Centralized and Decentralized Powertrain Controllers for an Earthmoving Vehicle

Gupta P. and Alleyne A., *Senior Member IEEE*

Abstract— **This paper discusses the performance, robustness and design tradeoffs between decentralized and centralized control schemes from a powertrain perspective. It also demonstrates how a gain scheduling technique can be used effectively to design controllers for non-linear powertrain systems both in a centralized and a decentralized framework. Stability and performance analysis have been a challenge in a decentralized framework. A robust analysis technique for gain scheduled controller has been applied to the decentralized network in this correspondence. With this analysis tool, a robustness and performance analysis can be performed on the decentralized network when all the subsystem controllers are designed using gain scheduled controllers.**

NOMENCLATURE

γ	Diesel engine fuel command
u_v	Flow valve input
α_{ref}	Swash-plate pump angle reference
D_p	Variable displacement pump displacement
D_m	Hydraulic motor displacement
Q_p	Pump flow
Q_m	Flow through the hydraulic motors
Q_v	Flow through the flow valves
$T_{m,l}$	External load on the hydraulic motors
T_e	Brake load of the diesel engine
n_e	Diesel engine speed
n_m	Load motor speed
e_m	Motor speed tracking error
p_d	Pressure downstream to the valve manifold
p_u	Pressure upstream to the valve manifold
η_{mani}	Valve manifold efficiency
η_{BFC}	Brake fuel conversion efficiency of the diesel engine
η_{pump}	Efficiency of the variable displacement pump
$\eta_{overall}$	Overall powertrain efficiency
η_{mech}	Mechanical efficiency
η_v	Volumetric efficiency
ρ	Scheduling variable
K_E	Engine controller
K_c	Centralized powertrain controller
K_T	Transmission controller

1. INTRODUCTION

Decentralized control schemes always have been popular in the powertrain industry. While a properly designed centralized controller is expected to perform better than a decentralized controller, there are several design and implementation issues that make decentralized control attractive to the powertrain community.

An interconnected system like a powertrain consists of various different subsystems. Oftentimes the subsystem dynamics are significantly different from each other. For example one subsystem might show linear dynamics while another might be highly nonlinear. Hence, different control strategies might be required to control the various subsystems of the interconnected system. While decentralized control schemes allow the design of different control structures for different subsystems, centralized controllers generally do not have such flexibility. Moreover, decentralized control schemes are commercially more viable, as the different subsystem controllers can be designed independently. Hence, if any of the subsystems are replaced, only the controllers of the corresponding subsystems have to be re-designed. In such cases a centralized controller has to be re-synthesized which may not be commercially viable. On the other hand, centralized control schemes have better performance and robustness properties and are essential for integrated control objectives.

Despite the popularity of decentralized control schemes in industry, stability and performance analysis has always been a challenge in a decentralized framework. Many researchers have devoted significant effort in this area. Advanced tools such as Lyapunov stability and input-output stability [1], passivity arguments [2], small gain theorem and μ tools [3] have been used for analysis of decentralized systems. The applicability of these results has been demonstrated via studies of models for powertrains, power systems [4], etc. Most of the analysis tools, however, are difficult to apply in a generic framework.

Gain scheduling is a popular tool for nonlinear control design [5]. In the current work, both centralized and decentralized controllers have been synthesized using a gain scheduled design. Devised controls strategies are then implemented on an Earthmoving Vehicles Powertrain Simulator (EVPS) at the University of Illinois. A robust analysis tool was developed by Zhang *et al* [6, 7] to analyze the performance and robustness of gain scheduled controllers. The centralized and decentralized controller's robustness and performance properties can be analyzed using this robust analysis tool, when the controllers are synthesized by gain scheduled design.

Gupta P., works with Caterpillar Inc. (e-mail: guptap@cat.com).
Alleyne A., is a professor in the Department of mechanical engineering at University of Illinois, Urbana Champaign, Urbana IL 61820 (corresponding author to provide phone: (217) 244-9993; fax: (217) 244-6534; e-mail: alleyne@uiuc.edu).

