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IMPROVING COMPONENT SWAPPING MODULARITY USING BI-DIRECTIONAL COMMUNICATION IN NETWORKED CONTROL SYSTEMS

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ABSTRACT

Increased availability of low-cost electronics has created a new breed of control system components; so called "smart" components, which can perform control responsibilities in the actuator and sensor components as well as in the controller. "Smart" components can communicate bi-directionally in networked control systems. We identify opportunities for improving control system performance and design due to the decentralized, yet more connected, nature of these systems. Current research on networked control systems primarily focuses on communication loss and delay of information transfer. This paper investigates the potential benefits of bi-directional communication in a feedback control loop for improving component swapping modularity of the feedback control system. The problem formulation is presented, for the first time, and also illustrated using a driveshaft speed control example.

INTRODUCTION

The idea of utilizing new communication paths using bi-directional communication among "smart" components, in Fig. 1, in Networked Control Systems was introduced in (Cakmakci & Ulsoy, 2005). Smart components can be defined as control system components (i.e actuators, sensors) which have on-board computing capabilities so that they can perform control related tasks (Cakmakci & Ulsoy, 2005). Networked Control Systems (NCSs) are systems where feedback control loops are closed via communication networks (Zhang *et al.*, 2001). There are considerable benefits to using networks, such as less wiring, better interfacing and lower costs with an open architecture, although disadvantages also exist (delays, bandwidth limitations, guaranteed delivery) (Zhang *et al.*, 2001; Walsh & Ye, 2001; Walsh *et al.*, 2002; Yook *et al.*, 2000). Flexibility of component-to-component communication emerging from having control system components use networks is a relatively untouched subject, and most NCS researchers currently focus on alleviating the disadvantages noted above. We have observed opportunities to improve traditional control system performance and design due to the decentralized yet more connected nature of these systems (Cakmakci & Ulsoy, 2005). In this paper, we focus on an improved control system design methodology to build systems which have superior component swapping modularity compared to their equivalent centralized controller alternatives.

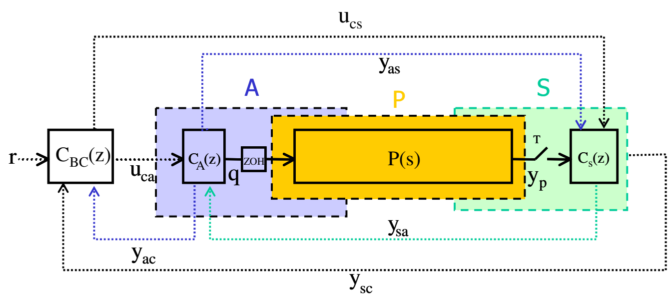


Figure 1: Networked Control System with Bi-Directional Communications among Smart Components.

In the next sections of this paper we first describe our definition of component swapping modularity for control system components. Then, we present our problem formulation, the solution of which maximizes component swapping modularity with the desired overall control algorithm found by using traditional control design methods. We illustrate our ideas with the feedback control problem for driveshaft speed control with a dc-motor and tachometer. The paper concludes with a discussion of results and our proposed future work.

COMPONENT SWAPPING MODULARITY FOR CONTROL SYSTEMS

Figure 2 describes physical and functional boundaries for a networked control system with bi-directional communications and smart components. Controller and plant hardware functions of both the actuator and the sensor (part a) makes it impossible to partition the system into plant and controller without crossing physical boundaries (parts b and c). Component-swapping modularity occurs when two or more alternative basic components can be paired with the same modular components creating different product variants belonging to the same product family (Ulrich & Tung, 1991). Control systems with modularly swappable components can then be defined as the systems in which the initial and final configurations due to a component change operate at their corresponding optimal performance. Figure 3 shows a control system configuration in which many different types of actuator and sensor configurations can be operated at the optimal settings.

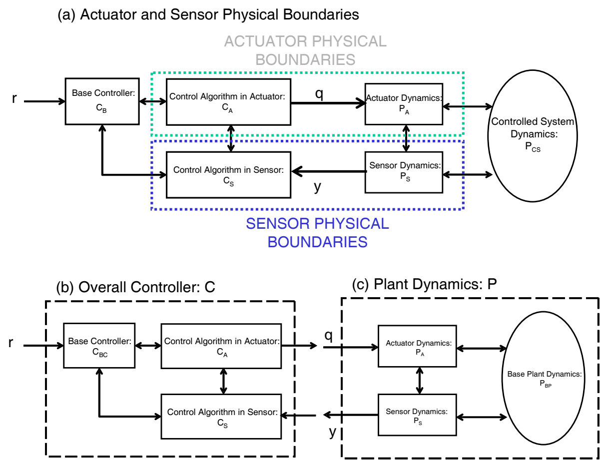


Figure 2: Control System Component Physical and Functional Boundaries.

