Mechatronic Systems Design

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Design is an engineering philosophy that can vary between different schools of thought.

MSD should follow a well-defined iterative design steps that incorporate synergetic design. It should include the following operations:

1. User and system requirements analysis
2. Conceptual Design
3. Mechanical, software, electronics, and interface design
4. System modeling and simulation
5. Prototyping and testing
Mechatronic System Block Diagram

**Mechanical Skeleton**
- **Actuator** (e.g. Electric Pneumatic Hydraulic)
- **Power Interface** (e.g. H-Bridge, Pump, Power OP AMPS)
- **Mechanical System** (e.g. Robot Production System Automobile)

**Electronics**
- **Sensor** (e.g. Position Speed Temperature Pressure)
- **Signal Conditioning** (e.g. Amplifiers ADC Filter)
- **Controller** (e.g. Computer, PLC, embedded system)

**Control/Computer/Software**
Design Stages

- **Stage 1: Define the Objective and Specifications**
- **Stage 2: Analyze and Design**
- **Stage 3: Build and Test**
Stage 1: Define the Objectives & Specifications

1. Identify the problem.
2. Research and literature review
3. Set the initial system specifications.
Design Stage 2: Analyze and Design

4. Establish a general block diagram and a flow chart
   - Specify system I/O
   - Specify control algorithm to use

5. Choose appropriate components
   - Sensors and actuators; Controller
   - Drive and signal conditioning circuits

6. Concurrent/Synergistic Design
   - Mechanical structure; Electronic system; Software/controller; Interface

7. Model and simulate the system
Synergistic Design
Stage 3: Build and Test

8. Emulate the controller hardware

9. Build prototype, test, and evaluate (modify if needed)
MSD Examples

- Liquid Level Control
- CNC Machine
Liquid Level Control

- Liquid level control systems are commonly used in many process control applications to control, for example, the level of liquid in a tank.

- Liquid enters the tank using a pump, and after some processing within the tank the liquid leaves from the bottom of the tank.

- The requirement in this system is to control the rate of liquid delivered by the pump so that the level of liquid within the tank is at the desired point.
Tank Level Control System

[Ref.] Dogan Ibrahim
Plant Input-Output

- Plant input: Flow rate in
- Plant output (controlled variable): Fluid Height
Required Components

- Actuator (pump) to supply flow
- Sensor to measure height
- Controller
- Drive Circuit
12-Volt Water Pump

TYPICAL PERFORMANCE

<table>
<thead>
<tr>
<th>PRESSURE</th>
<th>FLOW</th>
<th>CURRENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAR</td>
<td>PSI</td>
<td>GPM</td>
</tr>
<tr>
<td>0.0</td>
<td>0</td>
<td>2.8</td>
</tr>
<tr>
<td>0.7</td>
<td>10</td>
<td>2.2</td>
</tr>
<tr>
<td>1.4</td>
<td>20</td>
<td>2.0</td>
</tr>
<tr>
<td>2.1</td>
<td>30</td>
<td>1.7</td>
</tr>
<tr>
<td>2.8</td>
<td>40</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Graph: Flow (GPM) vs Pressure (PSI) and Current (AMPS)
# Sensors Choice

<table>
<thead>
<tr>
<th>Controller</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultrasonic</td>
<td>Needs added circuitry</td>
</tr>
<tr>
<td><strong>Potentiometer with float</strong></td>
<td><strong>Works well</strong></td>
</tr>
<tr>
<td>Electrodes</td>
<td>Works</td>
</tr>
<tr>
<td>Resistance probes</td>
<td>Discrete applications</td>
</tr>
<tr>
<td>Photo sensors</td>
<td>Discrete applications</td>
</tr>
<tr>
<td></td>
<td>Also, might not work with water</td>
</tr>
<tr>
<td>Controller</td>
<td>Comment</td>
</tr>
<tr>
<td>-------------------</td>
<td>----------------------------------------------</td>
</tr>
<tr>
<td>Microcontroller</td>
<td>Works well</td>
</tr>
<tr>
<td>PLC</td>
<td>Too expensive</td>
</tr>
<tr>
<td></td>
<td>Not usually used for SISO</td>
</tr>
<tr>
<td>DSP</td>
<td>Too complex</td>
</tr>
<tr>
<td></td>
<td>Not enough inputs to justify</td>
</tr>
<tr>
<td></td>
<td>No need for fast response to justify</td>
</tr>
<tr>
<td>FPGA</td>
<td>Too complex</td>
</tr>
<tr>
<td></td>
<td>No need for fast response</td>
</tr>
<tr>
<td>PC with DAQ</td>
<td>Too expensive</td>
</tr>
<tr>
<td></td>
<td>No need to visual graphics</td>
</tr>
<tr>
<td>Electronics Only</td>
<td>Works well, but difficult to modify</td>
</tr>
</tbody>
</table>
Power Op-Amp

