PURDUE UNIVERSITY | Mechanical Engineering

Simultaneous Achievement of High Control Performance and Energy Efficiency of EH Systems

via

Parallel Connection of Pump and Valve Control Units

Bin Yao

Professor of School of Mechanical Engineering
Purdue University
West Lafayette, IN47907, USA

Outline

- ***Motivation***
- ***Brand New Hardware Configuration:***

  *-**Parallel connection** of pump and valves*

- ***Control Design I***

  -Easy to implement, Feedforward control of the pump

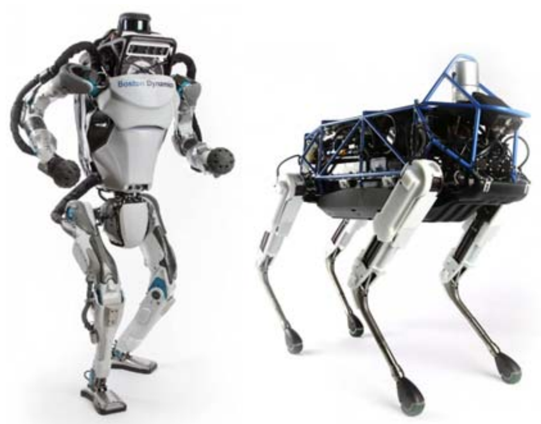
- ***Control Design II***

  -Minimized throttling losses

- ***Conclusions***

Motivation

☐ *Demand for high performance & high energy efficient electro-hydraulic systems*



Hydraulic robots: Atlas & Spot (Boston Dynamics)

Remote-controlled excavator

Heavy-duty manipulator

- ***Strict administrative regulations*** *demand energy consumption and CO_2 emissions reductions for the industry;*
- *Heating in a hydraulic system causes adverse effects;*
- *Operating costs would increase in energy-inefficient systems;*
- ***Energy sources must be carried on board*** *in mobile robotic systems.*

How to achieve objectives of high performance & high energy efficiency simultaneously?

Motivation

■ ***Valve controlled system***

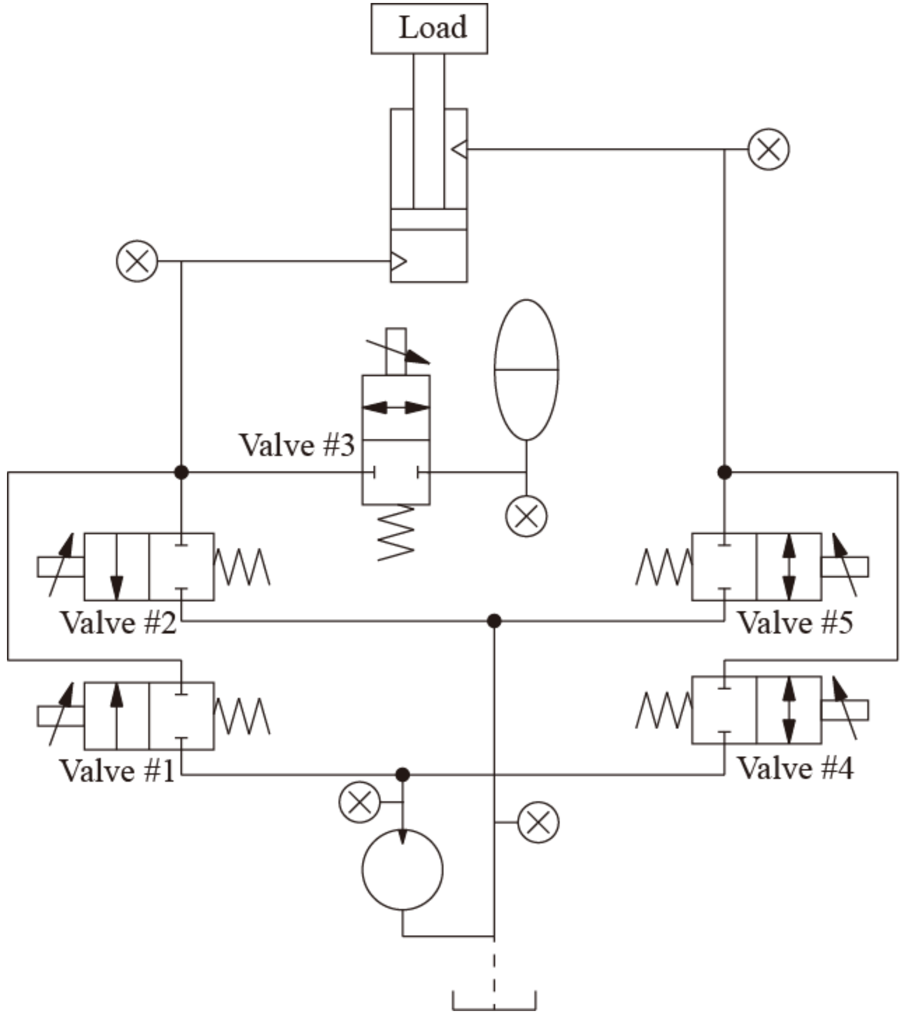
Single valve

Independent meter-in and meter-out

(J-O Palmberg, B. Eriksson, J. Mattila, A Shenouda...)

