2009 American Control Conference
Hyatt Regency Riverfront, St. Louis, MO, USA
June 10-12, 2009

Throttle Actuator Swapping Modularity Design for Idle Speed Control

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Abstract — **Swapping modularity refers to the use of common units to create product variants. As companies strive to rationalize engineering design, manufacturing and maintain processes, modularity is becoming a priority. Component swapping modularity in control systems can be achieved by utilizing "smart" components which can perform control actions within the module, and bidirectional network communication. In this paper we analyze an engine speed control system from the perspective of achieving swapping modularity of the throttle actuator. Specifically, we analyze approaches to distribute the optimal controller transfer function between a throttle actuator time constant dependent portion (which is swappable with the actuator) and throttle actuator time constant independent portion (which does not need to be changed when the actuator is swapped). Two distributed controller architectures, with unidirectional and bidirectional communications, are considered.**

I. INTRODUCTION

Swapping modularity occurs when two or more alternative basic components can be paired with the same modular components creating different variants belonging to the same product family [1]. There are many advantages to systems with high component swapping modularity. At present, the competitive market necessitates products with different suppliers, to meet various standards and regulations, and with various levels of performance and cost. Swapping modularity enables customization of an available product without redesign of the whole system. Increasing component swapping modularity can also shorten the engineering time and cost [2].

Control systems with modularly swappable components can be defined as ones where the initial and final configure-tions due to a component change operate at their correspon-ding optimal performance [3]. Fig. 1 shows a control system configuration in which many different types of actuators may be employed. Traditionally, a change in the actuator involves both the actuator and the base controller. By including the actuator related control algorithm into the actuator component, re-work (in terms of control algorithm, software and calibration changes) can be limited to only the actuator subsystem, thereby making an actuator a modularly swappable component, or in a way, a 'plug-n-play' compo-nent. With the proliferation of low cost electronics, many control system components, such as sensors and actuators, can now incorporate on-board computers (i.e. CPU, memory, I/O interface), which enable them to perform component specific control and diagnostic functions and to participate in distributed controller architectures. Bidirec-tional communication in networked control systems (NCSs) among the "smart" actuators and sensors has been shown to improve component swapping modularity. e.g., a case study of a driveshaft control with a DC motor considered in [3].

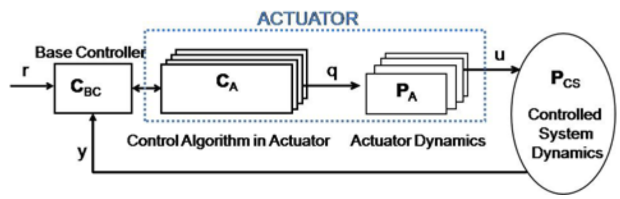

Fig. 1: Control system with modularly swappable actuator component.

In this paper we consider a case study of the controller design for the throttle actuator swapping modularity from the perspective of an automotive engine Idle Speed Control (ISC). The primary objective of the ISC system is to regulate the engine speed to a set-point despite torque disturbances due to accessory loads (e.g., air conditioning, power steering, alternator, etc.) and due to engagement of the transmission. A typical ISC strategy includes a PID control for the air loop, a proportional feedback control for the spark loop, and several feed forward controls realizing compensations for accessory loads, engine temperature, ambient temperature and barometric pressure [4]. Approaches to ISC based on modern control theory have been also considered, including LQ based optimization [5], H_∞ control [6], and l_1 control [7]. Additional ISC improvements are made possible through the preview and feed forward control of known or measurable disturbances, such as, for example, air conditioning or power steering load. A design technique, which includes lead compensation, feed forward and a disturbance observer, is presented for ISC systems with minimal spark reserve levels in [8].

