Control of Dead Time Systems Using Improved Tabu Search

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Abstract: This study introduces an approach to optimize the gains of a PID controller for a class of Time Delay Systems using directed tabu search algorithm. Metaheuristic applications to control theory have been a wide found topic of interest for research. Many research work have been done in choosing the proper choice of the parameters of the PID controller. The PID controller designed using the hybridized Tabu Search scheme guarantees boundedness of the closed loop system behaviour. In this study, attempt has been made to compare results of PID tuning obtained based on directed tabu search algorithm which is made continuous using Nelder Mead Method and adaptive random search algorithm. The algorithm used gives improved performance for an exhaustive class of dead time processes comparatively better than Luyben, Viscoli, Chidambaram, Kookos and Syros.

Key words: Proportional Integral Derivative (PID), directed tabu search, time delay systems, Integral Square Error (ISE), metaheuristic application, India

INTRODUCTION

Recent years have found remarkable research in the area of metaheuristics and its application to engineering and design. Metaheuristic intelligence is applied to the areas of optimal control design using Genetic algorithm, Evolutionary algorithm, Memetic algorithm, Greedy Random Adaptive Search algorithm, Differential Evolution algorithm, Swarm Intelligence, Simulated Annealing, Ant Colony optimization and Tabu Search algorithm. These heuristic techniques are further improvised as part of research by effective optimization and faster convergence achieved by modification of the general algorithm.

Tabu search is a heuristic if used properly can promise efficient near optimal solutions. The original research on Tabu search was carried out by Glover (1989, 1990) and Hu (1992) modified the earliest Tabu search for application to constrained optimization problems. Cviqovic and Klinowski (1995, 2002) extended the Tabu search to functions with variables that may be continuous or discrete.

Battiti and Tecchiolli (1996) proposed the continuous Tabu search namely the Continuous Reactive Tabu Search. Al-Sultan and Al-Fawzan (1997) gave the heuristics and jeeves-local search based modified form of Tabu search algorithm. The Enhanced Continuous Tabu Search given by Chelouah and Siarry (2000) performs diversified approach to locate the most promising solutions among the domain of possible solutions. The search further intensifies to locate the closest possible solution space. Hybrid forms of Tabu search involve combination of Tabu search with Local search techniques.

In this study, the method of directed Tabu search which is hybridized using local search technique of adaptive random search algorithm and Nelder Mead method is used to design PID controller for a class of Time delay systems. The role of the search technique is to stabilize the search especially in the vicinity of local minima.

There are three search procedures employed as part of the directed tabu search namely exploration, diversification and intensification. Exploration is based on Local search method of Nelder-Mead given by Nelder and Mead (1965), Ribeiro and Hansen (2002). Diversification of search to unvisited solution space is achieved using concept of visited regions list given by Hedar and Fukushima (2006).

This multi start approach aims to finally reach a global solution from the initial techniques of exploration and diversification through intensification making the Tabu search an intelligent search algorithm as given by Marti (2002) and Schoen (2002). The neighbourhood moves of the approximate solutions of the Tabu search is achieved using directed search technique adopted by Hedar and Fukushima (2006) through minimization of error for computing the PID controller gains. The resultant solution is used to tune various classes of time delay systems considered in the research by Kookos and

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Syreos (2005). The local search involved as part of exploration shall be modified using adaptive random search using approximate descent direction as given by Hedar and Fukushima (2004). The results of the direct search guided Tabu search PID scheme is compared with various methods proposed by (Tyreus and Luyben, 1992; Luyben, 1996, 2003; Visioli, 2001), (Chidambaram and Sree, 2003; Chidambaram, 1998), (Marlin, 1995) and (Rotstein and Lewin, 1991) based on the response characteristics.

**PID CONTROLLER DESIGN**

The PID controller is given by Eq. 1 as follows:

$$G(s) = K_p + \frac{K_i}{s} + K_c s$$  \hspace{1cm} (1)

Where:

$$K_p = k_p, \quad K_i = \frac{k_i}{T_i}, \quad K_c = k_c T_c$$

Under the case of unconstrained optimization of PID controller the cost function is chosen as ISE index given in Eq. 2:

$$J = \min \sum_{E_2} \left| e^f \right|$$  \hspace{1cm} (2)

Under the case of constrained optimization of PID controller the cost function shall be chosen as ISE index given in Eq. 3:

$$\min_{K_p, K_i, K_c} \frac{J}{f(g(e) < 1, \quad K_p, K_i, K_c \in s}$$  \hspace{1cm} (3)

Where:

$$K_p = \text{Proportional controller gain} \quad K_i = \text{Integral controller gain} \quad K_c = \text{Derivative controller gain}$$

where:

