INCREASING ENERGY EFFICIENCY BY MODEL BASED DESIGN

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FLANDERS MAKE

- **Strategic Research Center** for the manufacturing industry

- Integrating the power of **industry, industrial research centers** (FMTC, Flanders’ DRIVE) & **university research labs** in one common research agenda

- Open innovation environment enabling **structural collaboration** in research between industry - Flanders Make - academia

- **Accelerate** technological innovation in the Flemish manufacturing industry

- Cross-border and **international** collaboration
MISSION FLANDERS MAKE

“To strengthen the long-term international competitiveness of the Flemish manufacturing industry by carrying out excellent, industry-driven, pre-competitive research in the domains of mechatronics, product development methods and advanced manufacturing technologies”
FLANDERS MAKE RESEARCH PROGRAMS

- Clean energy efficient motion systems
- Smart monitoring systems
- High-performance Autonomous Mechatronic Systems
- **Intelligent product design methods**
  - Design and Manufacturing of Smart and Lightweight Structures
  - Additive Manufacturing
  - Manufacturing for high precision products
  - Agile & Human-centered production and robotic systems

- Model based design for energy efficiency!
Overview

- **Introduction**

- Example 1: energy storage in a hydrostatic drivetrain

- Example 2: energy efficiency increase of a badminton robot

- Summary and conclusions
INTRODUCTION

NEED FOR INCREASED ENERGY EFFICIENCY
Background: scarcity of energy

△ Societal awareness
  △ Consider energetic impact of the things you are doing
  △ Be ‘green’
  △ Increasingly stringent legislation

△ Economic angle
  △ Increasing prices for energy
  △ Contribution of cost of consumed energy during use phase of machine in Total Cost of Ownership increases

△ As a results
  △ Need to reduce energetic footprint machines
  △ Energy efficiency (during use phase) becomes a differentiating performance characteristic
Reduce energy consumption during the use phase (I)

General approach

1. Avoid useless energy consumption
   - E.g. Reduce stand-by losses

2. Minimize inevitable losses in functional components
   - E.g. Use energy efficient components, e.g. energy-efficient motors

3. If the process generates energy, recuperate it or reuse it
   - Braking energy
   - Waste heat
Reduce energy consumption during the use phase (II)

△ Applied to drivelines of production machines and vehicle
  △ Component level
    - Use energy efficient components
    - However: might cause performance changes, e.g. electrical motor for dynamic applications
  △ System level
    - Allows taking into account interaction between components in machine
    - Most opportunities, but less straightforward

⇒ Take energy consumption into account during the design of new machines
Motivation, vision, objective and approach

△ Vision
  △ Future mechatronic systems will be developed following a model-based design approach

△ Motivation
  △ Model-based design is essential to
    - Reduce development effort/cost
    - Decrease the time-to-market
    - Explore the space of possible designs more rigorously
    - Deal with increasing number of system requirements
Model based design taking into account energy efficiency

△ Model based design
   △ Opportunity to quickly evaluate the impact of design changes
     – Describe behavior components mathematically
     – Combine components
     – Simulate and analyze machine behavior

△ Difficulty with energy
   – Multi-disciplinary (mechanical, electrical, hydraulic, etc.)
   – Changes form during a machining process

   – 1D Simulation softwares exist that allow modeling of energetic behaviour
CASE STUDY 1: ENERGY STORAGE IN A HYDROSTATIC DRIVETRAIN
Hydrostatic drivetrain

- Heavy load vehicles
- Hydrostatic drivetrain
  - Combustion engine to pump to hydraulic motors to 1 or more loads
  - Variable stroke volumes
    → continuously variable transmission ratio
Hydrostatic drivetrain

▲ Experimental setup at FMTC
▲ Simulate a loaded hydrostatic drivetrain
  – Speed controlled electric motor instead of diesel engine
  – Torque controlled electric motors and flywheels to emulate load
▲ Energy storage?
Concept generation

Model-based concept analysis

Concept selection
Energetic model

- Start from model of original set-up
- Identify loss parameters based on experiments
- Expand model with models of energy storage elements
Component optimization

- Cost function
  - Total cost of ownership

- Optimal control

- Electrical hybrid
  - Capacitor bank dimensioning
    - Number of capacitors per serial branch
    - Number of parallel branches

- Hydraulic hybrid
  - Accumulator volume
Concept selection

**Total cost**

€ 0  | € 5,000  | € 10,000  | € 15,000  | € 20,000

No hybrid | Electrical hybrid | Hydraulic hybrid

**Energy losses**

- Others
- Hydraulic motors
- Pump
- Driving motor
- Brake energy

-16.20%  | -26.41%

No hybrid | Electrical hybrid | Hydraulic hybrid
Physical interpretation

- Electrical hybrid
- Hydraulic hybrid
CASE STUDY 2:
ENERGY EFFICIENCY INCREASE OF A BADMINTON ROBOT
Badminton robot

Demonstration platform
First attempt to reduce energy consumption

- Engineering reasoning of main losses
  - Robot is mainly accelerating and decelerating masses
  - Deceleration energy is ‘burned’ in braking resistor

- Reduce energy consumption?
  - Recuperate braking energy and reuse this energy
  - Capacitors added to system
  - Very little reduction in energy consumption (under 5%)!

- Why is this so?
  - More systematic analysis needed!
Goal of the analysis

- Energy consuming elements in model
  - E.g. Brake resistance, coil resistance, friction,…

- Parameter tuning
  - From catalogues (e.g. motor parameters)
  - Experimentally (e.g. friction parameters)
Energy flow analysis results

- Main loss can be attributed to copper losses and friction losses

Solution?

- Reduce friction losses
  - Other guides? => reduce friction
  - \( \sim I^2; I \sim F; F \sim \text{acceleration} \) => reduce acceleration!
Improvement: Energy efficient controller

▲ Go from Time Optimal to Just-In-Time controller
  ▲ Current implementation
    – Time optimal
  ▲ Just-in-time controller
    – Same structure
    – Bounds on trajectory parameters: $V_{\text{max}}$ and $A_{\text{max}}$
    – Parameters found using Multi-Objective optimization using the model of the robot
  ▲ Significant reduction in energy consumption!
    ... without loss of effectiveness!
    – more than 50% of energy reduction
Industrial application

Similar design analysis and controller development has been applied to the design of the drivetrain of a crane.
CONCLUSIONS


### Conclusion

△ Motivation: Energy reduction for environmental and economic reasons

△ Approach

△ Take energy consumption into account on system level
△ Following mechatronic model based approach allows to optimize (energy efficiency of) the design