The focus of this paper is to analyze the swapping modularity of the optimal ISC design for the air path of the engine with respect to the throttle actuator time constant. Specifically, we seek to distribute an optimal centralized ISC into a base controller part which does not depend on this time constant and into a time constant-dependent

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actuator controller part. While achieving swapping modularity of a fixed centralized ISC is relatively easy with a low order actuator controller based on pole-zero cancellation, our results indicate that achieving swapping modularity of an optimal ISC, i.e., that performs optimally for each choice of actuator time constant, is comparatively more difficult. In addition, we will demonstrate that the bidirectional communication capability can facilitate the development of controller architectures which provide swapping modularity.

II. PROBLEM FORMULATION

In this section the problem formulation to maximize the actuator swapping modularity in a single input single output (SISO) linear time invariant (LTI) system is discussed. The controller design for swapping modularity includes three steps, the centralized controller design, controller distribution, and swapping modularity optimization. The key idea is to match the distributed controller with the centralized controller, while maximizing the swapping modularity.

First we design the desired centralized controller $C_{\text{des}}(\mathbf{P})$ by any controller design method. Our approach in this paper is based on optimization to provide optimal performance of the system with each different actuator:

$$\min_{\mathbf{C}} J(\mathbf{P},\mathbf{C})$$

subject to

$$\mathbf{g}(\mathbf{P},\mathbf{C}) \le \boldsymbol{\sigma}$$

where the elements of the vector $\mathbf{P}$ are parameters of the actuator; the elements of the vector $\mathbf{C}$ are the undetermined coefficients of the centralized controller, which are variables of the optimization problem; J is a control-oriented objective function reflecting performance metrics, such as settling time, control effort, etc; $\mathbf{g}$ represent all the constraints such as an overshoot limit, stability requirements, etc.

Then the centralized controller is distributed into two components, the base controller $\boldsymbol{C}_{\text{BC}}(\mathbf{x}_{\text{BC}})$ and the actuator controller $\boldsymbol{C}_{\text{A}}(\mathbf{x}_{\text{A}})$, where $\boldsymbol{C}_{\text{BC}}(\mathbf{x}_{\text{BC}})$ and $\boldsymbol{C}_{\text{A}}(\mathbf{x}_{\text{A}})$ are controller transfer functions, or transfer function matrices, depending on the number of the inputs and outputs for each component. The vectors $\mathbf{x}_{\text{BC}}$, $\mathbf{x}_{\text{A}}$ represent numerator and denominator polynomial coefficients for these functions respectively. The distributed controller, $C_{\text{dis}}(\mathbf{x}_{\text{BC}}, \mathbf{x}_{\text{A}})$, is a function of $\boldsymbol{C}_{\text{BC}}(\mathbf{x}_{\text{BC}})$ and $\boldsymbol{C}_{\text{A}}(\mathbf{x}_{\text{A}})$.

The swapping modularity optimization process is to maximize the swapping modularity while satisfying $C_{\text{des}}(\mathbf{P}) = C_{\text{dis}}(\mathbf{x}_{\text{BC}}, \mathbf{x}_{\text{A}})$, to ensure that the distributed controller provides the same performance as the centralized controller. The variables in the optimization are the coefficients of the actuator controller $\mathbf{x}_{\text{A}}$, which depend on the parameters of the actuator $\mathbf{P}$, and the coefficients of the base controller $\mathbf{x}_{\text{BC}}$, which are independent of $\mathbf{P}$, since we only change the actuator controller $\boldsymbol{C}_{\text{A}}$ when we swap the actuator.

The swapping modularity of the actuator M_A, is defined in reference to Fig. 2 as follows [3].

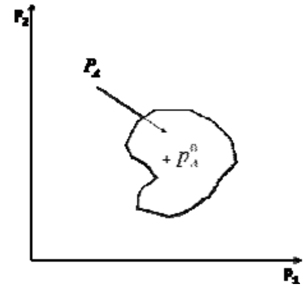

Fig. 2: Illustration of set $\mathbf{P}_{\text{A}}$ for a two parameter system.