FEATURES
- 3A Current Capability
- $A_{\text{VO}}$ Typically 90 dB
- 5.5 MHz Gain Bandwidth Product
- 8 V/μs Slew Rate
- Wide Power Bandwidth 70 kHz
- 1 mV Typical Offset Voltage
- Short Circuit Protection
- Thermal Protection with Parole Circuit (100% Tested)
- 16V–60V Supply Range
- Wide Common Mode Range
- Internal Output Protection Diodes
- 90 dB Ripple Rejection
- Plastic Power Package TO-220

APPLICATIONS
- High Performance Power Op Amp
- Bridge Amplifiers
- Motor Speed Controls
- Servo Amplifiers
- Instrument Systems

DESCRIPTION
The LM675 is a monolithic power operational amplifier featuring wide bandwidth and low input offset voltage, making it equally suitable for AC and DC applications.

The LM675 is capable of delivering output currents in excess of 3 amps, operating at supply voltages of up to 60V. The device overload protection consists of both internal current limiting and thermal shutdown. The amplifier is also internally compensated for gains of 10 or greater.
Components

- **Water tank**
  - A plastic container with measurements 12 cm × 10 cm × 10 cm.

- **Water pump**
  - 12V water pump drawing about 3A when operating at the full-scale voltage.

- **Level sensor**.
  - A rotary potentiometer type level sensor with a floating. The level of the floating arm, and hence the resistance, changes as the liquid level inside the tank is changed. The resistance changes from 430 to 40 Ohm.
Components

- **Microcontroller**
  - A PIC16F877 type microcontroller is used in this project as the digital controller. In general, any other type of microcontroller with a built-in A/D converter can be used.

- **D/A converter**
  - An 8-bit AD7302 type D/A converter is used in this project.

- **Power amplifier**
  - An LM675 type power (30W of power) amplifier is used to increase the power output of the D/A converter and drive the pump.
System Model: Water in the Tank

\[ Q_{\text{in}} = Q + Q_{\text{out}} \]

\[ Q_{\text{in}} = A \frac{dh}{dt} + C_d a \sqrt{2gh} \]

\[ A \frac{d\delta h}{dt} + C_d a \sqrt{2(\delta h + h_0)} = \delta Q_{\text{in}} + Q_0 \]

\[ A \frac{d\delta h}{dt} + \frac{Q_0}{2h_0} \delta h = \delta Q_{\text{in}} \quad \Rightarrow \quad \frac{h(s)}{Q_{\text{in}}(s)} = \frac{1}{As + Q_0/2h_0} \]
The pump, level sensor, and the power amplifier are simple units with proportional gains and no system dynamics. The input–output relations of these units can be written as follows: for the pump,

\[ Q_p = K_p V_p; \]

for the level sensor,

\[ V_l = K_l h; \]

and for the power amplifier,

\[ V_0 = K_0 V_l. \]
Hardware Set-up

[Ref.] Dogan Ibrahim
Identifying the Model by Experiment

- The system was identified by carrying out a simple step response test.

- The height of the water inside the tank (output of the level sensor) was recorded in real time.

- The D/A has 8-bit, its resolution is about 19.5mV with a reference input of 5V, and this causes the step discontinuities shown in the response.

- The value of the step was chosen as 200, which corresponds to a D/A voltage of \(5V \times \frac{200}{256} = 3.9V\).
Open-Loop Transfer Function

\[
G(s) = \frac{Ke^{-sT_D}}{1 + sT_1},
\]

- \(T_D\) is the system time delay
- \(T_1\) is the time constant
First Order System Review

\[ \tau \frac{dy(t)}{dt} + y(t) = f(t) \]

\[ \frac{Y(s)}{F(s)} = \frac{1}{\tau s + 1} \]
Ziegler–Nichols system model parameters are given by $T_1 = 31\, \text{s}$, $T_D = 2\, \text{s}$ and

$$K = \frac{2345 - 2150}{200 \times 5000/256} = 0.05$$
Identifying the Model

Notice that the output of the microcontroller was set to 200, which corresponds to $200 \times \frac{5000}{256} = 3906 \text{ mV}$, and this was the voltage applied to the power. We then obtain the following transfer function:

$$G(s) = \frac{0.05e^{-2s}}{1 + 31s}$$

The time constant of the system is 31 s

less than one-tenth of the system time constant, i.e. $T < 3.1$ s

the sampling time is chosen to be 100 ms, i.e. $T = 0.1$ s
## Table 9.1 Open-loop Ziegler–Nichols settings