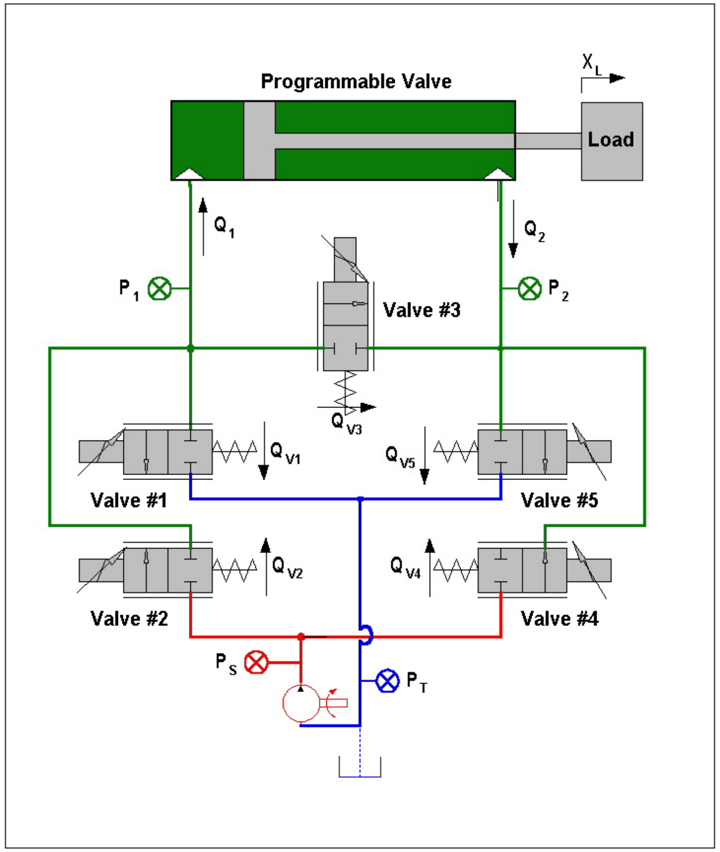
Energy-saving programmable valves with regeneration and energy recovery

(B. Yao, et al, 2000-2012)



INTEGRATED MECHATRNOIC DESIGNS

Automated Modeling and Energy Saving Adaptive Robust Control of Electro-Hydraulic Systems with Novel Programmable Valves



Better control performance achieved with cheaper valves and less energy usage!

Motivation

- ***Valve controlled system***

  Single valve

  Independent meter-in and meter-out

  (J-O Palmberg, B. Eriksson, J. Mattila, A Shenouda…)

  Energy-saving programmable valves with regeneration and energy recovery

  (B. Yao, et al, 2000-2014)

√ ***High control performance***

× *Unavoidable significant amount of throttling losses*

Motivation

- ***Pump controlled system***

Variable displacement or variable speed

(M. Ivantysynova, N. Manring, T. Minav, KK. Ahn, B. Xu…)

√ High energy efficiency

-Generally, lower bandwidth compared to the servo valve

-Improving the pump performance→ better control performance

-Asymmetric cylinder

One theme in IFK'2014 in Aachen:

√ Higher system energy efficiency demands have made pump controlled systems a trend

× Poor control performance due to limited closed-loop bandwidths of pump controlled systems

Motivation

Valve controlled system

Single valve

Independent meter-in and meter-out

(J-O Palmberg, B. Eriksson, J. Mattila, A Shenouda…)

Energy-saving programmable valves

(B. Yao…)

√ High control performance

✕ Large amount of throttling losses

Pump controlled system

Variable displacement or variable speed

(M. Ivantysynova, N. Manring, T. Minav, KK. Ahn, B. Xu…)

