods.

Fig. 10 - Complex multi-input simultaneous closed-loop transfer function identification with ultra-short duration data and with no step tests
Many process dynamics in the real world exhibit various levels of nonlinearities (10). A nonlinear transfer function is one whose parameters vary as a function of operating conditions. Nonlinearities pose challenging problems to existing system identification technologies that are unable to work with short-duration data sets.

4. **Industrial Control System Design and Applications**

The ability to identify multivariable transfer functions using closed-loop data can be used in many industrial applications. This capability can help to design and implement closed-loop control schemes residing wholly in DCS or PLC systems. A few of these applications are listed below:

- PID tuning optimization.
- Design of DCS, PLC or SCADA-based APC (advanced process control) systems, including cascades, feedforwards, model-based control, override constraint control and rule-based control.
- Improving model accuracy and control quality in MPC systems.
• Troubleshooting, debugging and maintenance of control schemes.
• Design and implementation of adaptive control, sequence control and inferential control strategies.
• Converting complex nonlinear control schemes into simpler and more robust sequential control schemes.

5. Summary

This paper illustrates the application of a brand-new, novel method of system identification called SLIC-ID algorithm. It is capable of processing completely closed-loop data without any step tests on the setpoints. Illustrations included both data generated from simulations (with known transfer functions) and also real industrial process data from DCSs. A notable distinguishing achievement of this new method is the ability to identify dynamics using ultra-short duration data sets. The term “ultra-short” in the context of data sets for system identification means data sets that are around one-half to one-tenth of the length of data sets required in current technologies. The ability to successfully work with closed-loop ultra-short data sets allows this new method to isolate nonlinearities in different operating zones. This capability in turn can be used to determine piece-wise nonlinear transfer functions which can then be used to implement robust adaptive closed-loop model-based control schemes inside DCS, PLCs and SCADA systems, something that is not commonly done currently. The new algorithm can be applied to SISO, MISO and MIMO systems. The algorithm works remarkably well even in the presence of superimposed high frequency noise, medium frequency drifts and slow noise. The algorithm is capable of extracting the true process dynamics while isolating the
residuals. This new method does not require data pre-processing, data slicing, data normalization and any of the other various data pre-processing steps required by existing technologies. This algorithm is expected to make applications of APC in industrial manufacturing processes inside a DCS/PLC or SCADA systems far easier, faster and less expensive. It is also expected to simplify the system identification methodology and make it practical and reachable to engineers, technicians and undergraduate semester courses in both four-year and community colleges.

REFERENCE