We assume, for the purpose of illustration, that the actuator has two parameters P_1 and P_2, which can change depending on the component. Let $\mathbf{P}_{\text{A}}$ be a connected set of the two parameters including the nominal parameter set $\mathbf{p}_{\text{A}}^{0}$, that satisfies $C_{\text{des}}(\mathbf{P}) = C_{\text{dis}}(\mathbf{x}_{\text{BC}}, \mathbf{x}_{\text{A}})$, by only changing the controller in the swappable component given a distribution solution $\mathbf{x}_{\text{dist}}^{0} = \{\mathbf{x}_{\text{BC}}^{0}, \mathbf{x}_{\text{A}}^{0}\}$, i.e. ,

$$\mathbf{P}_A = \{\mathbf{p}_A \in \mathbf{R}^2 \ \exists \mathbf{x}_A \in [\mathbf{x}_A^l, \mathbf{x}_A^h]\}$$

$$\text{such that } C_{des}(\mathbf{P}) = C_{dis}(\mathbf{x}_{BC}^0, \mathbf{x}_A)$$

where

$$\mathbf{p}_A^0 \in \mathbf{P}_A$$

$$\left\|\mathbf{p}_A^2 - \mathbf{p}_A^1\right\| < \varepsilon \ \ \forall \mathbf{p}_A^1, \mathbf{p}_A^2 \in \mathbf{P}_A$$

And where ε is a very small positive number. Then the swapping modularity M_A is defined as

$$M_A(\mathbf{p}_A{}^0, \mathbf{x}_{BC}, \mathbf{x}_A) = \int_{\mathbf{P}_A} d\mathbf{p}_A \tag{1}$$

corresponds to the area (see Fig. 2) in the parameter space around the nominal value, for which optimal performance can be achieved by changing only the variables $\mathbf{x}_{\text{A}}$ in the actuator controller. That is, for a nominal parameter set of the actuator $\mathbf{p}_{\text{A}}^{0}$, we search for the base controller variables $\mathbf{x}_{\text{BC}}$, and the actuator controller variables $\mathbf{x}_{\text{A}}(\mathbf{P})$, to maximize the swappable parameter set $\mathbf{P}_{\text{A}}$.

III. THROTTLE ACTUATOR SWAPPING MODULARITY DESIGN FOR ISC

A. ISC system description

The throttle actuator is modeled as a first order system with a time constant τ,

$$G_a(s) = \frac{1}{\tau s + 1} \tag{2}$$

An engine model [9] linearized around an idle speed operating point with the nominal throttle position, load torque and engine speed set, respectively, as $u_{th,0} = 3.15$ (deg), $M_L = 31.15$ (Nm) and $N = 800$ (rpm), is used to obtain the transfer function from the deviation in the throttle position (deg) to the deviation in engine speed (rpm) ,

$$G_e(s) = \frac{572.2997}{s^2 + 1.545s + 2.228} e^{-t_d s} \tag{3}$$

The transfer function from the deviation in the disturbance torque (Nm) to the deviation in the engine speed (rpm) is given as,

$$G_l(s) = \frac{-37.04s - 57.22}{s^2 + 1.545s + 2.228} e^{-t_d s} \tag{4}$$

The delay t_d is between the intake stroke of the engine and torque production, and corresponds to 360 degree of crankshaft revolution. Consequently, it is given by

$$t_d = \frac{60}{N} \approx 0.075 \text{ (sec)} \tag{5}$$

A first order Padé approximation of the delay has the form,

$$e^{-t_d s} = \frac{e^{-s\frac{t_d}{2}}}{e^{-s\frac{t_d}{2}}} \approx \frac{1 - \frac{t_d}{2}s}{1 + \frac{t_d}{2}s} = \frac{1 - 0.0375s}{1 + 0.0375s} \tag{6}$$

With this approximation, a pole-zero pair is added to the delay-free transfer function, thereby permitting the resulting plant model to be treated with conventional linear control methods.