<table>
<thead>
<tr>
<th>Controller</th>
<th>$K_p$</th>
<th>$T_i$</th>
<th>$T_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportional</td>
<td>$\frac{T_i}{KT_D}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PI</td>
<td>$\frac{0.9T_i}{KT_D}$</td>
<td>$3.3T_D$</td>
<td></td>
</tr>
<tr>
<td>PID</td>
<td>$\frac{1.2T_i}{KT_D}$</td>
<td>$2T_D$</td>
<td>$0.5T_D$</td>
</tr>
</tbody>
</table>
PID Controller Design

\[
\frac{U(z)}{E(z)} = K_p \left[ 1 + \frac{T}{T_i(1 - z^{-1})} + T_d \frac{(1 - z^{-1})}{T} \right]
\]

\[
K_p = \frac{0.9T_i}{KT_D} \quad \text{and} \quad T_i = 3.3T_D
\]

\[
K_p = \frac{0.9 \times 31}{0.05 \times 2} = 279 \quad \text{and} \quad T_i = 3.3 \times 2 = 6.6
\]

\[
D(z) = K_p + \frac{K_p T}{T_i(1 - z^{-1})}
\]
CNC Machine

- Computer Numerical Control (CNC) system

- Specifications:
  - Speed
  - Accuracy
  - Working material
  - Power and Torque
  - Work area size
  - CNC machine size
  - User Interface
  - Cost
CNC Machine

- Motors for positioning
- Motor for drilling
CNC Machine: Positioning Actuator Options

(a) Pulse train → Stepping motor → Gear → Leadscrew → Work table

(b) Input → Comparator → DAC → dc servomotor → Gear → Leadscrew → Work table

[Ref] Goodfry
Stepper Advantages over Servo Motor

- **Lower cost**
  - All of the components associated with stepper systems (i.e., motors, drives, etc.) are less costly

- **Very accurate and dependable under normal circumstances**
  - Intrinsic to stepper motors is their ability to achieve high positional accuracy.

- **No tuning required**
  - Other than operating just under maximum capabilities of your drive/motor, no tuning is necessary.

- **Less mechanical reduction needed**
  - These motors operate best at lower speeds, lower reduction ratios are required.

- **Simpler system to understand**
  - Straightforward and easy to implement.

[Ref] CNC Machining Handbook by Overby
Motor Torque Calculations

- Determine the motion profile and calculate acceleration, deceleration and maximum velocity required to make the desired move.

- Select mechanical drive mechanism to be used and calculated inertia, friction and load torque using formulas provided in this document.

- Determine required motor torque for the specific application.

- Select proper motor and driver based on their speed-torque characteristics

[Ref.] www.t2cnc.hu
Motor Torque Calculations

Inertia:

\[ J_L = m_{W+T} \left( \frac{P}{2\pi} \cdot \frac{N_2}{N_1} \right)^2 \quad [kg \cdot m^2] \]

\[ J_{G1} = \frac{1}{8} m_{g1} D_{G1}^2 \left( \frac{N_2}{N_1} \right)^2 \quad [kg \cdot m^2] \]

\[ J_{G2} = \frac{1}{8} m_{g2} D_{G2}^2 \quad [kg \cdot m^2] \]

\[ J_T = J_L + J_{G1} + J_{G2} + J_s \left( \frac{N_2}{N_1} \right)^2 + J_M \quad [kg \cdot m^2] \]

Torque:

\[ T_a = J_T \alpha = (J_L + J_{G1} + J_{G2} + J_s \left( \frac{N_2}{N_1} \right)^2 + J_M) \frac{\omega_1 - \omega_2}{t} \quad [N \cdot m] \]

\[ T_L = \frac{m_{W+T} g P (\sin \alpha + \mu \cos \alpha)}{2\pi \eta} \quad [N \cdot m] \]

\[ T_T = T_L + T_a \quad [N \cdot m] \]

\[ T_M = K_s T_T \quad [N \cdot m] \]

[Ref.] www.t2cnc.hu
Selecting Stepper Motor

- Calculate the total torque needed at the output shaft of the motor.

- Use the motor performance curve to select a motor with at least 50% more torque than that calculated at the required maximum Speed.