0-7803-9098-9/05/$25.00 ©2005 AACC

The rest of the paper is presented as follows. In Section 2, a brief description of the EVPS is given. The gain scheduling controller design methodology is briefly described in Section 3, followed by the description of the above mentioned robust analysis tool. Centralized and decentralized control designs adapted for the EVPS are described in Sections 4 and 5, respectively. The performance and robustness analysis of both centralized and decentralized schemes are presented in Section 6. The important design tradeoffs between centralized and decentralized schemes are presented in Section 7. The controller analysis predictions correspond well with the loading cycle results described in Section 8. A conclusion then summarizes the main points of this paper.

2. SYSTEM DESCRIPTION

A picture of the EVPS is shown in Figure 1 and a schematic is shown in Figure 2. The EVPS consists of power generation, transmission, and load units. The power generation unit is a diesel engine, emulated using an AC motor and a PC controller. The AC motor has clean operation and the versatility to emulate several different prime movers. The power transmission unit consists of a variable displacement hydraulic pump, hydraulic hoses, and proportional flow valves. The load unit consists of hydraulic motors and external loads. Further details on the EVPS are available in [8-10].

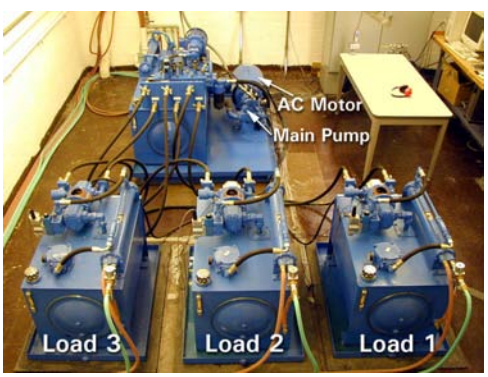

Fig. 1. Experimental EVPS setup at UIUC

The powertrain considered in this paper is a multi-input multi-output nonlinear system having five control inputs and nine measurements. The five inputs are: the engine fuel index, variable pump displacement and the three individual flow valve openings, one for each load. The nine measured outputs are: the three load speeds, the diesel engine speed, and the pressures upstream and downstream of the valve manifold. Henceforth, states upstream of the valve manifold will be designated by the subscript "upstream" and the states downstream will be similarly designated "downstream." The nonlinear model was linearized to get local linear models. The resulting model has 14 states, 5 inputs and 9 outputs [8, 9].

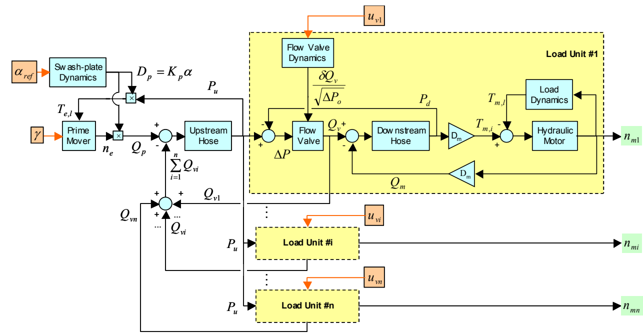

Fig. 2. System Interconnection of multi-node powertrain [7]

3. GAIN SCHEDULED CONTROLLER DESIGN AND ANALYSIS

A highly nonlinear plant such as the electro-hydraulic powertrain is difficult to control using a single robust linear controller. The system dynamics vary widely with operating points and therefore no single controller can work through the whole operating domain without being either unstable or too conservative to be useful. Therefore, a gain scheduling strategy based on the local controller network structure was chosen to solve this problem [6, 7].

Figure 3 shows the schematic of the global gain scheduled controller using a local controller network scheduler. The scheduler measures the current scheduling variables and then generates the interpolation weighting functions, w_i. These weighting functions apportion effort from each controller to add up to the overall system input [6,7] Inside the controller array, the local controllers are running in parallel, taking the same reference and measurements and generating individual control efforts based on the local plant dynamics.