√ High energy efficiency

-Generally, lower bandwidth compared to the servo valve

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Our idea

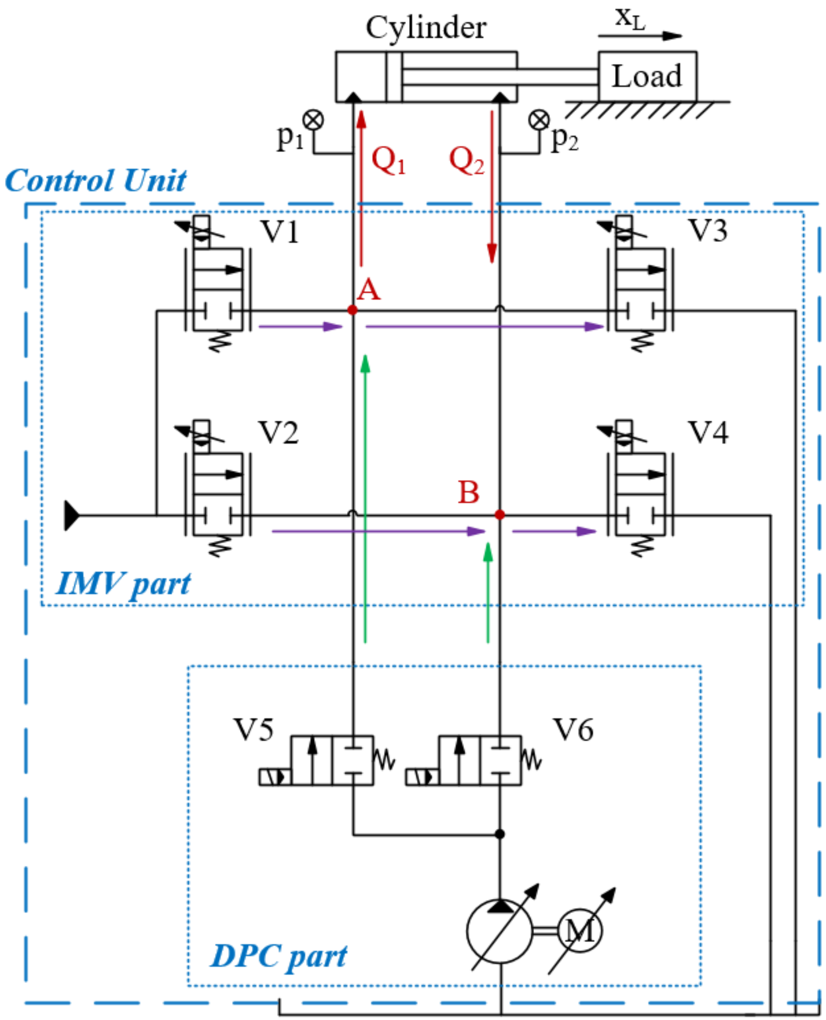
Combining and making full use of benefits of the two different types of control units

***parallel connection**: independent metering valves & pump*

Control performance → *Better valve controlled system*

Energy efficiency → *Pump controlled system*

Hardware Configuration



- *Two main parts:*

-Independent metering valves (IMV) part:

-Direct pump control (DPC) part:

- ***Parallel connection** of pump and valves*

-Flow @ point A and B

- *Basic working principles*

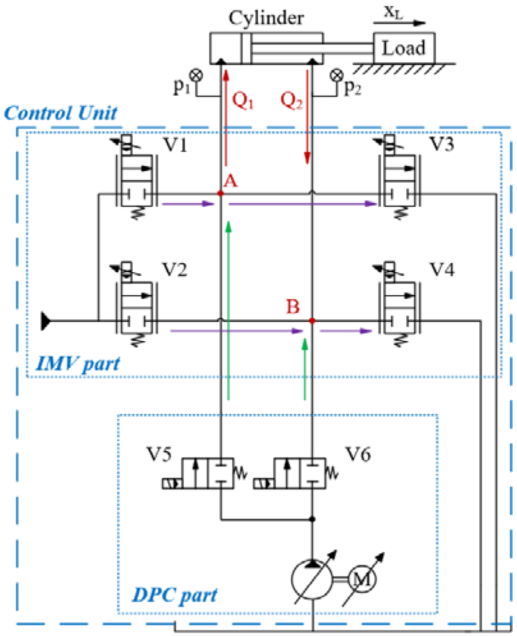
*-Pump provides the majority amount of flow---**energy-efficient***

*-Valves guarantee tracking performance with small amount of flow---**high control performance***

Hardware Configuration

Experimental Facilities at the State Key Laboratory of Fluid Power and Mechatronic Systems, Zhejiang University, Hangzhou, China, where I was honored as a Changjiang Chair Professor as well

Control Design



■ ***Challenges***

-parametric uncertainties, uncertain nonlinearities, disturbances…

*-**flexibilities** brought by the hardware configuration*

*-relatively poor **dynamic performance of the pump***

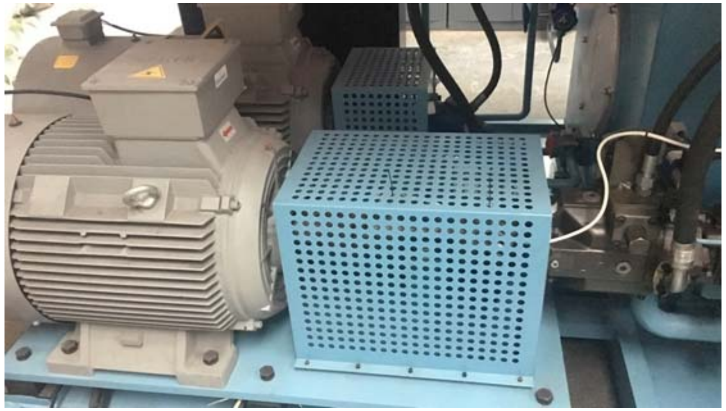
*-how to **minimize the throttling losses***

■ *How to control the two parts coordinately to achieve the two objectives simultaneously?*

Two control designs will be presented.