There are many advantages of having a system with high component swapping modularity. Traditionally, a change in one of the components involves two sub-systems, the component and the base controller. By attaching the component related control to the component, re-work can be limited to only one sub-system. Today's competitive environment requires one hit product with many compelling options, different suppliers, standards, regulations, perceptions of performance, add-ons etc. Product design engineers focus on design for product platforms rather than an individual product.

Designing a control distribution which is valid for many configurations may be the killer application for bi-direction communication control systems. Even though today's software updates can be done in seconds, coming up with the update which will either work for all configurations or keeping track of different versions of the update for different configurations of the product is a tremendous, and costly, effort for companies.

Increasing component-swapping modularity of control systems can be utilized in industry in four major scenarios:

1. Sustainable maintanence/upgrade of a product:
   We have described the life-cycle of a control system in (Cakmakci & Ulsoy, 2005). Increasing component swapping modularity shortens the engineering time and effort (i.e. cost) in the repeated phase of conceptual design, implementation and testing/validation after each maintanence and upgrade of the system.
2. Deploying platform based algorithms:
   Use of platform engineering is on the rise for companies which produce a variety of products. The idea of defining product platforms requires defining the common infrastructure with different cosmetics in a company's product line. Quality of control engineering can be increased drastically by focusing on designing control algorithms for product platforms (more engineering time, focus and experience) which will increase the overall performance of the end-product.
3. Deploying control algorithms for different builds of the same product:
   For companies which use many different suppliers, and operate in many different locations different builds of the same product are needed because of subsystem variance and difference in system specifications due to regulations, external disturbances, etc. For these type of global products, having component swapping modularity in control systems increases the overall efficiency of engineering by obtaining location specific optimal algorithms without redesigning the whole system.
4. Reducing costs by developing highly customizable but less variant components (supplier viewpoint):
   Supplier companies which supply sub-systems to more than one company can develop control systems with component swapping modularity to focus on fewer variants of their systems which optimally work on many customer's end-product.

Since the definition of component swapping modularity is based on being able to use different components, the measure of modularity is based on the amount of different component configurations that can be accommodated. Let us represent components

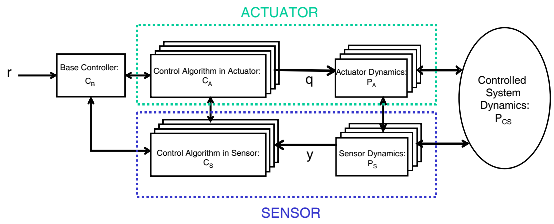


Figure 3: Control System with modularly swappable components.

via lumped physical properties and quantify modularity as

$$M = \int_{\mathbf{P}_X} 1 \cdot d\mathbf{p}_X \tag{1}$$

where $\mathbf{p}_X$ is the set of parameters that describe the component and $\mathbf{P}_X$ is the valid region of parameter values in which these components are modularly swappable. The larger the size of this region, the more modular the product. For example, for a dc-motor the vector $\mathbf{p}_X$ could have components representing a motor constant and gear ratio. If the range of values $\mathbf{P}_X$ for which the dc-motor is modularly swappable is large, then M is large.

The measure described in Eq. (1) can be used as the objective function of the distribution problem to maximize component swapping modularity of control systems as detailed in the next section.

PROBLEM FORMULATION

Design of the Overall Controller, C_{des}

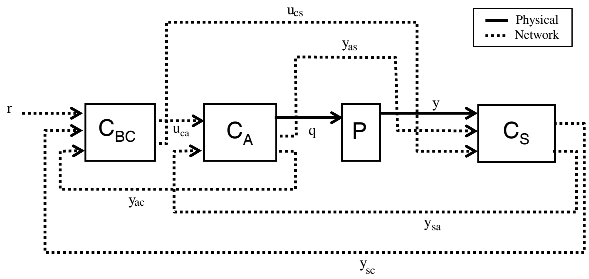
Given a plant transfer function $P(s)$ and a set of performance constraints, σ, there exists a controller design function f_C, such that desired (optimal) controller, $\mathbf{C}_{des}$ for the current configuration, i.e.,

$$\mathbf{C}_{des}(s) = f_C(\mathbf{P}, \sigma, s) \tag{2}$$

Various methods can be used to find f_C, as this is a classical control design problem (Ogata, 1990).