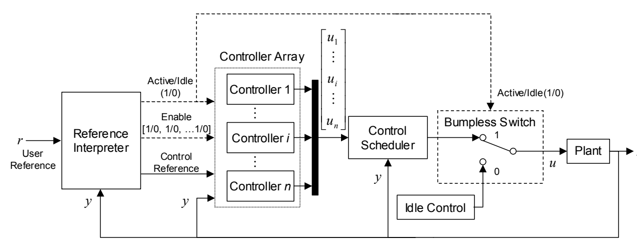

Fig. 3. Local Controller Network [7]

These control efforts contribute to the final control efforts, depending on the distance between the current operating point and the corresponding design point as measured in the scheduling space.

A robust tool was developed in [7] for analyzing the stability and performance of the gain scheduled controller. Because of the blending control law in Figure 3, the variation of the total control δu is related to both the output variation of the local controllers δu_{ci} and the variation of the weighting functions δw_i. By a first order Taylor expansion, δu is expressed by,

$$
\begin{aligned}
\delta u &= \begin{bmatrix}\delta u_{c2} & \delta u_{c2} & \delta u_{c3} & \delta u_{c4}\end{bmatrix} w_0 + \begin{bmatrix}u_{c10} & u_{c20} & u_{c30} & u_{c40}\end{bmatrix}\delta w \\
&= \begin{bmatrix}\delta u_{c2} & \delta u_{c2} & \delta u_{c3} & \delta u_{c4}\end{bmatrix} w_0 + (1+0.15\Delta_{\rho u})\begin{bmatrix}u_{e1} & u_{e2} & u_{e3} & u_{e4}\end{bmatrix}\delta w
\end{aligned} \tag{1}
$$

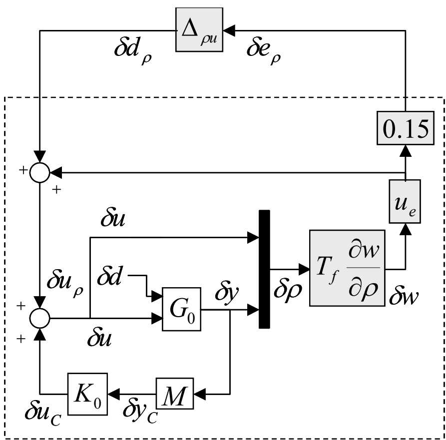

Fig. 4. Analysis plant model for H_∞/μ synthesis

u_{ci0} is the steady state output of the ith local controller at an operating point when it is working as a sub-controller inside the overall Local Controller Network. u_{ei} is the equilibrium steady state output of the i-th local controller. In general, these two values are different. u_{ei} is determined once the design equilibrium points are chosen. Although it is hard to determine the value of u_{ci0} analytically for each operating point, it is possible to find an upper bound by measuring the difference between u_{ci0} and u_{ei} when running the closed-loop system in steady state. The actual input to the system can be thus represented as the sum of frozen parameter input and an additive uncertainty $\Delta_{\rho u}$ (1), which will be referred as the 'scheduling uncertainty.'. The Jacobian matrices $\partial w/\partial \rho$, can be computed using the chain rule evaluated at the current operating point.

$$
\frac{\partial w}{\partial \rho} = \frac{\partial w}{\partial v}\frac{\partial v}{\partial \phi}\frac{\partial \phi}{\partial \hat{\rho}}\frac{\partial \hat{\rho}}{\partial \rho} \tag{2}
$$

The local robustness and performance properties of the global closed loop plant model can be analyzed by measuring induced norms of the analysis plant model described in Figure 4 where G_0 denotes the local linear model of the plant evaluated at the current operating point. K_0 is the local linear 'frozen parameter' [6, 7] controller network, evaluated at the current operating point.