Control Design I

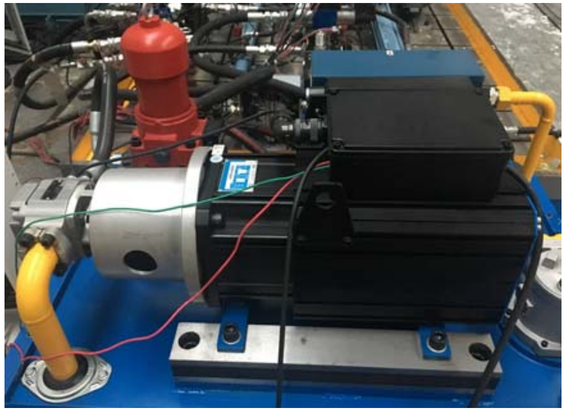
- ***Relatively poor dynamic performance of the pump in the test rig***



Variable displacement pump
-slow dynamic response
-time-delay
-large outlet compressible volume

time-delay & 2nd order

$$G_{p1}(s) = \frac{Q_{p1}(s)}{u_{p1}(s)} = e^{-\tau_{d1}s} \frac{k_{p1}\omega_n^2}{s^2 + 2\varepsilon\omega_n s + \omega_n^2}$$

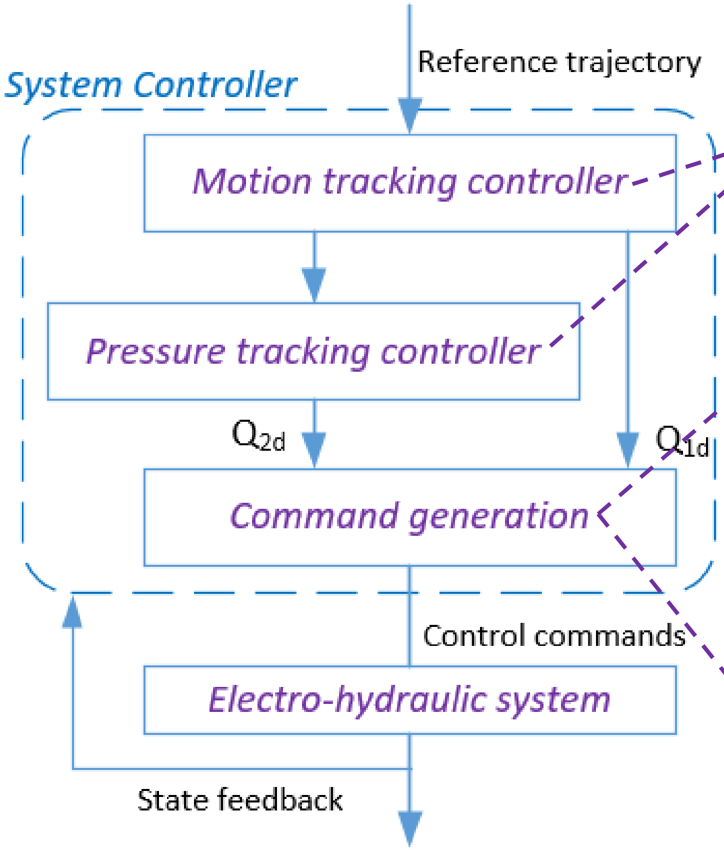


Servo-motor pump
-better, but still not as good as the valve

time-delay & 1st order

$$G_{p2}(s) = \frac{Q_{p2}(s)}{u_{p2}(s)} = e^{-\tau_{d2}s} \frac{k_{p2}}{\tau_n s + 1}$$

Control Design I



- ***Desired cylinder flow*** $\boldsymbol{Q_{1d}}$ *and* $\boldsymbol{Q_{2d}}$ *based on adaptive robust control (**ARC**)approach*

- ***Feedforward control*** *of the pump*

$$u_p(s) = \frac{1}{G_p(s)} Q_{ideal}(s)$$

*-to provide the **ideal cylinder flow*** $\boldsymbol{Q_{1\ ideal} = A_1 \dot{x}_d}$ *and* $\boldsymbol{Q_{2\ ideal} = A_2 \dot{x}_d}$

-no feedback---easy to implement in practice

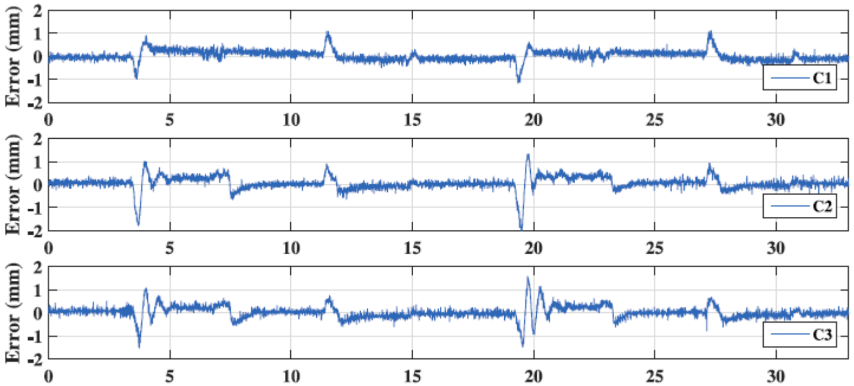
- *Valves control the rest amount of flow*

-differences *between the desired flow* $\boldsymbol{Q_{1d}}$ ***&*** $\boldsymbol{Q_{2d}}$ *and the ideal flow* $\boldsymbol{Q_{1\ ideal}}$ ***&*** $\boldsymbol{Q_{2\ ideal}}$