Distribution of Control

As a first step to analyze the new NCS communication paths (see Figs. 1-3), and their effect on the feedback control system performance, we model the entire system as a linear time-invariant (LTI) system with no communication loss or delays (see Fig. 4). Note that we do not constrain what can be communicated among components. In such an "ideal" case, the controller using bi-directional communications is an LTI system which can in fact be reduced to a single loop controller equivalent to $\mathbf{C}_{des}$ in Eq. (2). We can define a distribution function, f_D, from which



$$C_{BC} = \begin{bmatrix} C_{BC11} & C_{BC12} & C_{BC13} \\ C_{BC21} & C_{BC22} & C_{BC23} \end{bmatrix} \quad C_S = \begin{bmatrix} C_{S11} & C_{S12} & C_{S13} \\ C_{S21} & C_{S22} & C_{S23} \end{bmatrix} \quad C_A = \begin{bmatrix} C_{A11} & C_{A12} \\ C_{A21} & C_{A22} \\ C_{A31} & C_{A32} \end{bmatrix}$$

Figure 4: Bi-Directional Communications in a "Ideal" Continuous Control System.

we can calculate the overall effect of the component controllers, $\mathbf{C}_{dist}$, i.e.,

$$\mathbf{C}_{dist}(s) = f_D(\mathbf{C}_{BC}, \mathbf{C}_A, \mathbf{C}_S) \tag{3}$$

Equations (4)-(10) show the controller equations for the "'ideal"' general NCS with bi-directional communications shown in Fig. 4.

$$u_{ca} = C_{BC11} r + C_{BC12} y_{sc} + C_{BC13} y_{ac} \tag{4}$$
$$u_{cs} = C_{BC21} r + C_{BC22} y_{sc} + C_{BC23} y_{ac} \tag{5}$$
$$y_{as} = C_{A21} u_{ca} + C_{A22} y_{sa} \tag{6}$$
$$y_{ac} = C_{A31} u_{ca} + C_{A32} y_{sa} \tag{7}$$
$$y_{sc} = C_{S11} y + C_{S12} y_{as} + C_{S13} u_{cs} \tag{8}$$
$$y_{sa} = C_{S21} y + C_{S22} y_{as} + C_{S23} u_{cs} \tag{9}$$
$$q = C_{A11} u_{ca} + C_{A12} y_{sa} \tag{10}$$

In order to solve for q (i.e., the controller output) given r and y (i.e., the controller inputs), we obtain the system of equations given in Eqs. (11)-(12) by using Eqs. (4)-(10).

$$\begin{bmatrix} u_{ca} \\ u_{cs} \\ y_{ac} \\ y_{as} \\ y_{sc} \\ y_{sa} \end{bmatrix} = \begin{bmatrix} -1 & 0 & C_{BC13} & 0 & C_{BC12} & 0 \\ 0 & -1 & C_{BC23} & 0 & C_{BC22} & 0 \\ C_{A31} & 0 & -1 & 0 & 0 & C_{A32} \\ C_{A21} & 0 & 0 & -1 & 0 & C_{A22} \\ 0 & C_{S12} & 0 & C_{S13} & -1 & 0 \\ 0 & C_{S22} & 0 & C_{S23} & 0 & -1 \end{bmatrix}^{-1} \begin{bmatrix} C_{B11} & 0 \\ C_{B21} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & C_{S11} \\ 0 & C_{S21} \end{bmatrix} \begin{bmatrix} r \\ y \end{bmatrix} \tag{11}$$

$$q = [C_{A11} C_{A12}] \begin{bmatrix} u_{ca} \\ y_{sa} \end{bmatrix} \tag{12}$$

We then define the distributed controller function C_{dist} as in Eq.(13).

$$C_{dist} = \begin{bmatrix} C_{A11} & 0 & 0 & 0 & 0 & C_{A22} \end{bmatrix} \begin{bmatrix} -1 & 0 & C_{BC13} & 0 & C_{BC12} & 0 \\ 0 & -1 & C_{BC23} & 0 & C_{BC22} & 0 \\ C_{A31} & 0 & -1 & 0 & 0 & C_{A32} \\ C_{A21} & 0 & 0 & -1 & 0 & C_{A22} \\ 0 & C_{S12} & 0 & C_{S13} & -1 & 0 \\ 0 & C_{S22} & 0 & C_{S23} & 0 & -1 \end{bmatrix}^{-1} \begin{bmatrix} C_{BC11} & 0 \\ C_{BC21} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & C_{S11} \\ 0 & C_{S21} \end{bmatrix} \tag{13}$$