4. CENTRALIZED POWERTRAIN CONTROLLER DESIGN

The first step in the gain scheduled global controller design is the local controller network design. H_∞ and μ-tools based MIMO controllers were designed around several local linear models for this purpose. The swashplate pump dynamics is considerably faster than the rest of the powertrain. Hence to decrease computational burden the original model was reduced to a 12 state model. $P_{12 \times 12}$ is the reduced order local plant with 12 states; u consists of the 5 inputs to the powertrain. The exogenous signal d includes all the references and the disturbances. The generalized error e includes the engine speed tracking error, the load speed tracking errors, and the pressure error. To make the steady state motor speed tracking errors converge to zero, free integrators were augmented to the design plant model. A mixed input\output multiplicative uncertainty model is considered for the robust controller design. Details of the control design are available in [11, 12].

The second step in the global controller design is the choice of an adequate scheduling strategy. The local system dynamics variations in the EVPS are mostly related to the (flow, power) domain. Hence pump flow and the pump power were chosen as the scheduling functions. These can be derived from the scheduling variables; engine speed n_e, the pump displacement D_p, and the upstream pressure p_u. A schematic of the closed loop powertrain with a centralized controller, K_c, is shown in Figure 5.

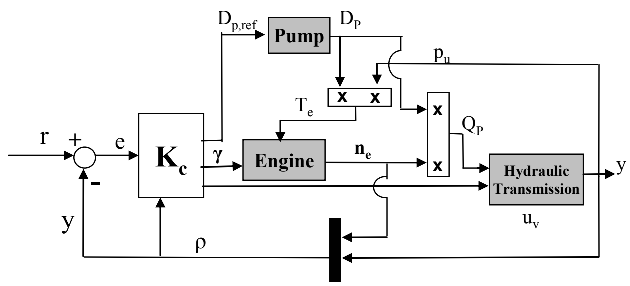

Fig. 5. Interconnection of the centralized network

The final step in the control design is optimization. The continuously varying pump displacement acts as a variable transmission in the hydraulic powertrain and can be used to optimize the power flow for transient response, fuel economy, or other desired performance metrics. In this paper only the powertrain efficiency optimization scheme is presented. The overall powertrain efficiency can be optimized by tracking the ideal brake specific engine speed and simultaneously minimizing the upstream pressure [11].

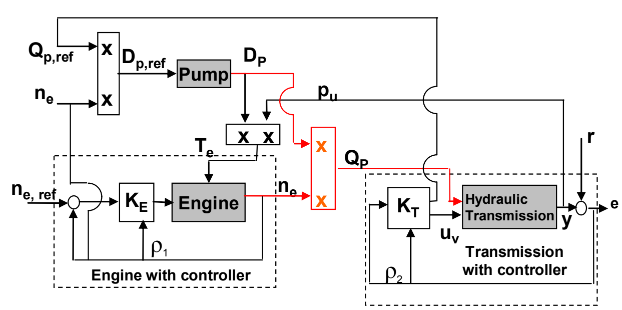

Fig. 6. Interconnection of the decentralized network

5. DECENTRALIZED POWERTRAIN CONTROLLER DESIGN

The first step in a decentralized control scheme is decentralization of the overall task. There are multiple ways of decentralizing an interconnected system. Standard tools such as relative gain array [13] can be used as an index for comparing different decentralization schemes. In this paper the choice of decentralization scheme is not the prime focus since we anticipate the method of how to separate subsystems would be driven by industry concerns. For example, we assume the prime mover (diesel engine) controller is designed separately from the rest of the powertrain. Henceforth in this paper the powertrain without the prime mover and the pump will be referred to as the transmission unit. Fig 6 displays a pictorial description of the decentralization scheme.