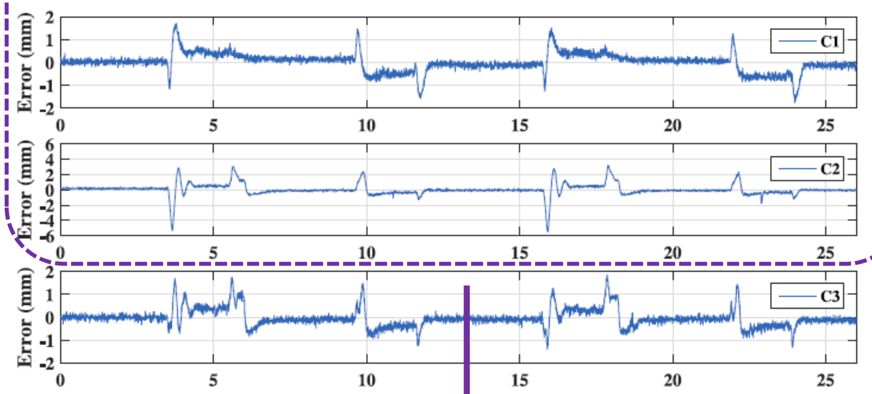
Comparative Experiments with Controller I

- ***Tracking performance*** *(using the variable displacement pump)*
- *With (C1) and without (C2) feedforward control of the pump*
- *Four-valve independent metering control method (C3)*

Low speed & acceleration$(0.15m/s,\ 0.3m/s^2)$



High speed & acceleration$(0.25m/s,\ 3m/s^2)$



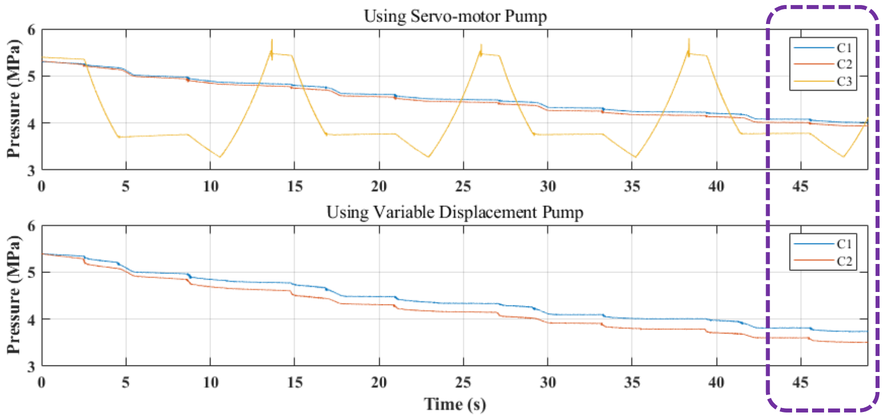
✓ *Same level of* ***high tracking performance:*** *C1 & C3*

✓ ***Effectiveness of the feedforward control*** *method in C1 (such a pump can hardly be used in a precise motion control project)*

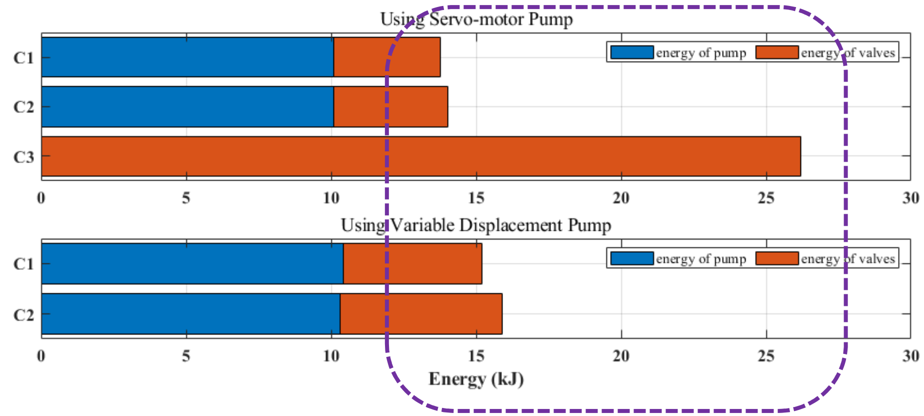
Comparative Experiments with Controller I

- ***Energy consumption analyses***

Accumulator pressure comparison



Energy calculation results



✓ ***High level of energy efficiency****: both C1 & C2 (about 40%~50% less than C3)*

C3: an energy efficient valve controlled system

✓ *C1 is a little better than C2 (more obvious with the variable displacement pump due to the poor dynamic performance)*

L. Lyu, Z. Chen and B. Yao, "Development of Pump and Valves Combined Hydraulic System for Both High Tracking Precision and High Energy Efficiency," in ***IEEE Transactions on Industrial Electronics****, vol. 66, no. 9, pp. 7189-7198, Sept. 2019.*

L. Lyu, Z. Chen and B. Yao, " Pump and Valves Coordinated System with Further Improved Energy Efficiency", Joint IFAC CAMS & WROCO, September 18-20, 2019, KAIST, Daejeon, Korea