- Select a driver that is capable of supplying the needed current to the motor of choice and providing the resolution needed.
# NEMA34 Stepper Motor

## Electrical Specifications

<table>
<thead>
<tr>
<th>Model</th>
<th>Step Angle (°)</th>
<th>Holding Torque Oz-In</th>
<th>Current / Phase A</th>
<th>Inductance / Phase mH</th>
<th>Resistance / Phase Ohm</th>
<th># of Leads</th>
<th>Rotor Inertia g.cm²</th>
<th>Motor Weight lb</th>
<th>Motor Length Inch</th>
</tr>
</thead>
<tbody>
<tr>
<td>863S22</td>
<td>1.2</td>
<td>283</td>
<td>5</td>
<td>1.7</td>
<td>2.8</td>
<td>6</td>
<td>1200</td>
<td>4.63</td>
<td>2.87</td>
</tr>
<tr>
<td>863S42</td>
<td>1.2</td>
<td>566</td>
<td>5.0</td>
<td>1.35</td>
<td>4.5</td>
<td>6</td>
<td>2500</td>
<td>6.61</td>
<td>4.13</td>
</tr>
<tr>
<td>863S68H</td>
<td>1.2</td>
<td>960</td>
<td>3.5</td>
<td>1.7</td>
<td>20</td>
<td>6</td>
<td>3300</td>
<td>8.37</td>
<td>5.00</td>
</tr>
</tbody>
</table>
Stepper Motor Torque-Speed Curves

NM23C10 Torque-Speed

![Graph showing the torque-speed characteristics of the NM23C10 stepper motor. The x-axis represents speed (RPM), and the y-axis represents torque (Nm and lbf-ft). The graph shows a decline in torque as speed increases.]
# Stepper Motors

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step Angle</td>
<td>1.8 degrees</td>
</tr>
<tr>
<td>Coil type</td>
<td>Two phase, unipolar six lead</td>
</tr>
<tr>
<td>Voltage</td>
<td>3.2 V</td>
</tr>
<tr>
<td>Amperage</td>
<td>2 A</td>
</tr>
<tr>
<td>Resistance</td>
<td>1.8 Ohm</td>
</tr>
<tr>
<td>Inductance</td>
<td>2.5 mH</td>
</tr>
<tr>
<td>Holding torque:</td>
<td>250 oz-in</td>
</tr>
</tbody>
</table>
Speed Profile
Stepper Motor Driver

Cytron Tech SD02B

- Support up to 2A per phase
- Smoother stepper motor rotation with 2/5/10 micro-stepping feature
- Able to drive stepper motor from 3V to 40V.
- 8V to 24V compatible for driver circuit supply voltage
- 5V logic level compatible inputs.
- Maximum speed up to 1000 steps per second or 1KHz pulses
- Enable/Disable pin for low power consumption mode.
- Heat sink with fan for fast thermal release

<table>
<thead>
<tr>
<th>Label</th>
<th>Function</th>
<th>Label</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Heat sink with fan</td>
<td>F</td>
<td>Push button to reset SD02B</td>
</tr>
<tr>
<td>B</td>
<td>Connector to stepper motor</td>
<td>G</td>
<td>Push button to test SD02B</td>
</tr>
<tr>
<td>C</td>
<td>Stepper motor coil power indicator (4 LEDs)</td>
<td>H</td>
<td>Small green LED as VCC indicator</td>
</tr>
<tr>
<td>D</td>
<td>Manufacturing test point</td>
<td>I</td>
<td>Voltage selector</td>
</tr>
<tr>
<td>E</td>
<td>UART communication</td>
<td>J</td>
<td>Connector to Host (Signal)</td>
</tr>
</tbody>
</table>
CNC Machine Specs Design

- The controller coordinates all the system actions. Its output is connected to an interface card that sends signals to the stepper motors.

- The stepper motors carry the worktable on which the work-piece is supported.
  - Load on steppers is 30 N
  - Torque of 1.75 N.m (250 oz-in)

- Two stepper motors are required to provide movement, one in the x-direction and one in the y-direction.
  - The stepper motors are synchronous 1.8° motors giving a half step angle of 0.9° per revolution.
The linear displacement of the load for the gear wheel (with a radius of 5 mm), using gear ratio of 5:1 is 0.0157 mm.

- This means that one pulse of the stepper motor is equivalent to a 0.0157 mm movement of the load being carried.
- The control resolution, which is the distance between two adjacent addressable points in the axis movement, is 0.0157 mm, and the accuracy is 0.05 mm.

The drilling machine navigates in the z-direction to drill the points located directly below it.
Conclusion

- Mecahtronics Design follows well-defined iterative steps that include synergistic design.

- It is composed of three stages:

1. Define the Objective and Specifications
   - Includes customer needs and engineering specs

2. Analyze and Design
   - Understand I/O to select appropriate sensors and actuators
   - Choose controller algorithm and hardware
   - Model and Simulate

3. Build and Test
   - Build prototype and measure performance according to specs