The engine controller tries to track the reference engine speed and reject the load disturbance on the engine. It takes the engine speed error as input and produces the engine fuel index command as an output. The pump is separated from the rest of the transmission to conserve the non-linear interconnection, which will be explained shortly. The transmission controller is designed for tracking the reference load motor speeds and rejects the powertrain load disturbances. The transmission controller takes the plant outputs and generates the required pump flow and the flow valve signals. The required pump flow is then fed to the pump along with the engine speed measurement. The reference displacement of the pump can be obtained by dividing the reference pump flow by the engine speed. The pump dynamics are considerably faster than the rest of the powertrain. Hence the pump displacement can be assumed to be equal to the reference pump displacement, as described in (3).

$$D_p = D_{p,ref} = \frac{Q_{p,ref}}{n_e} \tag{3}$$

Using the assumption in (3), the actual pump flow can be assumed to be equal to the reference pump flow (4).

$$Q_p = n_e \text{ x } D_p = n_e \text{ x } D_{p,ref} = n_e \times \frac{Q_{p,ref}}{n_e} = Q_{p,ref} \tag{4}$$

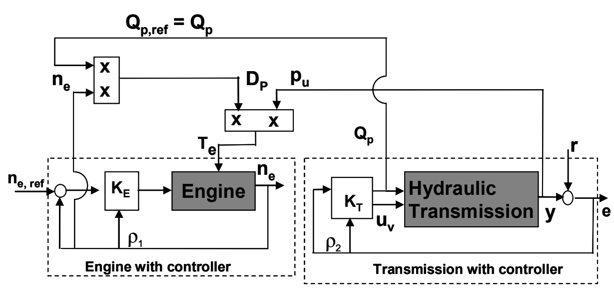

Fig. 7. Simplified decentralized network

Pictorially, this assumption simplifies the decentralized network described in Figure 6 to the network described in Figure 7. It is important to note that the nonlinear interconnections of the non-linear powertrain model in Figure 3 are conserved in the decentralized framework in Figure 6 and 7. The centralized controller in Figure 5 is, however, derived from the linearized model of the powertrain, which does not conserve the nonlinear interconnections such as flow products.

The engine and the transmission controllers are designed using the local controller network gain scheduling strategy developed in [6,7]. The engine controller is scheduled on the engine speed and the transmission controller is scheduled on the upstream pressure. The numbers of local controllers in their respective local networks are 6 and 4. More local controllers are needed for the engine since it is the most non-linear part of the powertrain. This is another design flexibility offered by the decentralized scheme, where the non-linearity associated with a particular subsystem can be addressed locally. The choice of scheduling variables comes from the knowledge of the non-linear models of the corresponding subsystems. The design steps for the individual gain scheduled controllers follow the steps of the gain scheduled centralized powertrain controller design in Section 4.

In the optimization step, the engine controller tracks the ideal brake specific fuel consumption (IBSFC) engine speed. However, it is difficult to incorporate the upstream pressure minimization objective in the transmission controller design, as it needs a simultaneous control action on the whole powertrain. This is one of the drawbacks of the decentralized design.

6. PERFORMANCE AND ROBUSTNESS ANALYSIS

Performance and robustness properties of both centralized and decentralized controllers can be predicted using the robustness tool introduced in Section 3. The analysis plant model for the powertrain with the centralized controller is presented in Figure 8. An output multiplicative uncertainty is considered for checking the controller's robustness to model uncertainty.

The induced norms for this analysis plant model were evaluated at different operating points throughout the entire operating range of the powertrain. These results are depicted in Figure 9