Control Design I

- ***High control performance & high energy efficiency***
- *Easy to implement in practice (feedforward control of the pump)*

↓ *What still can be improved?*

A. ***discrepancies*** *between the desired one* $\boldsymbol{Q_{1d}}$ **&** $\boldsymbol{Q_{2d}}$ *and the ideal flow* $\boldsymbol{Q_{1\ ideal}}$ **&** $\boldsymbol{Q_{2\ ideal}}$
-will lead to extra energy wastes & cannot be reduced or minimized

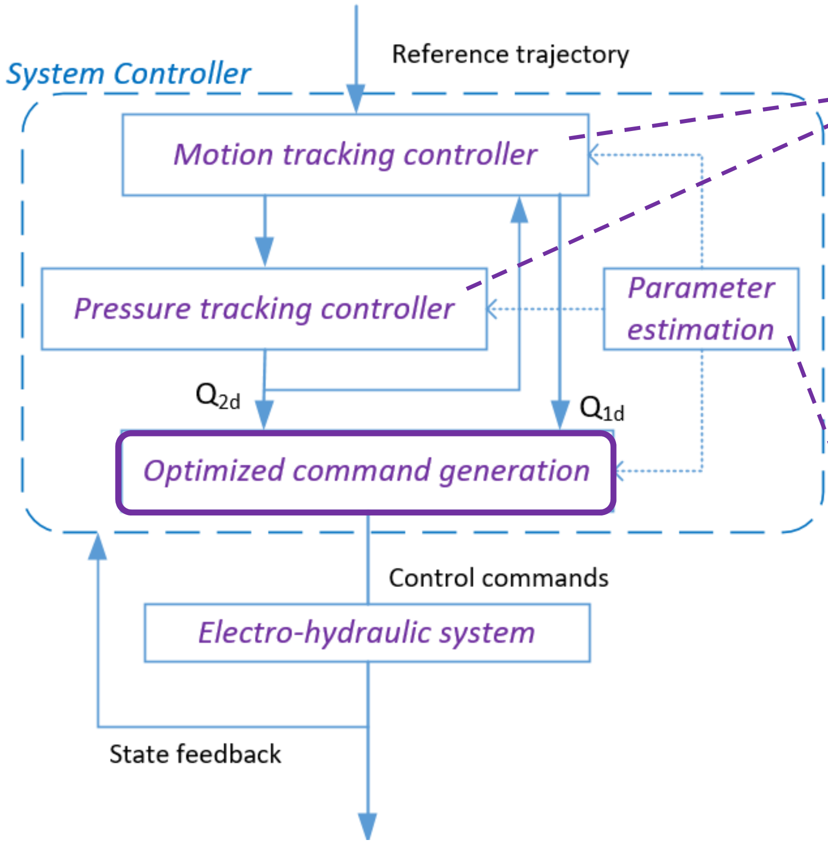
B. ***The pump is not "actively controlled"***
-the control command has been decided once the reference trajectory is given
-the pump would not adjust based on the real-time information about the system

How to minimize the throttling losses by controlling the pump actively?

Control Design II

- *Same hardware configuration* ***using the <u>servo-motor pump</u>***

  *-**Better** dynamic performance, but **still not as good as** the valves*



- ***Desired compensation integrated direct/indirect ARC (DCDIARC)***

  -Desired cylinder flow $\boldsymbol{Q_{1d}}$ and $\boldsymbol{Q_{2d}}$

  *-**Desired states** ($\boldsymbol{x_d}, \boldsymbol{\dot{x}_d}$…) instead of the feedback signals in the model compensation terms*

  -Separated parameter estimation

L. Lyu, Z. Chen and B. Yao, "Advanced Valves and Pump Coordinated Hydraulic Control Design to Simultaneously Achieve High Accuracy and High Efficiency," in IEEE Transactions on Control Systems Technology, under review.

Control Design II

- ***Optimized command generation***

  -Desired cylinder flow $\boldsymbol{Q_{1d}}$ *and* $\boldsymbol{Q_{2d}}$ *are given by the motion & pressure tracking controller*

$$Q_{1d} = Q_{1da} + Q_{1ds}$$

$$Q_{1da} = Q_{1da1} + Q_{1da2} + Q_{1da3}, Q_{1ds} = Q_{1ds1} + Q_{1ds2}$$

$$Q_{1da1} = \frac{V_{1d}}{A_1}[(\frac{A_1^2}{V_{1d}} + \frac{A_2^2}{V_{2d}})\dot{x}_d - \frac{A_2}{V_{2d}}Q_{2da} - \frac{A_1}{V_{1d}}\hat{\theta}_7 - \frac{A_2}{V_{2d}}\hat{\theta}_8 + (\frac{\partial F_{Lda1}}{\partial t} + \frac{\partial F_{Lda1}}{\partial \hat{\theta}_{s1}}\dot{\hat{\theta}}_{s1} + \frac{\partial F_{Lda2}}{\partial t})\hat{\theta}_5]$$

$$Q_{1da3} = -\frac{V_1}{A_1}\frac{A_2}{V_2}Q_{2ds} \qquad Q_{1da2} = -\frac{V_{1d}}{A_1}\hat{d}_2$$