B. Centralized controller design

The closed-loop system is shown in Fig. 3,

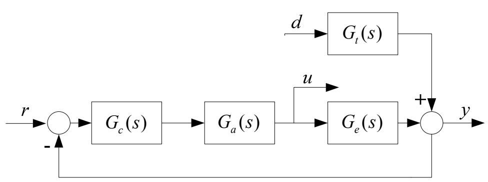

Fig.3: Feedback control system

If we consider an objective of maximizing swapping modularity, an actuator controller which uses pole-zero cancellation to cancel the dynamics of the new actuator and maintain the dynamics of the original/nominal actuator, will provide full swapping modularity (within actuator physical constraints). The shortcoming of such an approach is that we maintain the response of the system designed for the original actuator and do not achieve optimality with respect to the changed actuator. It is, thus, of interest to understand if the optimal centralized controller, which depends on the throttle actuator time constant, can be distributed with only actuator controller dependent on the actuator time constant.

The open loop system, including the throttle actuator, is 4$^{\text{th}}$ order, after including the Padé approximation of the delay. The controller is assumed to be 4$^{\text{th}}$ order, as per equations (7)-(9), and includes an integrator to ensure zero steady state error:

$$G_c(s) = S(s)/R(s) \tag{7}$$

$$R(s) = sR'(s) = s(s^3 + r_2 s^2 + r_1 s + r_0) \tag{8}$$

$$S(s) = s_4 s^4 + s_3 s^3 + s_2 s^2 + s_1 s + s_0 \tag{9}$$

The controller design is formulated as an optimization problem in reference to the response of the system to d = 10 (Nm) load disturbance step and r = 0 (rpm) set-point, and in reference to controller and closed-loop pole locations:

$$\min_{\mathbf{C}} \; t_s(\mathbf{C}, \tau)$$

subject to

$$\begin{aligned}
&\text{g1:} \;\; M_p \le M_{p_\max} \\
&\text{g2:} \;\; u \le u_{\max} \\
&\text{g3:} \;\; u \ge u_{\min} \\
&\text{g4:} \;\; real(root(R')) + e_1 \le 0 \\
&\text{g5:} \;\; real(root(A_{CL})) + e_1 \le 0 \\
&\text{g6:} \;\; mag(root(R')) - e_2 \le 0 \\
&\text{g7:} \;\; mag(root(A_{CL})) - e_2 \le 0
\end{aligned}$$

where t_s denotes the 2% settling time; variables **C** represent the undetermined controller coefficients s_0, s_1, s_2, s_3, s_4, r_0, r_1, r_2; M_P represents the maximum deviation from the idle speed; u is the throttle actuator position. Since the nominal throttle position is $u_{th,0}$=3.15 (deg), we limit u to the range [-2, 12] (deg), and M_p to 10% of the idle speed (800 rpm). Constraints g4, g5 ensure the stability of the controller and the closed loop system, while e_1>0 ensures a stability robustness margin. Constraints g6, g7 ensure that the magnitude of the poles of the controller and the closed loop system are not too large to avoid extending the bandwidth into the region where measurement noise and model uncertainties are dominant.

A parameter study was conducted to find the optimal controller coefficients for each time constant of the throttle actuator in the range [0.01, 0.21]. The coefficients s_0, s_1, s_2, s_3, s_4, r_0, r_1, r_2 can be derived as polynomial functions of τ by curve fitting. With the optimal controllers, the system response to 10 (Nm) load torque disturbance is shown in Fig. 4. The poles and zeros of the optimal controllers for each actuator time constant τ are shown in Fig. 5.

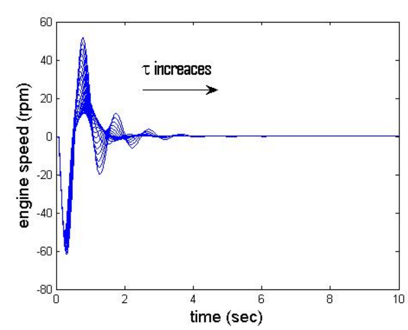

Fig. 4: Optimal system response to a step disturbance torque

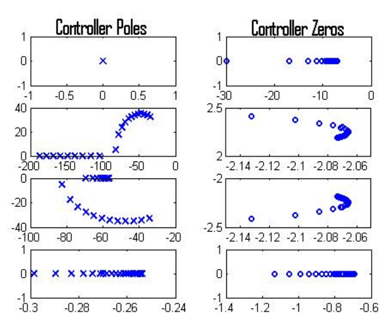

Fig. 5: Optimal controller poles and zeros for τ in [0.01, 0.21]

As can be seen from Fig. 4, the optimal system response changes as the value of the time constant of the throttle actuator decreases. Fig. 5 shows that some of the poles and zeros of the optimal controllers are unchanged for a range of the actuator time constant τ.