- $K_p$: Proportional controller gain
- $K_i$: Integral controller gain
- $K_c$: Derivative controller gain
- $J$: Integral Square Error (ISE)
- $e$: Error signal
- $T_i$: Integral time constant/Reset time
- $T_d$: Derivative time constant
- $g(e)$: Process output

**DIRECTED SEARCH TABU SEARCH ALGORITHM**

The algorithm given by Hedar and Fukushima (2006) is realized for design of PID controller as follows:

**Initialization:** Choose positive integers $l_{max}$, $l_{max}$, $l_{max}$ and $l_{max}$ as loop parameters. Choose initial solution for the PID gains as $(K_p, K_i, K_c)^0$ and set the Tabu list and Visited regions list to be empty.

**Main loop**

**Exploration and diversification search:** Set the main loop $j = 0$ until $l_{max}$ consecutive iterations fail to seek improved solution or $j > l_{max}$.

**Inner loop**

**Exploration search (Nelder-Mead search/adaptive pattern search):** Set the main loop $k = 0$ until $l_{inner}$ consecutive iterations fail to seek improved solution or $k > l_{inner}$.

**Search directions:** If current value $(K_p, K_i, K_c)^0$ lies in the Semi-Tabu region then construct step size and search directions as follows. Let the trial point $(K_p, K_i, K_c)$ lie in the Semi-TRs and with centres $T_1, ..., T_v$. Compute the Centroid $t_i$ of the semi Tabu region's centres and the maximum distance between $(K_p, K_i, K_c)$ and the centres $i.e.,$

$$t_i = \frac{1}{v} \sum_{i=1}^{v} t_i$$  \hspace{1cm} (4)

$$d_{max} = \max \{ \| [K_p, K_i, K_c] - t_i \| \}$$  \hspace{1cm} (5)

Construct neighbourhood search directions that are parallel to the coordinate axes but point towards the direction $C$ where $C = (K_p, K_i, K_c)$. The neighbourhood trial points are generated along these search directions with a suitable step size $\beta > 0$.

**Neighbourhood search:** Generate $n$ neighbourhood trial points:

$$y_i = [K_p, K_i, K_c] + \Delta d_{i}, i = 1, 2, ..., n$$  \hspace{1cm} (6)

Where:

$$y_i = [K_p, K_i, K_c]$$

Whenever better improved solution is found set the new obtained move as better.

**Local search (Nelder-Mead search/adaptive pattern search):** In case of Nelder-Mead based local search apply Nelder-Mead local search method to obtain improved solution from the obtained $y_i$, and if improved solution is obtained, set $q = 1$. Else, set $q = 0$ and

$$[K_{q+1}, K_{q+1}, K_{q+1}]^0 = \arg \min_{i=1, 2, ..., n} f(y_i)$$  \hspace{1cm} (7)

Which is the ISE index given by:

$$\varphi = \min \sum \left| e^f \right|$$
Where $e$ is the error signal. In case of adaptive pattern search based local search, use Approximate Descent Direction method (ADD) given by (Hedar and Fukushima, 2004) to compute the descent direction $v$ as given by Eq. 8:

$$v = \sum_{i=1}^{n} w_i u_i \tag{8}$$

Where:

$$w_i = -\frac{\Delta f_i}{\Delta f}, \quad i = 1, 2, \ldots, n$$

$$u_i = \frac{(y_i - x) \cdot f(y_i)}{||y_i - x||}, \quad i = 1, 2, \ldots, n$$

$$\Delta f_i = f(y_i) - f(x), \quad i = 1, 2, \ldots, n$$

Choose step sizes $\alpha_i$ and $\alpha_i$ to generate trial points to generate:

$$[K_{p_{i}}, K_{i}, K_{v_{i}}]$$

$$[K_{K_{i}}, K_{d_{i}}, K_{i}] + \alpha \frac{v_i}{||v_i||}, \quad i = 1, 2, \ldots, n$$

Set

$$[K_{p}, K_{d}, K_{v}] = \arg \min \{f(y_i)\} \tag{9}$$

**Parameter update:** Let $(K_{p}, K_{d}, K_{v})$ replace the element with smallest membership value in the Tabu list and re-rank the Tabu list elements using and increment the inner loop count $k = k+1$. Update the Visited Regions Tabu (VRT) List.