The overall design problem, to maximize component swapping modularity for the actuator component while ensuring desired controller performance, can then be stated as:

Given nominal settings for the plant parameters denoted as $\mathbf{p}^0_{CS}$, $\mathbf{p}^0_A$, $\mathbf{p}^0_S$ for controlled system, actuator and sensor respectively, we can formulate the distribution problem which maximizes M_A as:

$$\max_{\mathbf{x}_{BC}, \mathbf{x}_A, \mathbf{x}_S} M_A(\mathbf{p}^0_{CS}, \mathbf{p}^0_A, \mathbf{p}^0_S, \mathbf{x}_{BC}, \mathbf{x}_A, \mathbf{x}_S) \tag{14}$$

subject to

Distribution Constraint:

$$C_{des}(\mathbf{p}^0_{CS}, \mathbf{p}^0_A, \mathbf{p}^0_S, s) = C_{dist}(\mathbf{x}_{BC}, \mathbf{x}_A, \mathbf{x}_S, s) \tag{15}$$

Additional Constraints:

$$\mathbf{x}^l_{BC} \le \mathbf{x}_{BC} \le \mathbf{x}^h_{BC} \tag{16}$$
$$\mathbf{x}^l_A \le \mathbf{x}_A \le \mathbf{x}^h_A \tag{17}$$
$$\mathbf{x}^l_S \le \mathbf{x}_S \le \mathbf{x}^h_S \tag{18}$$

Actuator modularity function M_A can be defined as follows: Let's assume D_A is the set of all possible optimal controllers corresponding to changing actuators which can be obtained by changing actuator controls only, i.e,

$$D_A = \{\forall \mathbf{d}_A \in \mathbf{D}_A \; \exists \, \mathbf{x}_A \in [\mathbf{x}^l_A, \mathbf{x}^h_A] \; s.t. \; C_{des}(\mathbf{p}^0_{CS}, \mathbf{d}_A, \mathbf{p}^0_S, s) = C_{dist}(\mathbf{x}^0_{BC}, \mathbf{x}_A, \mathbf{x}^0_S, s)\} \tag{19}$$

Then it is possible, given $\mathbf{p}^0_A$, to define a connected set, $\mathbf{P}_A(\mathbf{p}^0_{CS}, \mathbf{p}^0_A, \mathbf{p}^0_S, \mathbf{x}^0_{BC}, \mathbf{x}^0_A, \mathbf{x}^0_S)$, which satisfies the two conditions below:

1. $\mathbf{p}^0_A \in \mathbf{P}_A$
2. $||\mathbf{p}^+_A - \mathbf{p}_A|| > \varepsilon, \forall \mathbf{p}^+_A \in \mathbf{D}_A \setminus \mathbf{P}_A$ and $\mathbf{p}_A \in \mathbf{P}_A$.

where ε is small and definitions for C_{des} and C_{des} are given in Eqs. (2) and (3) respectively. We then define the function M_A as (see Fig. 5

$$M_A(\mathbf{p}^0_{CS}, \mathbf{p}^0_A, \mathbf{p}^0_S, \mathbf{x}^0_{BC}, \mathbf{x}^0_A, \mathbf{x}^0_S) = \int_{\mathbf{P}_A} d\mathbf{p}_A \tag{20}$$

This formulation and method are illustrated in an example in the following section for speed control of a driveshaft with dc-motor and tachometer.

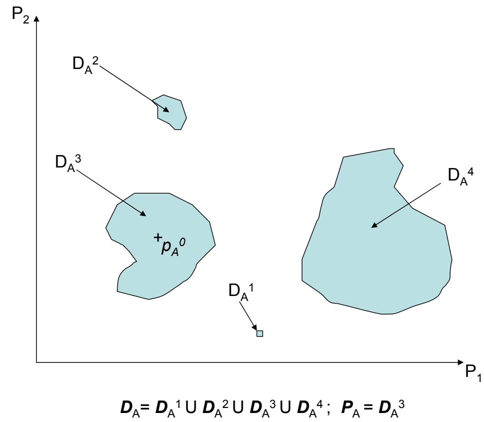


Figure 5: Illustration of Sets D_A and P_A for a Two Parameter System.

EXAMPLE: FEEDBACK CONTROL OF DRIVESHAFT SPEED WITH DC-MOTOR AND TACHOMETER

The purpose of this section is to present a simple, yet sufficiently complex, example that illustrates the potential benefits of bi-directional communication among "smart" components in a networked control system. Specifically, the feedback control of driveshaft speed for a system with a dc-motor and tachometer is considered (see Fig. 6).