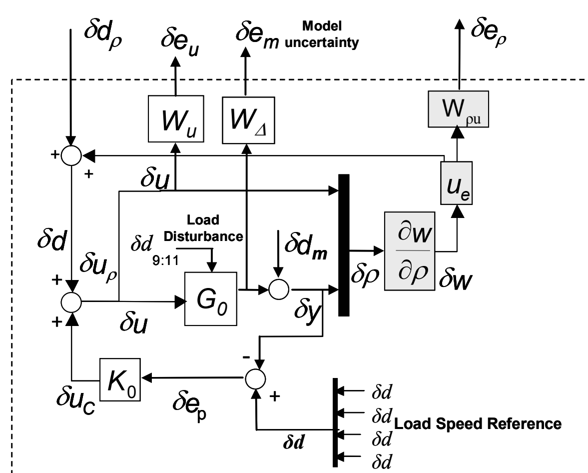

Fig. 8. Analysis plant model for the centralized controller

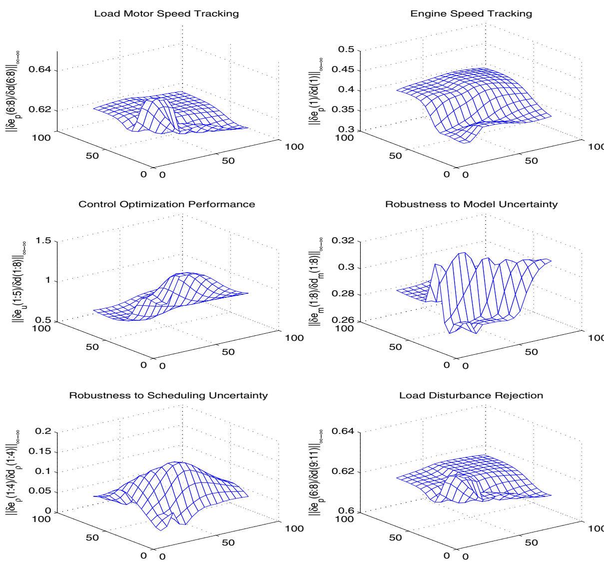

Fig. 9. Nominal performance and robustness analysis for the centralized controller

Similarly, the induced norms for the decentralized controller for the whole operating range are presented in Figure 10. By comparing Figure 9 with Figure 10 we can see that the nominal performance, in terms of motor speed and engine speed tracking, have similar norms in both the schemes. But the centralized controller shows better robustness properties by being more robust to model uncertainty, load disturbance, and scheduling uncertainty. Moreover, the centralized schemed also requires less control effort.

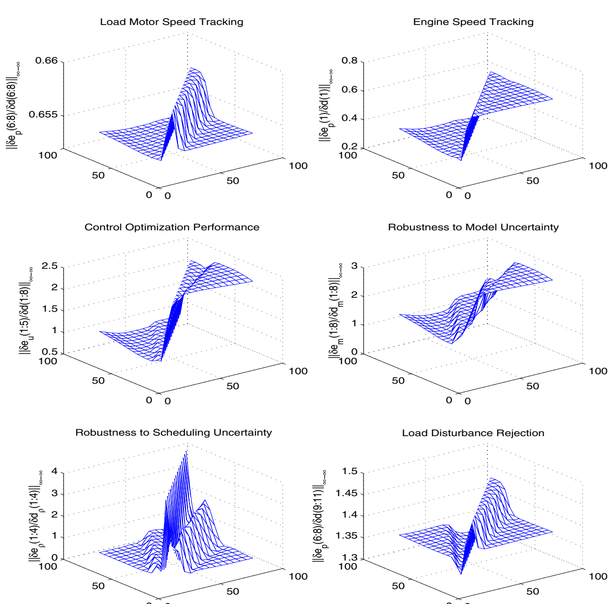

Fig. 10. Nominal performance and robustness analysis for the decentralized controller

7. DESIGN COMPARISON

One of the benefits of decentralized control is that it gives much more design flexibility to the control engineer. However, integrated design objectives are better addressed in the centralized framework. Some of the important design tradeoffs between the centralized and the decentralized framework are discussed in this section.

In the decentralized framework, controllers are first designed for individual subsystems and then integrated into the overall system. The control strategy is solely based on the particular subsystem for which the controller is designed and all the interactions are generally treated as exogenous signals. Failure or replacement of one of the subsystems doesn't require redesign of the controllers for the other subsystems. However in a centralized scheme the whole controller must be re-synthesized if even a single subsystem is replaced. This design flexibility is illustrated on the EVPS by replacing the diesel engine prime mover with a spark ignition (SI) engine prime mover in [12]. In the decentralized framework, one can continue with the same transmission controller and only design a new engine controller for the SI engine [12].

