Optimal Design of Motion Control Systems

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What is Optimal Design

A. System components must have the capability to move in minimum time

Hardware capability + trajectory planning

B. System must use its capabilities and be tuned for optimum performance

When the motion time, T, gets shorter:

- acceleration increases by $1/T^2$
- current and power dissipation increase
- motor overheats

Motion time should be long enough to avoid damages to the motors

Another formulation of objective:

Perform a move within time T, while minimizing the motor temperature

Design Steps

- Best motor selection **(Higher utility, yet no overheating)**
- Best coupling between motor and load
- Best velocity profile

Optimality

- Rotate a motor by an angle θ and stop within T
- Select the best velocity profile that results in minimum motor temperature

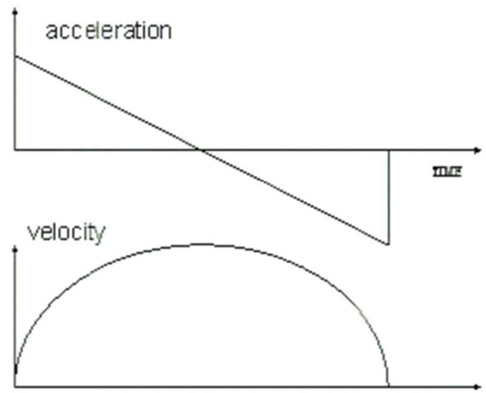
minimum power dissipation

Optimal Velocity Profile

From Optimal Control Theory

The optimal velocity profile is a parabola

Minimum energy dissipation



Energy dissipation per step is

$$E = \frac{12 r J^2 \theta^2}{K_t^2 T^3}$$

Where:

r = armature resistance
J = moment of inertia
θ = rotation angle
K_t = torque constant
T = motion time

High currents at the ends saturates the Amp. Thus, parabolic profiles are not commonly used

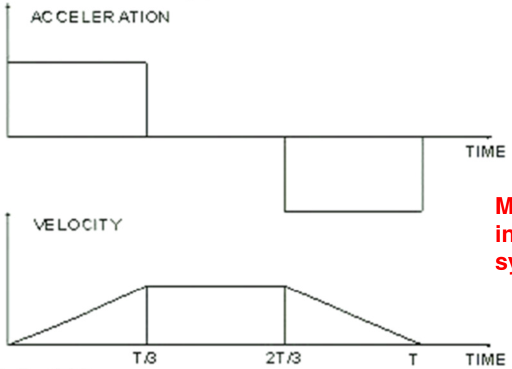
Optimum profile is not practical

Suboptimal Profile: Trapezoidal

- The closest to the optimal (parabolic) is the trapezoidal velocity profile. Then, what's the optimum combination of acceleration - uniform velocity - deceleration ?

The best trapezoidal velocity profile is where the three intervals are equal

From Optimization Theory



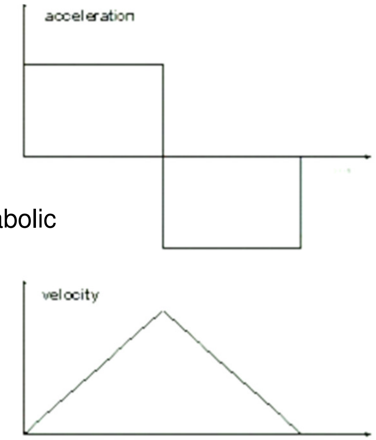
Most popular profile in motion control systems

Here $E = \dfrac{13.5 r J^2 \theta^2}{K_t^2 T^3}$ ⟹ 12% increase in power dissipation compared to parabolic velocity profile

Suboptimal Profile: Triangular

- Acceleration Bang-Bang
  - Not optimal in terms of power dissipation

Triangular profile



33.3% increase in power dissipation compared to parabolic velocity profile

$E = \dfrac{16 r J^2 \theta^2}{K_t^2 T^3}$

Optimal Coupling

Examples of coupling:
- Gear box
- Reduction by pulleys
- Belt and pulley
- Rack and pinion
- Lead screw

Coupling is optimal when motor and load inertia are matched

⇓

minimum temperature rise in the motor

Objective: Select coupling ratio to minimize motor temperature

Solution: Select coupling ratio to achieve inertial match between motor and reflected load

Rotary Load ⇒

Motor inertia - J_m

Load inertia - J_{LO}

Reduction ratio - N

Reflected Load - $J_L = J_{LO} / N^2$

Inertial match - $J_m = J_{LO} / N^2$

Optimal Coupling - $N = \sqrt{J_{LO}/J_m}$

Optimal Coupling

Ex: A motor with inertia $J_m = 0.0002 kgm^2$ drives 0.5kg load through a pulley. Calculate the pulley radius for optimal performance

Motor inertia - J_m

Load mass - M

Pulley radius - R

Reflected Load - $J_L = MR^2$

Inertial match - $J_m = MR^2$

$$R = \sqrt{\frac{J_m}{M}} = \sqrt{\frac{0.0002}{0.5}} = 0.002m$$

Non-optimal Coupling
Torque and Power Penalty

What if we cannot achieve optimal coupling ?