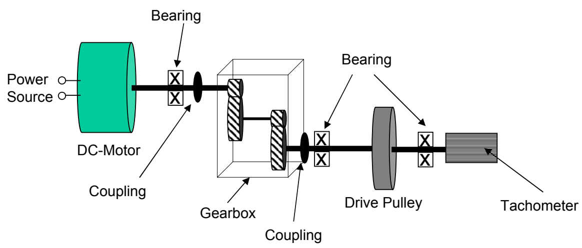


Figure 6: Schematic of System used in the Example.

Symbol	Description (Value in the example)
R	Armature resistance, (1Ohm)
L	Armature inductance, (1$Henry$)
J_eq	Equivalent moment of inertia of the motor shaft, (0.1$kg-m^2$)
b_eq	Viscous friction coefficient of the motor shaft, (0.1$Nms/rad/$
K_m	Motor torque constant, (0.01Nm/A)
K_b	Motor voltage constant, (0.01rad/sV)
r	Gearbox reduction ratio, (1/10)
K_s	Sensor gain constant, (1)
$v(t)$	Input voltage, Volts
$\omega(t)$	Drive Shaft Speed, rad/s
$\omega_s(t)$	Measured Drive Shaft Speed, rad/s

Table 1: Plant Model Variables and Parameters.

Plant Model and Physical Boundaries

A schematic of the drive shaft system is given in Fig. 6. When an input voltage supplied to the dc-motor, the drive torque is supplied by the dc-motor through the gearbox to the drive shaft. Speed of the drive shaft is measured at the tachometer. Table 1 provides a list of the plant model variables and parameters for the example.

$$\Omega_s(s) = \frac{K_s K_m / r}{J_{eq}Rs + K_m^2/r^2 + b_{eq}R} V(s) \tag{21}$$

Parameter values which will be used for this example are taken from (Michigan, 1996) except the gear reduction ratio, r. Physical boundaries for actuator, controlled system and sensor are defined as shown in Fig. 7. The dc-motor and the gearbox provide actuation to the system. The tachometer is the sensor which measures the driveshaft speed. The driveshaft, with drive pulley, is considered to be the controlled system. According to the physical boundaries defined in Fig. 7 using a different actuator would potentially change the values of the parameters L, R, K_m, r in Eq. (21) as well as the equivalent inertia, J_{eq}, and equivalent viscous friction, b_{eq}, of the system.

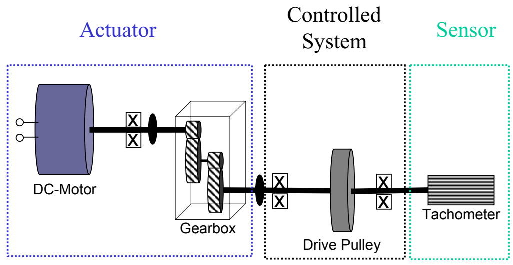


Figure 7: Physical Boundaries for Model Parameters.

Design of the Controller

In Chapter 4 of (Ogata, 1990) (pages 295-300), the integral-of-time-multiplied absolute error criterion (ITAE) is given as

$$J(t) = \int_0^\infty t|e(t)|dt \tag{22}$$

In Table 4-2 of same reference, the optimal form of the closed loop transfer functions for various orders are given. Specifically, for a system of third order, the optimal form of the closed loop transfer function is given as

$$G_{cl}(s) = \frac{\omega_n^3}{s^3 + 1.75\omega_n s^2 + 2.15\omega_n^2 s + \omega_n^3} \tag{23}$$

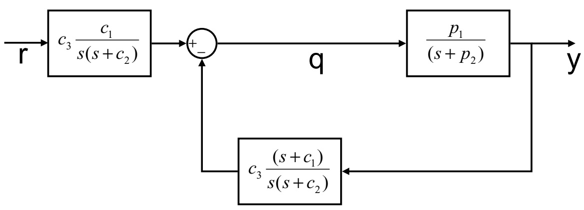


Figure 8: Closed loop system block diagram with Optimal ITAE controller.