**Diversification:** Generate the trial point $(K_{p}, K_{d}, K_{v})$ as follows. Randomly generate trial point $(K_{p}, K_{d}, K_{v})$ in the search domain and compute the search distance:

$$d_{i} = ||[K_p, K_d, K_v] - \xi_i ||/(1 + \Phi(\xi_i)); \quad i = 1, 2, \ldots, M \tag{10}$$

Where, $\xi_i$ is the centre of the visited region. The function $\Phi(\xi) = \gamma (1 - e^{\gamma(\xi-1)})$. $\gamma$ is a random constant. The Visited Region List (VRL) is given by:

$$\text{VRL} = \{\xi_1, \xi_2, \ldots, \xi_M\} \tag{11}$$

Where:

$M$ = The number of all visited regions

$\rho_i$ = The radius of the visited region

If:

$$\min \leq i \leq M \frac{d_i}{\xi_i} \geq 1$$

then accept $(K_{p}, K_{d}, K_{v})$ otherwise again repeat the diversification starting from generating trial point $(K_{p}, K_{d}, K_{v})$ in the search domain and compute the search distance. Update the Tabu list and the Visited Region Tabu. Increment the outer loop count $j = j+1$.

**Intensification search:** Start with another local search method namely the Kelly’s modification of the Nelder Mead method to improve the present obtained solution of $(K_{p}, K_{d}, K_{v})$.

**CASE STUDIES**

The response for unit step set point change was simulated for the case studies having different time-delay/ Lag ratios. The computation was performed using a Core 2 duo processor based, 2 Ghz/3 gigabyte computer with computational time in the range same as that of Kookos and Syrcos (2005) having values in the order of few seconds to estimate the optimal values of the controller gains. The controller configuration used in most of the simulation was Smith PID configuration given by Chidambaram and Sree (2003) except for some cases.

**Control of Integrating Processes with Time Delay (IPTD)**

**Example 1:** Integrating processes with time delay are most commonly modeled among industrial processes. For example, processes involving level exhibit the integrating behavior. They are found in distillation columns, boiler controls and several industrial applications. The transfer function of an integrating process with time delay is given by Eq. 13 as:

$$g(s) = \frac{k_p e^{-\tau s}}{s} \tag{12}$$

The PID controller tunings for this model have been given by a number of researchers. With reference to initial research done on Integrating systems with delay by Kookos and Syrcos (2005), Chidambaram and Sree (2003), Chidambaram (1998), Tyreus and Luyben (1992) and Luyben (1996), consider the industrial example of level control in a distillation column having the open loop transfer function as in Eq. 14 with parameters $k_p = 0.0506$ and $k_d = 6$ sec.

$$g(s) = \frac{0.0506 e^{-6s}}{s} \tag{13}$$

The directed tabu search optimization was carried out for minimization of the ISE and the tuning parameters achieved by the directed tabu search based controller using Smith PID given by Chidambaram and Sree (2003) configuration is compared with other methods as shown in Table 1. Figure 1 compares the closed loop performance.
of the directed tabu search based Smith PID controller and the tunings proposed by Tyreus and Luyben (1992), Visioli (2001), Chidambaram (1998), and Chidambaram and Sree (2003). In Fig. 1, the unit step set point response for the directed tabu search based controller configuration results in a more or less dead beat response compared to the other schemes. The comparison of the tuning factors and the value of the performance index, ISE, is shown in Table 1.

**Example 2**: Consider the second example of level control process given by Chen and Fruehau referred by Kookos and Syrcos (2005) in a distillation column having the open loop transfer function as given in Eq. 15:

\[ g(s) = \frac{0.2}{s}e^{-7.4s} \quad (15) \]

<table>
<thead>
<tr>
<th>Method</th>
<th>( K_c )</th>
<th>( K_i )</th>
<th>( K_d )</th>
<th>ISE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luyben (1995)</td>
<td>2.563</td>
<td>0.0455</td>
<td>9.130</td>
<td>8.2763</td>
</tr>
<tr>
<td>Visioli (2001)</td>
<td>4.5</td>
<td>0.5033</td>
<td>15.93</td>
<td>14.1482</td>
</tr>
<tr>
<td>Chidambaram (1998)</td>
<td>4.066</td>
<td>0.1304</td>
<td>10.979</td>
<td>9.1920</td>
</tr>
<tr>
<td>Chidambaram and Sree (2003)</td>
<td>DTS Smith PID</td>
<td>100.5738</td>
<td>107.2608</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18.0802</td>
<td>3.7089</td>
<td>6.2874</td>
</tr>
</tbody>
</table>

Fig. 1: Closed loop response of the closed loop IPDT system example 1

Fig. 2: Unit set point response of the closed loop IPDT system-example 1
Control of Integrating Process with Time Delay and Inverse Response (IPTD and IV): Consider the general form of transfer function of an integrating process with time delay and inverse response given in Eq. 17 having a right half plane zero at $\frac{1}{\tau_s}$ delay d and a pole at zero (Table 4).