As mentioned in Section 4, the overall powertrain efficiency is optimized by decreasing the upstream pressure along with tracking the IBSFC engine speed [11]. The upstream pressure state is affected by the engine, pump, and the valve dynamics. This means that it is one of the pivotal states which interconnect different subsystems. Hence the upstream pressure control was unrealizable in the decentralized scheme as it demands integrated control action. However, upstream pressure can be controlled in the centralized framework [11, 12].

8. LOADING CYCLE COMPARISON

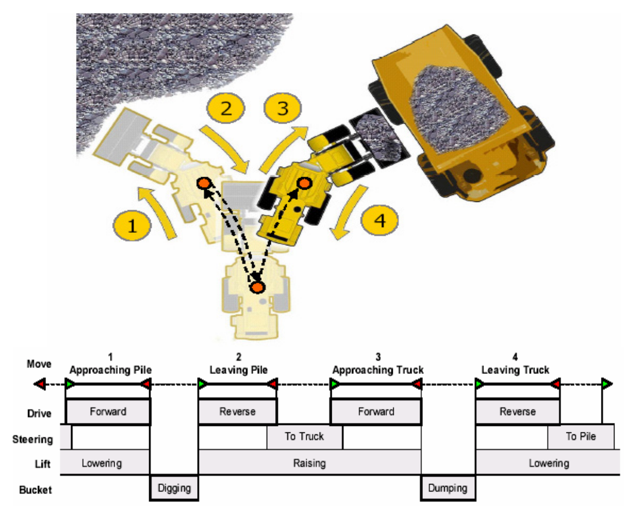

Fig. 11. 180° loading cycle

A standard loading cycle for a wheel loader earthmoving vehicle is described in Figure 11. The task is split into the four basic moves of approaching and leaving the dirt pile and the dumping truck. Loading cycle metrics such as cycle time, average speed tracking error and average fuel consumption rate are used to evaluate the powertrain controllers. To make the comparison more accurate, the human driver is replaced with a virtual driver simulator, which provides a high degree of repeatability in the reference signal generator [6].

Load motor reference speeds and the actual motor speed outputs using centralized and decentralized controllers are provided in Figure 12. Results from different loading cycles are tabulated in Table 1. By comparing the centralized and the decentralized controllers, we see that the centralized controller performs better in terms of average tracking error. The decentralized controller does not perform as well because of its poor robustness properties. Both controllers have engine speed tracking error of the same order of magnitude, as predicted by the analysis, which in turn results in similar brake fuel conversion efficiencies. The decentralized controller improves the pump efficiency whereas the centralized controller improves the valve manifold efficiency. The overall powertrain efficiency is best for the centralized controller because of its ability to incorporate the integrated objective of upstream pressure minimization in its design.

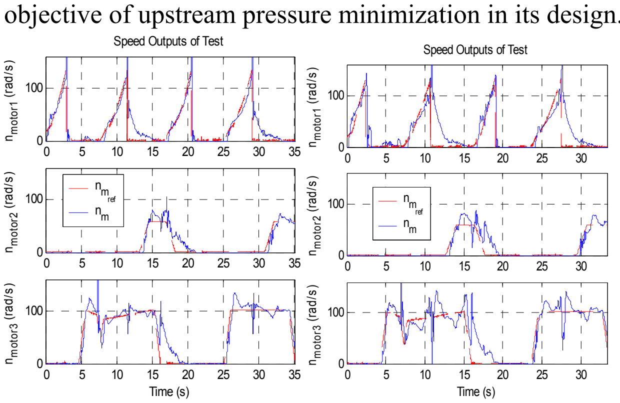

Fig. 12. Load motor speed response for the loading cycles

TABLE I
AVERAGE CYCLE METRICS FOR VARIOUS LOADING CYCLES

Controller	Centralized	De-Centralized
Cycle Time (sec)	35.05	33.5
η_{BFC} (%)	14.86	14.11
$\eta_{manifold}$ (%)	68.42	52.01
η_{pump} (%)	78.49	90.60
$\eta_{overall}$ (%)	7.98	6.65
Motor speed tracking error (rad/s)	8.70	11.39
Engine speed tracking error (rad/s)	14.93	16.78