For a plant which can be represented with first order dynamic characteristics as in Eq.(24), we have the plant model formulated as

$$P(s) = \frac{p_1}{s + p_2} \tag{24}$$

It is possible to design a second order controller, $C(s)$, given in Eq. (25) below, which produces the optimal closed-loop form given in Eq. (23).

$$C(s) = \begin{bmatrix} \frac{c_3 c_1}{s(s+c_2)} & \frac{c_3(s+c_1)}{s(s+c_2)} \end{bmatrix} \begin{bmatrix} r \\ y \end{bmatrix} \tag{25}$$

Parametric solutions for optimal values of the controller gains, c_1,c_2 and c_3 which describe the optimal controller, can be found by following the steps described below:

1. Obtain closed loop transfer function formulation $G_{cl}(s)$:

$$G_{cl}(s) = \frac{c_3 c_1 p_1}{s^3 + (c_2 + p_2)s^2 + (c_2 p_2 + c_3 p_1)s + c_3 c_1 p_1} \tag{26}$$

2. The equivalence of Eq. (23) and Eq. (27), for both numerator and denominator polynomials, gives

$$c_3 c_1 p_1 = \omega_n^3 \tag{27}$$
$$c_2 p_2 + p_1 c_1 = 2.15\omega_n^2 \tag{28}$$
$$c_2 + p_2 = 1.75\omega_n \tag{29}$$

3. For a specific value of ω_n we can solve Eqs. (27)-(29) to obtain values for c_1, c_2 and c_3 which minimizes the ITAE criterion for our system. We also require $c_2 > 0$ in order to avoid unstable controller response due to non-linearity, disturbance and noise in the system.

For the first order plant model of the dc-motor and driveshaft we have

$$p_1 = \frac{(K_m/r)}{JR} \tag{30}$$
$$p_2 = \frac{(K_m/r)^2 + bR}{JR} \tag{31}$$

Figure 9 presents different values for optimal controller parameters with respect to changing K_m/r value. In order to keep our analysis simple, we assume that changing the actuator will only affect the (K_m/r) ratio in our controller design calculations (i.e. $\mathbf{p}_A = [R^0, (K_m/r), J_m^0, b_{eq}^0]$ in Eqs. (14)-(20)). Also, instead of using the most general bi-directional communications case shown in Fig. 4, a simpler multicast communication configuration will be used (Fig. 10). We assume that our base controller will still be the smartest device in the system so maximum order of transfer functions in C_{BC} will be of first order and the actuator and sensor controllers will consist of gains (i.e., transfer functions are of order 0). The vector $\mathbf{x}$ describes the gains of our distributed controller as shown in Eqs.(36)-(38). For convenience we also define $\mathbf{x_{BC}}$, $\mathbf{x_A}$ and $\mathbf{x_S}$ to refer to the gains of $\mathbf{x}$ related to base

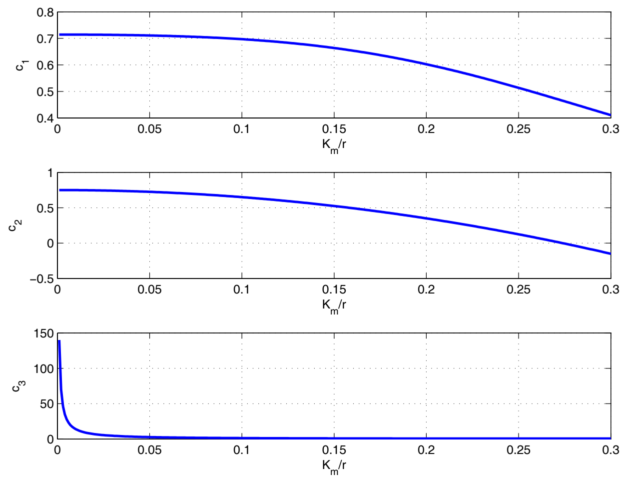


Figure 9: Optimal Controller Parameters.

controller, C_{BC}, actuator, C_A, and sensor, C_S, controllers respectively. In order to improve the actuator component swapping modularity of the system in this example, we search through the distributed controllers not only equivalent to the overall desired controllers but also to provide the optimal solution for widest range of (K_m/r) values by only changing the actuator controller gains, $\mathbf{x_A}$.

Defining C_{des} and C_{dist}

In previous section, we have defined the formulation for C_{des} as shown in Eq. (32):

$$C(s) = \begin{bmatrix} \frac{c_3 c_1}{s(s+c_2)} & \frac{c_3(s+c_1)}{s(s+c_2)} \end{bmatrix} \begin{bmatrix} r \\ y \end{bmatrix} \tag{32}$$

where

$$c_2 = 1.75\omega_n - p_2 \tag{33}$$
$$c_1 = (2.15\omega_n^2 - c_2 p_2)/p_1 \tag{34}$$
$$c_3 = \omega_n^3 / c_1 p_1 \tag{35}$$