If we accept an approximation of the poles and zeros, i.e., if the poles (zeros) for different τ are within the circular region centered at the pole (zero) of the optimal controller corresponding to nominal $\tau = 0.05$, we consider it as unchanged. If we assume the radius of the circular region is 5% of the absolute value of the pole (zero) for the nominal case. We observe the pole p = 0 is unchanged for τ in [0.01, 0.21], the pole p = - 0.27 is unchanged for τ in [0.03, 0.18], and the zeros $z_{1,2}$= - 2.07±2.3i are unchanged for τ in [0.03, 0.21]. Now assume the unchanged poles and zeros to be fixed at the value for the nominal case, the approximate optimal controller poles and zeros are shown in Fig. 6, and the closed loop system performances based on the approximate optimal controllers are shown in Fig. 7.

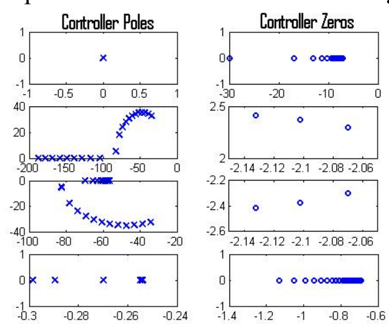

Fig. 6: Approximate optimal controller poles and zeros for τ in [0.01, 0.21]

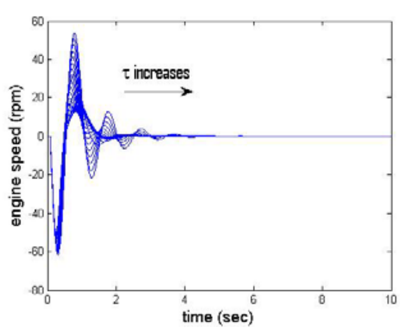

Fig. 7: system response to a step of disturbance torque with approximate controllers

As shown in Fig. 7, the closed loop system responses with the approximate optimal controllers are almost the same as that with the original optimal controllers shown in Fig. 4. Therefore it is acceptable to take the approximate optimal controller for each τ as the desired centralized controllers $C_{des}(\tau)$. The approximation made here will be employed in step 3) bellow (i.e., swapping modularity design), to maximize the actuator swapping modularity.

C. Controller distribution

1) With unidirectional communication

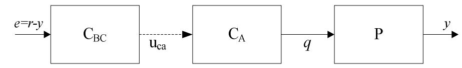

Fig. 8: Controller configuration with unidirectional communication

As shown in Fig. 8, the centralized controller is distributed into the base controller $C_{BC}(\boldsymbol{x}_{BC})$ and the actuator controller $C_A(\boldsymbol{x}_A)$, where C_{BC} and C_A are both SISO transfer functions and can be assumed to be of different orders. For example, if C_{BC} is 3[rd] order and C_A is 1[st] order, then

$$C_{BC} = \frac{x_1 s^3 + x_2 s^2 + x_3 s + x_4}{s^3 + x_5 s^2 + x_6 s + x_7} \tag{11}$$

$$C_A = \frac{x_8 s + x_9}{s + x_{10}} \tag{12}$$

From the perspective of computational efficiency and ease of implementation, it is desirable if the two controllers are of low order. This is especially desirable for the swappable component. Table 1 describes the test cases we used for our analysis. The case B4A1, which can achieve consistent control for each *τ* by pole-zero cancellation, is included here to investigate if one can achieve the full range of swapping modularity while guaranteeing optimal control for each τ .