9. CONCLUSIONS

This paper compares the performance, robustness and design properties of a centralized and a decentralized powertrain control scheme. A gain scheduling approach has been adopted for the controller designs. A robust analysis tool originally developed for analyzing centralized control networks, has been used here to analyze a decentralized powertrain control approach. The overall conclusion is that there is a tradeoff to be made. A centralized controller, by virtue of greater system knowledge, is able to be more robust and have higher performance. However, the tradeoff is that it less flexible to interchanging subsystems. A decentralized approach is more flexible, allowing separate controllers to be designed for the individual subsystems and then combined. The price to pay is lower performance or robustness since the decentralized approach doesn't allow full system information to be obtained by each decision making element.

ACKNOWLEDGMENT

The authors would like to thank Caterpillar Inc. for their generous support of this work.

REFERENCES

[1] Michel, A.N., "On the status of stability of interconnected systems", 1983, IEEE Transactions on Automatic Control, **AC-28,** pp. 639-653.

[2] Zhang W.Z, Bao. J and Lee. P.L, "Decentralized unconditional stability conditions based on the Passivity Theorem for multi-loop control systems", 2002, Industrial and Engineering Chemistry Research, **41**, n 6, pp. 1569-1578.

[3] A. Rapaport and A.Astolfi, "A Remark on the Stability of Interconnected Nonlinear Systems", 2001, Proceedings of the IEEE Conference on Decision and Control, **3**, pp. 3004-3008.

[4] Guo. Yi , Hill, D.J. and Wang. Y., "Nonlinear decentralized control of large-scale power systems", 2000, **36**, n 9, pp. 1275-1289.

[5] Leith, D.J and Leithead, W.E, "Survey of gain-scheduling analysis and design", 2000, International Journal of control, **73**, n 11, pp. 1001-1025.

[6] Zhang, R., Alleyne, A. and Carter, D.E., 2003, "Robust gain scheduling control of an earthmoving vehicle powertrain", Proceedings of ACC, **6**, pp. 4969-4974.

[7] Zhang, R., 2002, "Multivariable robust control of nonlinear systems with application to an electro-hydraulic powertrain", PhD dissertation, University of Illinois at Urbana Champaign, Urbana, IL.

[8] Prasetiawan, E., Zhang, R., Alleyne, A. and Tsao.T, 1999, "Modeling and control design of a powertrain simulation testbed for earthmoving vehicles", ASME, FPST, **6**, pp. 139-146.

[9] Zhang, R., Alleyne, A. and Prasetiawan, E., "Modeling and H2/H-infinity MIMO control of an earthmoving vehicle powertrain", Transactions of the ASME Journal of Dynamic Systems, Measurement and Control, **124**, pp. 625-636.

[10] Carter, D.E. and Alleyne, A., 2003, "Load Modeling and Emulation for an Earthmoving Vehicle Powertrain", Proceedings of ACC, **6**, pp. 4963-4968.

[11] Gupta, P. and Alleyne, A, 2001, "Powertrain optimization for an earthmoving vehicle", IMECE 2004, Anaheim.

[12] Gupta, P, 2004, "Powertrain optimization and controller design for an Earthmoving vehicle powertrain", MS dissertation, University of Illinois at Urbana Champaign, Urbana, IL.

[13] Skogestad, S and Postlethwaite, S, "Multivariable feedback control", New York, 2003.