If optimal coupling is N, and

actual coupling ratio is n=D*N, where

D= Deviation from optimum

then,

Torque penalty: RT = ½ (D+1/D) → **Unnecessary torque developed**

Power dissipation penalty: PT = ¼ $(D+1/D)^2$

→ **Unnecessary power dissipation**

Non-optimal Coupling

Ex: A motor with J_m=0.0002kgm² direct drives a load J_L=0.005kgm². Check whether direct drive is optimal, if not, calculate the torque penalty and power penalty

Optimal reduction is N=5 ⇐ $Jm = JL \times \frac{1}{N^2}$

If direct drive is used n=1, then D=0.2 ⇐ $D = \frac{n}{N}$

Torque penalty: RT=2.6

Power penalty: RP=6.76

Optimum Motor Selection
Quality Factor

Objective: Select the motor that results in minimum temperature

Answer: Select a motor with minimum:

$$Q = \frac{rJ_m R_{th}}{K_t^2}$$

⇒ **Calculate Q for all candidate motors. Q is proportional to temperature rise**

Where:

R – armature resistance

J_m – motor inertia

R_{th} – thermal resistance of motor

K_t – torque constant

Optimum Motor Selection

Design procedure:

Motion requirements are defined

Motor is selected

Optimal coupling between motor and load is used.

Ex: Following three motors satisfy the design requirement of a certain application. Select the most optimal motor

Motor	A	B	C
r (Ω)	4.0	2	1.8
J_m [Kg · m²]	0.00012	0.0002	0.0005
R_{th} [°C / W]	3	2.2	1.8
K_t [N_m / A]	0.08	0.12	0.15

Flexible Control Systems

- Centralized Control Systems
- Distributed Control Systems
- Flexible-Distributed Control Systems

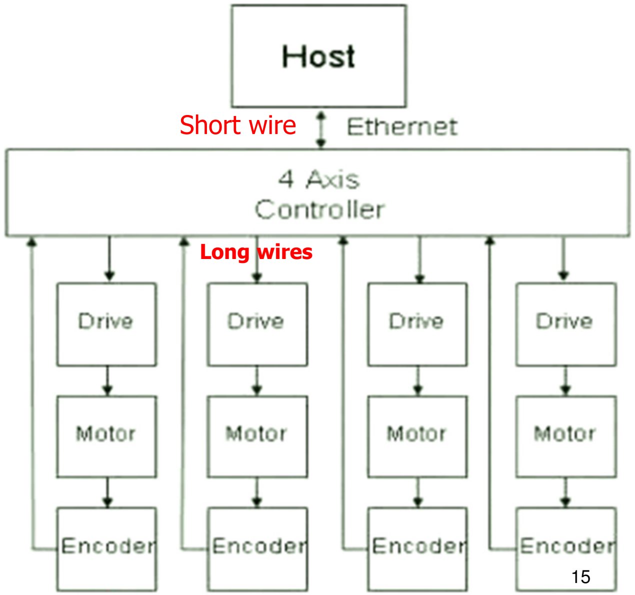
Centralized Control Systems

- All motors are controlled directly by one multi-axis motion controller
  - E.g. **DMC-2183: 8axis, Ethernet**
- Advantages
  - Simple communication – host communicates with a single motion controller
  - Easy programming – information about all motors is present in one controller
  - Coordinated motion is performed by motion controller
  - Low controller cost per axis
- Disadvantages
  - Long wiring – wires from drives, encoders and switches must be connected to the central controller

Centralized Control Systems cntd..

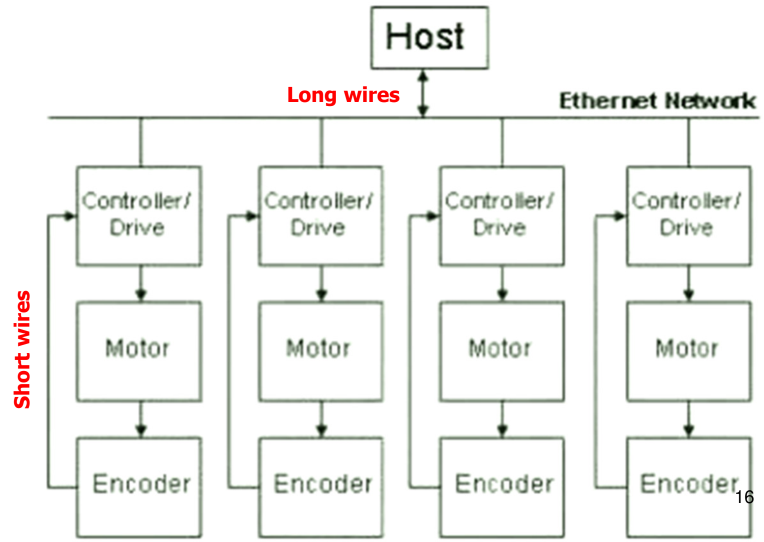
Sometimes, machine design dictates that controllers be distributed through the machine to minimize wiring. In this case, central control is not an option