$$Q_{1ds1} = -k_{3s1}z_3, \; Q_{1ds2} = -k_{3s2}z_3$$

$$Q_{2d} = Q_{2da} + Q_{2ds}$$

$$Q_{2da} = Q_{2da1} + Q_{2da2}, Q_{2ds} = Q_{2ds1} + Q_{2ds2}$$

$$Q_{2da1} = A_2\dot{x}_d - \hat{\theta}_5 V_{2d}\dot{p}_{2d} - \hat{\theta}_8 \qquad Q_{2da2} = V_{2d}\hat{d}_p$$

$$Q_{2ds1} = -k_{ps1}z_p, \; Q_{2ds2} = -k_{ps2}z_p$$

Low-frequency terms *(desired model compensation)---to generate* ***pump commands***

Q_{1da1}, Q_{1da2} & Q_{2da1}, Q_{2da2}

High-frequency terms *(directly related to the* ***errors****)---to generate* ***valves commands***

Q_{1da3}, Q_{1ds1}, Q_{1ds2} & Q_{2ds1}, Q_{2ds2}

- ***Theoretical analyses***

✓ *Considering the* ***dynamic properties of the pump and the valves***

✓ ***Optimized*** *to achieve high energy efficiency*
-errors→0, valve flow→0, throttling losses→0

Comparative Experiments with Controller II

■ ***Tracking performance***

-Set 1 low speed & Set 2 high speed

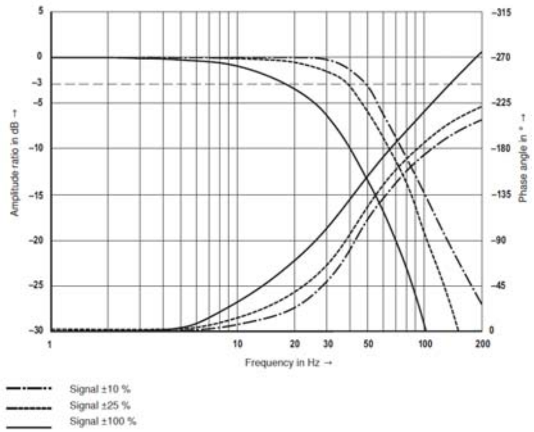
-C1: controller II   C2: controller I using DCDIARC   C3: four-valve independent metering

		$\|e\|_1\ 10^{-3}m \cdot s$	$\|e\|_2\ 10^{-6}m^2 \cdot s$	$\|e\|_{max}\ 10^{-3}m$
Set 1	***C1***	***8.7***	***1.9***	***0.70***
	C2	*9.1*	*2.2*	*0.94*
	C3	*13.8*	*4.7*	*0.97*
Set 2	***C1***	***9.7***	***3.3***	***1.1***
	C2	*10.1*	*3.6*	*1.3*
	C3	*12.5*	*5.3*	*1.2*

✓ *C1, C2 & C3 achieved same level of **high tracking performance***

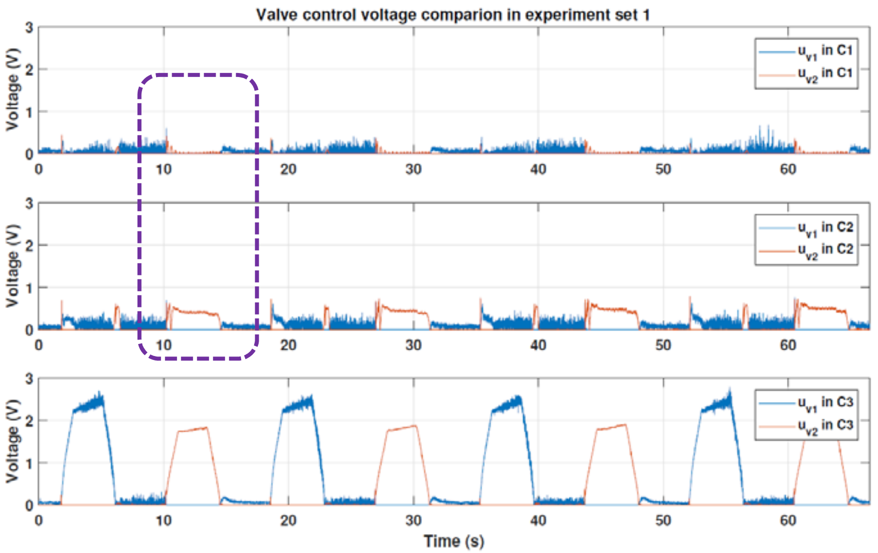
✓ ***Promising results:*** *C1 even a little better than C3* ***(same valves)***

