Integrated Trajectory Planning, System Modeling, & Control Design for Optimized Motor Selection
Trajectory Planning with Electronic Cams

- What do Leonardo da Vinci and the Nautilus exercise machine have in common?
- Leonardo da Vinci invented the cam hammer (see picture) around 1497 and the Nautilus exercise machine, invented around 1970, uses a cam to modulate resistance.
  - The cam – an irregularly-shaped member on a rotating shaft that transfers motion – has been around for centuries. Up until recently, the study of cam design and application was foundational in a mechanical engineering curriculum. But today, it seems its study is nowhere to be found.
Leonardo da Vinci’s Cam Hammer 1497
In mechatronic design, integration is the key as complexity has been transferred from the mechanical domain to the electronic and computer software domains.

Cams are a prime example of that mechatronic principle as mechanical cams are gradually being replaced by electronic cams.

But transfer implies that we first understand the fundamental principles in the mechanical domain. Since MEs aren’t learning cam fundamentals anymore and it was never part of an EE’s training, motion systems today most often use crude motion trajectories that stress the machine and motor, produce unwanted vibrations, and result in poor performance.
Trajectory planning is the computation of motion profiles for the actuation system of automatic machines, e.g., packaging machines, machine tools, assembly machines, industrial robots.

- Kinematic (direct and inverse) and dynamic models of the machine and its actuation system are required.
- Desired motion is usually specified in the operational space, while the motion is executed in the actuation space, and often these are different. The trajectory is usually expressed as a parametric function of the time, which provides at each instant the corresponding desired position.
- Once the trajectory is defined, implementation issues include time discretization, saturation of the actuation system, and vibrations induced on the load.
In past decades, mechanical cams have been widely used for transferring, coordinating, and changing the type of motion from a master device to one or more slave systems.

Replacing them are electronic cams, with the goal to obtain more flexible machines, with improved performances, ease of re-programming, and lower costs.

With electronic cams, the motion is directly obtained by means of simpler mechanisms with electromechanical actuators, properly programmed and controlled to generate the desired motion profiles, which also allows synchronization of actuators on a position or time basis.
• Once the displacement and its duration have been defined, the **choice of the manner of motion** from the initial to the final point has important implications with respect to the sizing of the actuators, the efforts generated on the structure, and the tracking error.

• The engineer must carefully consider the **different types of point-to-point trajectories** which could be employed with a specific system. Both **time-domain and frequency-domain analyses** must be performed on the **complete system**, i.e., actuator, mechanism, and load, along with the motion profile, to achieve optimal performance.

• **Input shaping and feedforward control** are two techniques used to improve tracking performance.

• Knowledge from the past combined with new technologies results in **innovation**. Engineers must never forget this fact!
\[ C_v = \frac{\dot{q}_{\text{max}}}{h / T} = \text{coefficient of velocity} \]
\[ C_a = \frac{\ddot{q}_{\text{max}}}{h / T^2} = \text{coefficient of acceleration} \]
\[ C_j = \frac{\dddot{q}_{\text{max}}}{h / T^3} = \text{coefficient of jerk} \]

In the following figures, \( h = 1 \) and \( T = 1 \), and three profiles are shown – velocity \( V \), acceleration \( A \), and jerk \( J \) – for a selection of main trajectories.
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<th>Constant Acceleration</th>
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| ![Graph](image5.png) | ![Graph](image6.png) | ![Graph](image7.png) | ![Graph](image8.png) |

| 16 | 40 | 12 | 12 |

Model-Based Motor Selection

K. Craig 9
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Modeling & Simulation Improve the Motor Selection Process

• Trajectory Planning, System Modeling, & Control Design are Essential for Optimized Motor Selection

• Multidisciplinary engineering systems are complex, with increased risk, development time, and integration challenges.

• Model-based system design helps to manage the complexity and enhance integration while reducing the development time and risk.

• How does model-based design improve the process of choosing a motor for a motion application?
• System requirements dictate a **desired end-point trajectory**. The motion can be defined as an electronic cam, characterized by different profiles and maximum values of velocity, acceleration, and jerk, which will affect the level of mechanical stress, vibration, and noise in the motor, transmission system, and mechanical load.

• It is essential that the **desired motion profile be chosen first** because the required torque vs. speed curve to size the motor depends on it. In addition, the motion profile has relevant implications on the tracking errors through the control system.

• A kinematic (geometry of motion) model of the mechanical system is then developed and, through inverse kinematics, the **required motor motion profile** is determined.
• The torque-speed requirements for the motor are determined by developing a **kinetic (geometry plus all torques and mass moments of inertia) model** of the complete mechanical system.

• A computer simulation (e.g., MatLab Simulink) of the **mechanical system** will result in the necessary torque-speed curve of the load to size the motor.

• Candidate servo motors (e.g., permanent-magnet synchronous motors) can now be identified. Additional requirements, e.g., cost, energy efficiency, and load-to-motor inertia ratio, will shorten the list.

• The chosen motor, including any flexible couplings or gearing, becomes an integral part of the system and its properties must be included in the **system model**.
• An appropriate feedback control system (e.g., PID) is then designed and tuned, with the chosen motor as part of the system.

• A computer simulation will reveal new torque-speed requirements for the system.
  – Is the motor’s torque-speed capability satisfactory?
  – Is the control system stable?
  – Does the system meet application-specific requirements regarding time response, relative stability, and steady-state error?
  – If the answer is to any of these questions is no, iteration is required.

• A model-based design approach, together with computer simulation, will lead to an optimal motor selection with all the benefits that implies.