Distributed Control Systems



Distributed Control Systems

Motors are controlled by several motion controllers that are distributed throughout the machine



Distributed Control Systems

Typical distributed control systems use single-axis controllers or drives

Advantages:

- Short wires – eliminates associated problems

Disadvantages:

- Complicated communication
- Complex motion programming
- High cost of network components
- High cost of controller per axis

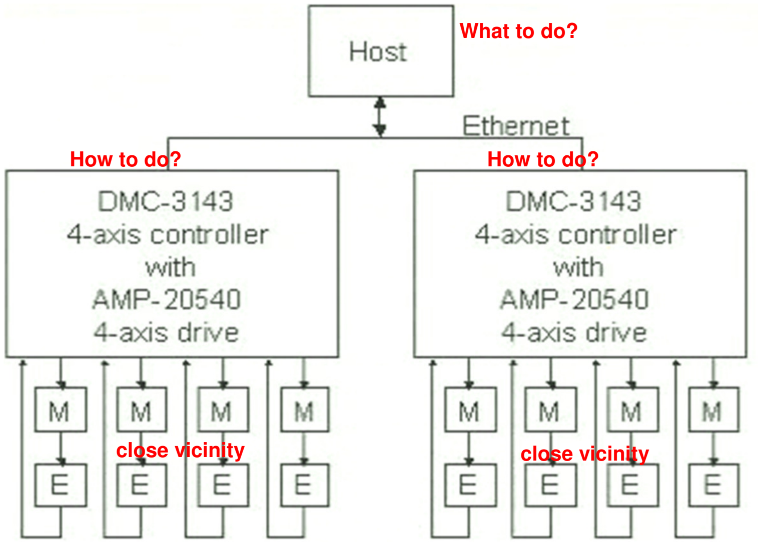
Ethernet Based Distributed Control

Popular and widely used in Industry. A cost effective choice

Ethernet offers advantages over other networks

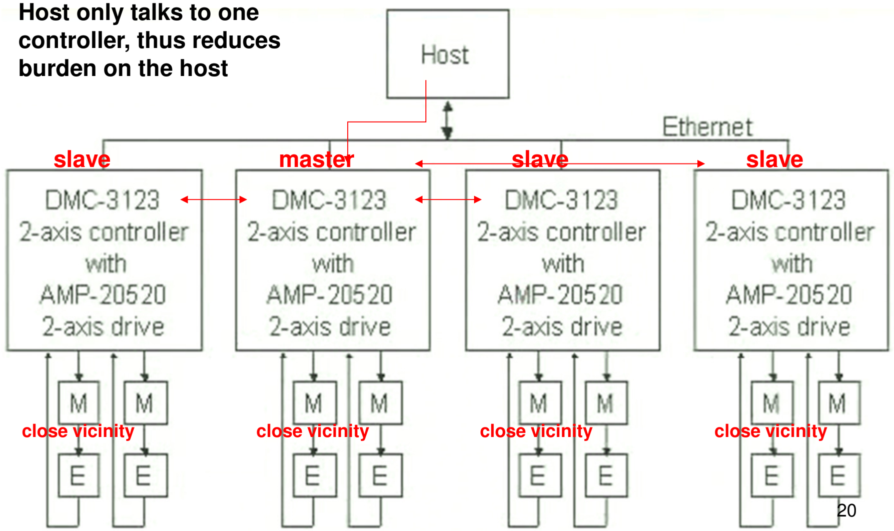
1. Lower cost of network components
2. TCP/IP protocol is well known
3. Network allows mixing components such as controller, I/O devices, camera, etc.
4. Ethernet systems are non-deterministic, and data sent more frequently than 1 msec may be delayed. Since communication is at a high-level between the host and the controller (commands sent less frequently than 1 msec) the non-deterministic nature of Ethernet is not an issue.

Flexible Distributed Control Systems: Centralized Islands



Flexible Distributed Control Systems: Centralized Islands

Host only talks to one controller, thus reduces burden on the host



Flexible Distributed Control Systems

- Combines the advantages of central and distributed control systems
- Compared to distributed control systems, FDCS is

  Flexible

  Reduces host communication burden

  Performs coordinated motion

  Lower cost

  } **multiple axis controllers**

- Flexible-distributed control is not restricted to single-axis motion controllers.
- The user divides his system into islands with each island having from 1 to 8 axes
- This gives designer *flexibility*.
- Example- An 8-axis machine can use:

  4# of 2-axis controllers, or
  2# of 4-axis controllers, or
  2# of 3-axis controller+1# of 2-axis controller