TABLE 1
UNIDIRECTIONAL CASE DESCRIPTIONS

Case	Case description
B4A0	C_{BC} : 4th order, C_A : gain
B4A1	C_{BC} : 4th order, C_A : 1st order
B3A1	C_{BC} : 3rd order, C_A : 1st order
B2A2	C_{BC} :2nd order, C_A : 2nd order
B1A3	C_{BC} : 1st order, C_A : 3rd order
B0A4	C_{BC} : gain, C_A : 4th order

The overall distributed controller with *e* as the input and *q* as the output is then given by

$$C_{dis}(\mathbf{x}_{BC}, \mathbf{x}_A) = C_{BC} C_A \tag{13}$$

where $\mathbf{x}_{BC}$, $\mathbf{x}_A$ are undetermined coefficients of the distributed controllers C_{BC} and C_A respectively. Only $\mathbf{x}_A$ can depend on actuator parameters.

2) With bidirectional communication

The communication network is shown in Fig. 9.

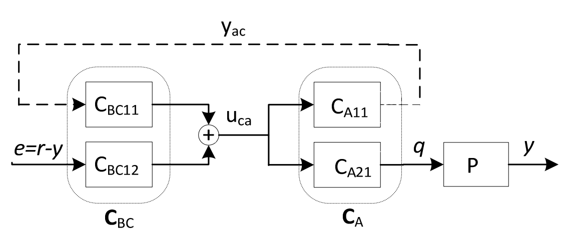

Fig. 9: Distributed controller with bi-directional communication

When bidirectional communication between the base controller and the actuator controller in the “smart” actuator is introduced, $\boldsymbol{C}_{BC}$ and $\boldsymbol{C}_A$ become transfer function matrices,

$$\mathbf{C}_{BC} = \begin{bmatrix} C_{BC11} & C_{BC12} \end{bmatrix} \tag{14}$$

$$\mathbf{C}_{A} = \begin{bmatrix} C_{A11} \\ C_{A21} \end{bmatrix} \tag{15}$$

Table 2 shows some of the test cases to see the effect of the order distribution. From a large set of possible solutions, we have selected the relatively low-order ones that provide good swapping modularity.

TABLE 2
BIDIRECTIONAL CASE DESCRIPTIONS

Case	Case description
B22A00	C_{BC11}: 2nd order, C_{BC12}: 2nd order, C_{A11}: gain, C_{A21}: gain
B12A10	C_{BC11}: 1st order, C_{BC12}: 2nd order, C_{A11}: 1st order, C_{A21}: gain
B21A01	C_{BC11}: 2nd order, C_{BC12}: 1st order, C_{A11}: gain, C_{A21}: 1st order
B02A11	C_{BC11}: gain, C_{BC12}: 2nd order, C_{A11}: 1st order, C_{A21}: 1st order
B20A11	C_{BC11}: 2nd order, C_{BC12}: gain, C_{A11}: 1st order, C_{A21}: 1st order
B11A11	C_{BC11}: 1st order, C_{BC12}: 1st order, C_{A11}: 1st order, C_{A21}: 1st order
B01A21	C_{BC11}: gain, C_{BC12}: 1st order, C_{A11}: 2nd order, C_{A21}: 1st order
B10A21	C_{BC11}: 1st order, C_{BC12}: gain, C_{A11}: 2nd order, C_{A21}: 1st order
B01A12	C_{BC11}: gain, C_{BC12}: 1st order, C_{A11}: 1st order, C_{A21}: 2nd order
B10A21	C_{BC11}: 1st order, C_{BC12}: gain, C_{A11}: 2nd order, C_{A21}: 1st order
B10A12	C_{BC11}: 1st order, C_{BC12}: gain, C_{A11}: 1st order, C_{A21}: 2nd order
B00A22	C_{BC11}: gain, C_{BC12}: gain, C_{A11}: 2nd order, C_{A21}: 2nd order