In order to define $C_{dist}(s)$ given in Eq. (13) properly, so that a solution algorithm can be implemented, we have to set component controller transfer function matrices $\mathbf{C}_{BC}(\mathbf{x}_{BC})$, $\mathbf{C}_A(\mathbf{x}_A)$, $\mathbf{C}_S(\mathbf{x}_S)$. One example is given in Eq. (36) to Eq. (38). It is important to note that formulating $\mathbf{C}_{BC}(\mathbf{x}_{BC})$, $\mathbf{C}_A(\mathbf{x}_A)$, and $\mathbf{C}_S(\mathbf{x}_S)$ as given in Eq. (36) to Eq. (38) implies assumptions about the amount of computation and communication by each components. We assume maximum order of transfer functions as 2 for the base controller while actuator and sensor controllers are just gains, i.e transfer functions of order 0. Also since first and second rows of

C_{BC} and C_S are the same we understand this definition represent a communication scheme where these components multicast. That is, each component send the same message to the other two. A block diagram for this configuration is shown in Fig. 10.

$$C_{BC}(\mathbf{x_{BC}},\mathbf{s}) = \begin{bmatrix} \frac{x_1s^2+x_2s+x_3}{x_{10}s^2+x_{11}s+x_{12}}, & \frac{x_4s^2+x_5s+x_6}{x_{10}s^2+x_{11}s+x_{12}}, & \frac{x_7s^2+x_8s+x_9}{x_{10}s^2+x_{11}s+x_{12}} \\ \frac{x_1s^2+x_2s+x_3}{x_{10}s^2+x_{11}s+x_{12}}, & \frac{x_4s^2+x_5s+x_6}{x_{10}s^2+x_{11}s+x_{12}}, & \frac{x_7s^2+x_8s+x_9}{x_{10}s^2+x_{11}s+x_{12}} \end{bmatrix} \quad (36)$$

$$C_A(\mathbf{x_A}) = \begin{bmatrix} x_{13} & x_{14} \\ x_{15} & x_{16} \\ x_{17} & x_{18} \end{bmatrix} \quad (37)$$

$$C_S(\mathbf{x_S}) = \begin{bmatrix} x_{19} & x_{20} & x_{21} \\ x_{19} & x_{20} & x_{21} \end{bmatrix} \quad (38)$$

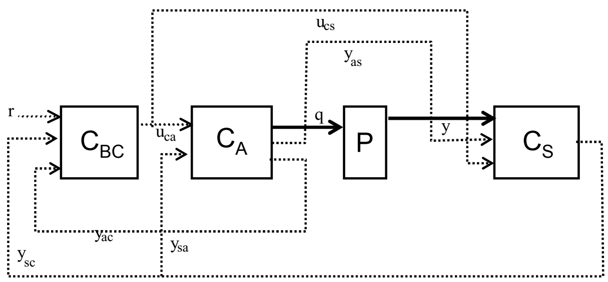


Figure 10: Communication Configuration of the Example Controller.

Optimal Distribution Problem

After we define our distribution constraints, we are ready to solve the distribution problem formulated in Eqs. (14)-(18). In order to keep the example problem simple we are going to use K_m/r as our only actuator parameter (i.e. $\mathbf{p}_A = [R^0, (K_m/r), J_m^0, b_{eq}^0]$). List of parameters used in general problem formulation and their definitions in the example problem is given in Table 2.

Figure 11 illustrates the sets D_A and P_A for the case where the actuator can be represented with only one parameter (i.e., K_m/r). The optimization problem given in Eqs. (14)-(18) was solved using the Matlab Optimization Toolbox and a traditional controller using unidirectional communications as the initial point. For the optimal distribution solution given in Table 3 the optimal actuator swapping modularity, M_A^*, turns out to be 0.26 and an optimal control can be obtained for all values of $0.01 \leq (K_m/r) \leq 0.27$ by modifying only the gains, $\mathbf{x_A}$, in the actuator controller $C_A(s)$. This is a significant improvement on the actuator swapping modularity of the original system with centralized controller, where the only optimal system configuration is the default component configuration, i.e., $M_A^* = 0$ and $(K_m/r) = 0.1$.

General Formulation	Example Formulation
$\mathbf{p}_{CS}^0$	$[J_d^0, b_d^0]$
$\mathbf{p}_A^0$	$[R^0, (K_m/r)^0, J_m^0, b_{eq}^0]$
$\mathbf{p}_S^0$	$[K_s^0]$
$\mathbf{p}_A$	$[R^0, (K_m/r), J_m^0, b_{eq}^0]$

Table 2: List of Parameters for Example Distribution Solution.