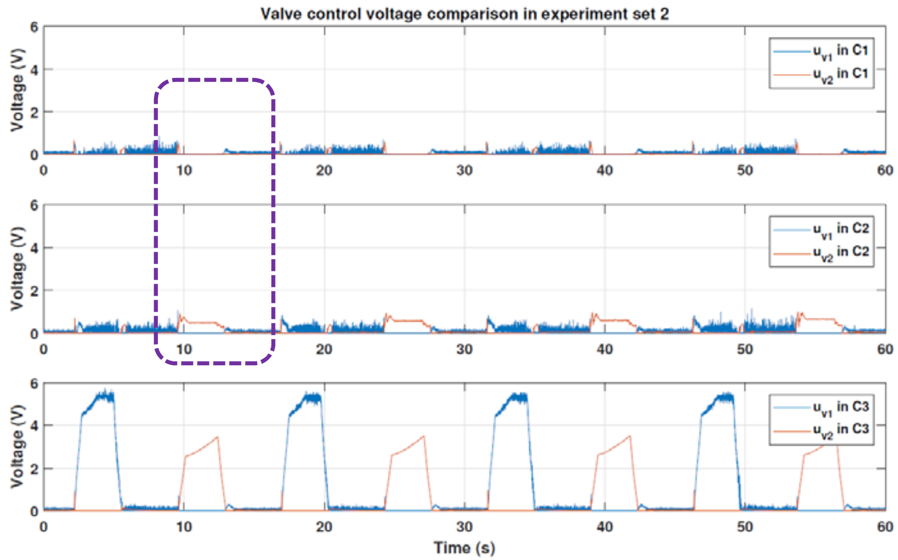
higher available controller gains *in C1 & C2:*
small-signal range → higher bandwidth



Comparative Experiments with Controller II

- ***Control command comparison of the valves***



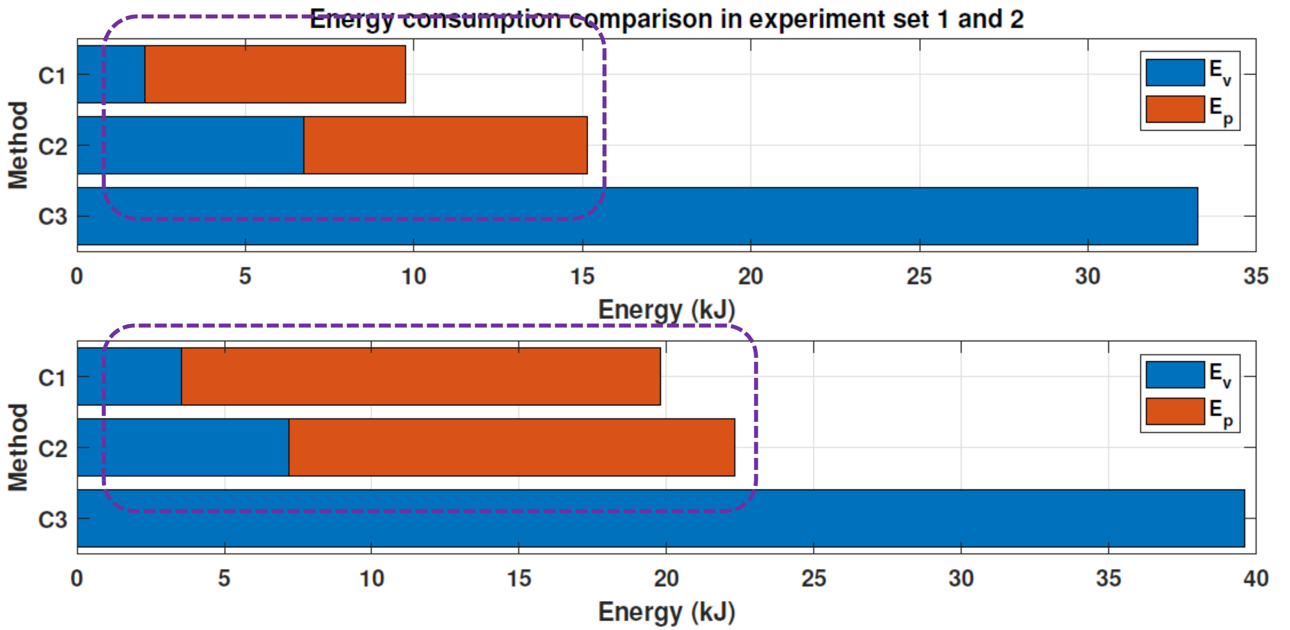


✓ *The control commands are within small-signal range in C1 & C2*

✓ *The control commands in C1→0 --- **optimized results, minimized throttling losses***

Comparative Experiments with Controller II

■ *Energy consumption comparison*



- ✓ ***Energy consumption*** *C1 (about 50%~70% less than C3)*
- ✓ ***High level of energy efficiency****: C1 (about 50%~70% less than C3)*
- ✓ *Obvious energy saving effects* compared with controller I ***(about 14%~30% less than C2)***

L. Lyu, Z. Chen and B. Yao, "Advanced Valves and Pump Coordinated Hydraulic Control Design to Simultaneously Achieve High Accuracy and High Efficiency," in IEEE Transactions on Control Systems Technology, under review.

Conclusions

- ***Brand new hardware configuration***

  Parallel connection *of the pump and independent metering valves*

- ***Control design I***

  Easy to implement, feedforward control of the pump

- ***Control design II***

  Minimized throttling losses

High control performance & High energy efficiency

Thank You!