By analyzing Fig. 9 and using the notation presented in (14)-(15), the equations representing individual signals are

$$u_{ca} = C_{BC11} y_{ac} + C_{BC12} e \tag{16}$$

$$y_{ac} = C_{A11} u_{ca} \tag{17}$$

$$q = C_{A21} u_{ca} \tag{18}$$

Equations (16)-(18) can be rewritten in matrix form as

$$\begin{bmatrix} u_{ca} \\ y_{ac} \end{bmatrix} = \begin{bmatrix} 1 & -C_{BC11} \\ -C_{A11} & 1 \end{bmatrix}^{-1} \begin{bmatrix} C_{BC12} \\ 0 \end{bmatrix} e \tag{19}$$

$$q = \begin{bmatrix} C_{A21} & 0 \end{bmatrix} \begin{bmatrix} u_{ca} \\ y_{ac} \end{bmatrix} \tag{20}$$

Therefore the distributed controller with e as input, q as output is given by

$$C_{dis}(\mathbf{x}_{BC}, \mathbf{x}_A) = \begin{bmatrix} C_{A21} & 0 \end{bmatrix} \begin{bmatrix} 1 & -C_{BC11} \\ -C_{A11} & 1 \end{bmatrix}^{-1} \begin{bmatrix} C_{BC12} \\ 0 \end{bmatrix}$$

$$C_{dis}(\mathbf{x}_{BC}, \mathbf{x}_A) = \frac{C_{A21} C_{BC12}}{1 - C_{BC11} C_{A11}} \tag{21}$$

D. Swapping modularity optimization

Fig. 10 illustrates the set $\mathbf{P}_A$ for the case where the actuator can be represented using only one parameter (i.e. τ). The swapping modularity measure is a real number representing the range of this parameter for which swappable modularity is achievable.

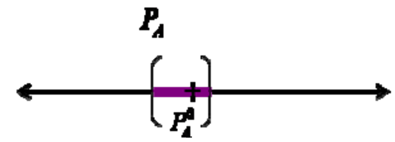

Fig. 10: Illustration of set $\mathbf{P}_A$ for a one parameter system

The optimization problem to maximize swapping modularity is formulated as follows,

$$\max_{\mathbf{x}_{BC}} \left(\max_{\mathbf{x}_A} \tau - \min_{\mathbf{x}_A} \tau \right)$$

subject to:

$h1$: $C_{des}(\tau) = C_{dis}(\mathbf{x}_{BC}, \mathbf{x}_A)$

$g1$: stability of each distributed controller

$g2$: $0.01 \le \tau \le 0.21$

Note that the design variables in this optimization problem are $\mathbf{x}_{BC}$ and $\mathbf{x}_A(\tau)$. This optimization problem was solved numerically using the following steps:

a) Initialize $\mathbf{x}_{BC}$ and $\mathbf{x}_A$

b) Vary τ about the nominal value $\tau_0 = 0.05$, to find the maximum and minimum value of τ that satisfy the constraints $h1$, $g1$ and $g2$, by varying $\mathbf{x}_A$ only, for a fixed $\mathbf{x}_{BC}$. Compute $M_A = \max_{\mathbf{x}_A} \tau - \min_{\mathbf{x}_A} \tau$

c) Repeat step b), choosing different values for $\mathbf{x}_{BC}$; Compute and store $M_A(\mathbf{x}_{BC})$