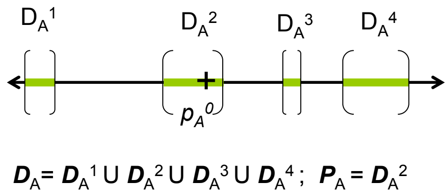


Figure 11: Illustration of Sets D_A and P_A for a One Parameter System.

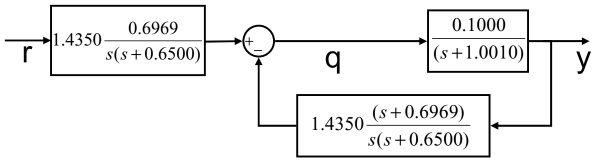
Element	Value	Element	Value	Element	Value
x_1	0	x_8	-0.4265	x_{15}	-0.7676
x_2	0	x_9	0.2447	x_{16}	-0.2757
x_3	2.3571	x_{10}	1.1529	x_{17}	1.0027
x_4	0.138	x_{11}	1.019	x_{18}	0.5269
x_5	-2.1737	x_{12}	0.4671	x_{19}	1.5717
x_6	-1.724	x_{13}	0.7365	x_{20}	0.0292
x_7	-0.5815	x_{14}	0.0714	x_{21}	0.2307

Table 3: Optimal Distributed Controller Solution.

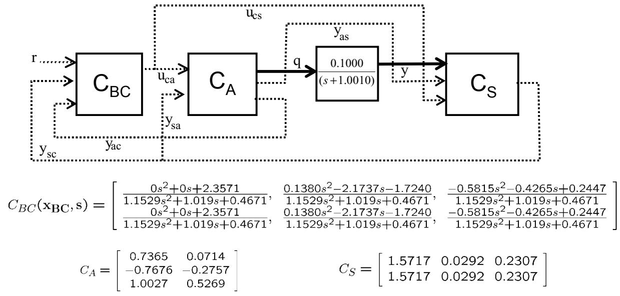
CONCLUSION AND FUTURE WORK

In this paper we have focused on improving component swapping modularity of control systems using bi-directional communication in networked control systems. We have presented our problem formulation to solve the distribution problem and illustrated our ideas on a driveshaft speed controller design problem.

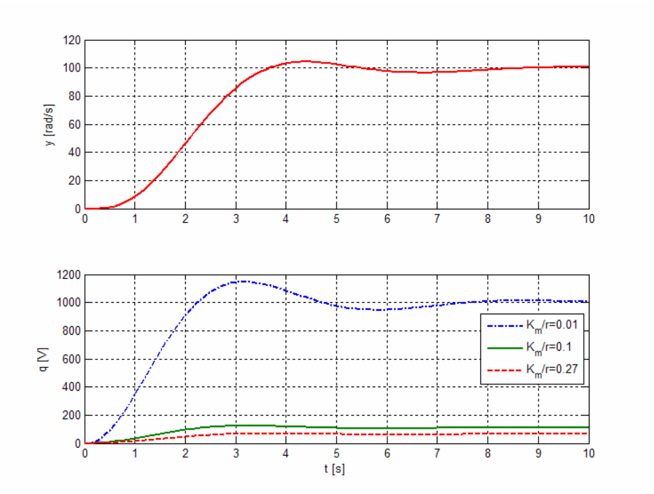
The result of the distribution problem presented in Section shows significant improvement in the actuator modularity of



(a) Centralized Controller using Traditional Feedback Communications



(b) Distributed Controller utilizing Bi-directional Communications in NCS



(c) Closed Loop System Response

Figure 12: Summary of Results.

the control system: the original system configuration with uni-directional communications only provides the optimal controller for $(K_m/r) = 0.1$, whereas the communication configuration described in Fig. 10 can provide optimal solutions for all (K_m/r) values in the range of $0.01 \leq K_m/r \leq 0.27$ (i.e $M_A^* = 0.26$) by changing only the gains in the actuator controller, $C_A(s)$. The traditional controller, and the controller designed for swapping modularity are compared in Fig. 12. They have identical closed loop performance. However, the new controller can maintain that performance for all values of $0.01 \leq K_m/r \leq 0.27$ (i.e $M_A^* = 0.26$ by modifying only the gains x_{13} to x_{18} in the actuator controller $C_A(s)$.

Future work on this project will include finding a design method which maximizes overall component-swapping modularity of the system, including computation and communication constraints in the problem, and extending the component swapping modularity problem presented here for single-input single-output to multi-input multi-output systems.

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