$$g(s) = k_p \frac{1 - \tau_s s}{s \left( \tau_s s + 1 \right)} e^{-\omega_d t}$$ (17)

Kookos and Syrcos (2005) and Luyben (1996) have proposed PID controller setting for a integrating process with time delay and inverse response. Consider an IPTD and IV system having transfer function of form given in Eq. 18:

$$g(s) = 0.457 \frac{1 - 0.418 s}{s(0.6 s + 1)^{0.11}}$$ (18)

Figure 4 compares the closed loop performance of the DTS based PID/Smith PID and the tunings proposed by Kookos and Syrcos (2005). The DTS based PID/Smith PID shows a comparatively similar response to that of Kookos with closeness in performance.

Control of First Order Processes with large Time Delay (FOPTD): The transfer function of a first order plus time delay process is given in Eq. 19 where the value of $\theta$ is 1 and even larger. The DTS based PID/Smith PID was applied to a process having $k_p = 1$ and $\theta = 2, 3, 4$ and 5.

$$g(s) = \frac{k_p e^{-\theta s}}{s + 1}$$ (19)

Figure 5 and 6 compare the closed loop performance of the proposed PID controller scheme based on DTS algorithm and the tunings proposed by Kookos and Syrcos (2005).

The response of the proposed PID controller scheme is found to be comparatively equal in performance to the settings given by Kookos and Syrcos (2005) for various values of dead-time/Lag ratios. Table 5 compares the performance index versus the Tuning parameters against the method of mathematical programming based PID controller given by Kookos and Syrcos (2005) and the Direct Search based Tabu search.
Table 5: Comparison of the tuning parameters for unit step set point response of FOPTD system-case study 4.4

<table>
<thead>
<tr>
<th>θ</th>
<th>Kp</th>
<th>Kc</th>
<th>Ke</th>
<th>ISE (μ)</th>
<th>Kp</th>
<th>Kc</th>
<th>Ke</th>
<th>ISE (μ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.8447</td>
<td>0.6303</td>
<td>0.8466</td>
<td>2.4097</td>
<td>0.8403</td>
<td>0.4469</td>
<td>0.4469</td>
<td>2.3841</td>
</tr>
<tr>
<td>3</td>
<td>0.7025</td>
<td>0.3785</td>
<td>0.8970</td>
<td>3.4820</td>
<td>0.7006</td>
<td>0.2998</td>
<td>0.2998</td>
<td>3.6944</td>
</tr>
<tr>
<td>4</td>
<td>0.6385</td>
<td>0.2642</td>
<td>0.9118</td>
<td>4.5451</td>
<td>0.6407</td>
<td>0.2226</td>
<td>0.2226</td>
<td>4.9494</td>
</tr>
<tr>
<td>5</td>
<td>0.6031</td>
<td>0.2013</td>
<td>0.9193</td>
<td>5.6122</td>
<td>0.6072</td>
<td>0.1757</td>
<td>0.1757</td>
<td>5.5394</td>
</tr>
</tbody>
</table>

Fig. 3: Unit step set point response of an unstable system with delay-case study 4.2

Fig. 4: Unit step set point response of the integrating process with inverse response and time delay-case study 4.4

method. It is observed that direct search Tabu based PID scheme exhibits more or less the same response characteristics and closed loop behaviour as the (Kookos and Syrcos, 2005) scheme. The ISE index is nearly close for all the cases of the delay values considered.
Fig. 5: Unit step set point response of the FOPTD system based on tunings proposed by Kookos and Syrcos (2005) case study 4.5

Fig. 6: Unit step set point response of the FOPTD system based on directed tabu search algorithm-case study 4.5

CONCLUSION

In this study, a novel meta heuristic based PID controller is designed for a class of time delay systems using hybridized Tabu search. The usefulness of the designed controller scheme is compared with different case studies involving delays.

The results show that the DTS based PID/Smith PID scheme offers good sensitivity for the closed loop performance with reduced performance index and the results are comparatively similar and even easier than the techniques proposed by Kookos and Syrcos (2005), Hedar and Fukushima (2004), Tyreus and Luyben (1992), Luyben (1996, 2001, 2003), Visioli (2001),
Encouragingly, the settling time and integral square error for the PID controller coefficients selected by DTS are seemingly the best compared to the choices made by other schemes for the case studies considered. Such evaluation helps to determine the value of the new intelligent control methods and provide the process engineer with general guidelines on how to apply them to more complex real world applications. The designed control scheme shall further be applied to MIMO systems and improved for even better performance.

REFERENCES