d) Determine maximum of M_A with respect to tried $\mathbf{x}_{BC}$

To initialize $\mathbf{x}_{BC}$ and $\mathbf{x}_A$, one may solve the equality constraint $h1$ (matching the poles and zeros) for the nominal value of $\tau = \tau_0$. Steps c) and d), to search for different $\mathbf{x}_{BC}$ for $M_A(\mathbf{x}_{BC})$ and then maximize M_A with respect to $\mathbf{x}_{BC}$, represent a nonlinear optimization problem. If we make use of the information that, for a certain range of τ, the poles and zeros of the centralized controller $C_{des}(\tau)$ are constant, as illustrated in section B, it is possible to predict an upper bound on the maximum $M_A(\mathbf{x}_{BC})$ that can be achieved. For example, if the distributed controller $C_{dis}(\mathbf{x}_{BC}, \mathbf{x}_A)$ has a zero, which is determined by $\mathbf{x}_{BC}$ only, i.e., it cannot be manipulated by $\mathbf{x}_A$, then this zero has to be equal to one of the constant zeros of $C_{des}(\tau)$ in order to achieve swapping modularity. Since that zero of $C_{des}(\tau)$ is only constant for a certain range, then this range puts an upper bound on the maximum M_A we can achieve. In this way, we may terminate the search for $\mathbf{x}_{BC}$, if we obtain the predicted upper bound on M_A. In our case, the predicted upper bound on M_A

was always achievable, frequently, just for the starting value of $\mathbf{x}_{BC.}$

E. Results and discussion

We consider the range of the time constant of the actuator as [0.01, 0.21]. Note that, for this range, full swapping modularity corresponds to M_A = 0.2, and implies that any actuator with τ in the range [0.01, 0.21] can be used to achieve optimal performance by making changes only to the gains $\mathbf{x}_A$ of the actuator controller $\boldsymbol{C}_A$. A value of M_A = 0, indicates that the optimal performance can only be achieved for the nominal value of the time constant, τ = 0.05. Any internal value of M_A, like 0.15, corresponds to a certain range of τ, in which the actuator has swapping modularity. Table 3 shows the modularity results for the cases described in Table 1, with the configuration in Fig. 8. Table 4 shows the modularity results for the cases described in Table 2, with the configuration in Fig. 9.

TABLE 3
EFFECTS OF CONTROLLER DISTRIBUTION WITH UNIDIRECTIONAL COMMUNICATION

Case	M_A (range)
B4A0, B4A1, B3A1	0 (0.05-0.05)
B2A2, B1A3	0.15 (0.18-0.03)
B0A4	0.2 (0.21-0.01)

The results in Table 3 show that for the configuration with unidirectional communication, when the order of the actuator controller is of 2 or 3, the swapping modularity is 0.15. Only when all the control, except a gain, is moved to the actuator, can we achieve full range swapping modularity. Note that if our objective were to match the performance of a fixed centralized controller, the solution in the B4A1 case with a first order actuator controller may exist, as this case includes an actuator controller based on pole-zero cancellation. But the solution for matching the optimal centralized controller does not exist in this case.

TABLE 4
EFFECTS OF CONTROLLER DISTRIBUTION WITH BIDIRETIONAL COMMUNICATION

Case	M_A (range)
B22A00, B12A10, B21A01	0 (0.05-0.05)
B02A11, B20A11	0.15 (0.18-0.03)
B11A11, B01A21, 10A21, B01A12, B10A21, B10A12	0.18 (0.21-0.03)
B00A22	0.2 (0.21-0.01)

The swapping modularity results for the bidirectional communication configuration are shown in Table 4. We can achieve larger swapping modularity when the order of the actuator controller is of 2, in case B11A11, and we have many controller configurations to achieve larger swapping modularity, compared to the unidirectional communication configuration.

IV. SUMMARY AND CONCLUSION

Approaches to achieving swapping modularity for an engine speed control system with respect to changes in the throttle actuator time constant have been analyzed. It has been shown that an optimal centralized controller can be distributed between an actuator controller and a base controller, where only the actuator controller depends on the throttle actuator time constant. With such a distributed controller implementation, a throttle actuator and its controller can be swapped without touching the software or the calibration of the base controller in such a way that the performance of the closed-loop system is automatically configured to be optimal for the new throttle component. Comparing to the unidirectional communication configuration, the bidirection-al communication capability provides extra flexibility in developing distributed controller architectures which enhance swapping modularity.

In this paper we focused on a case study for achieving swapping modularity of the engine speed control with respect to the throttle actuator time constant. A similar approach can be followed to analyze the pathways to achieving swapping modularity with respect to other components and parameters, including throttle actuator time delay, intake manifold volume, engine displacement volume and/or engine inertia.

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