Individual Electro-Hydraulic Drives for Off-Road Vehicles
(project ID: ft084)

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Overview

Maha Fluid Power RESEARCH CENTER PURDUE UNIVERSITY

Timeline

Project start date: May 2018
Project end date: April 2021
Percent complete (April 2019): 30%

Budget

Total project funding: $1,919,142
DOE share: $1,500,000
Funding for FY 2018: $ 250,000

Barriers

- New technologies to reduce fluid power system losses. *Potential to integrate components to reduce frictional and parasitic losses*
- New architectures to level and reduce the peak system load requirements. *Energy storage to reduce the peak demands on the engine and pump(s)*
- Component design*. Industry is interested in optimization of component design to reduce frictional losses and has a payback period of less than two years (ex: integrated components).*

Partners

- Purdue University – *project lead*
  Dr. Vacca (PI), Dr. Sudhoff (co-PI)
- Bosch Rexroth
- Case New Holland Industrial (CNHi)

Relevance

Background

Off-road vehicles often require working hydraulics

State of art: hydraulic systems have high controllability, reliability and power capability. However, energy efficiency can be as low as 20% !

Concepts based on hydraulic system decentralization have shown high potential for fuel economy improvement (up to 60%), but haven't found commercial application.

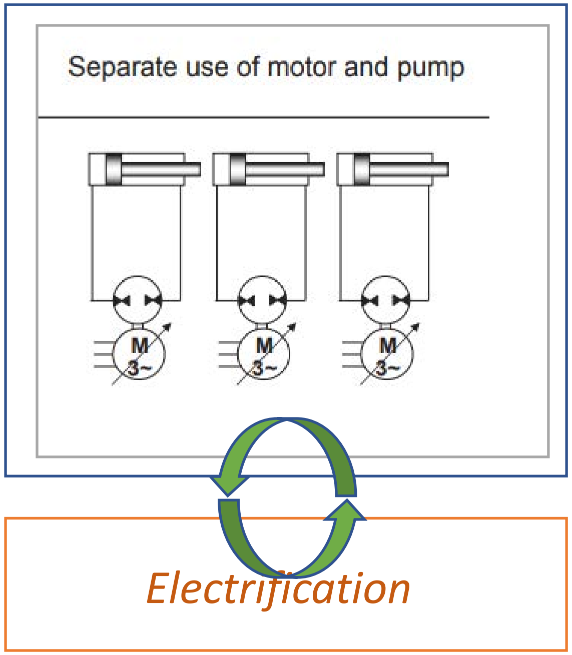
Objective

To develop and demonstrate an electro-hydraulic technology that, with respect to current state-off art solutions for off-road vehicles, can:

- ✓ Lower power consumption of the fluid power system up to 70%
- ✓ Can reduce noise and vibrations
- ✓ Allow for "zero emission" operation of the vehicle (engine off)
- ✓ Enable "smart actuators", operating as modern "plug & play" elements

Relevance

Hydraulic Individualization



Past Purdue's research

- *Displacement controlled off-road machinery*
- *Tribological models for hydraulic pumps/motors*
- *New design concepts for pumps*

- *Electro Hydraulic Actuators*

- *Electric machine modeling and optimization*

Sub-objectives:

Objective 1 (O1): 4-quadrant EH unit

Objective 2 (O2): Individualized EH System

Objective 3 (O3): Technology Demonstration

Period 1 (12 months):
"Preliminary Design"

GNG1. EH system performance (*simulated efficiency above 0.75 at best points*)

GNG2. EH unit performance (*proven feasibility, efficiency above 0.6 in the operating range, greater than 0.8 at best efficiency points*)

Milestones

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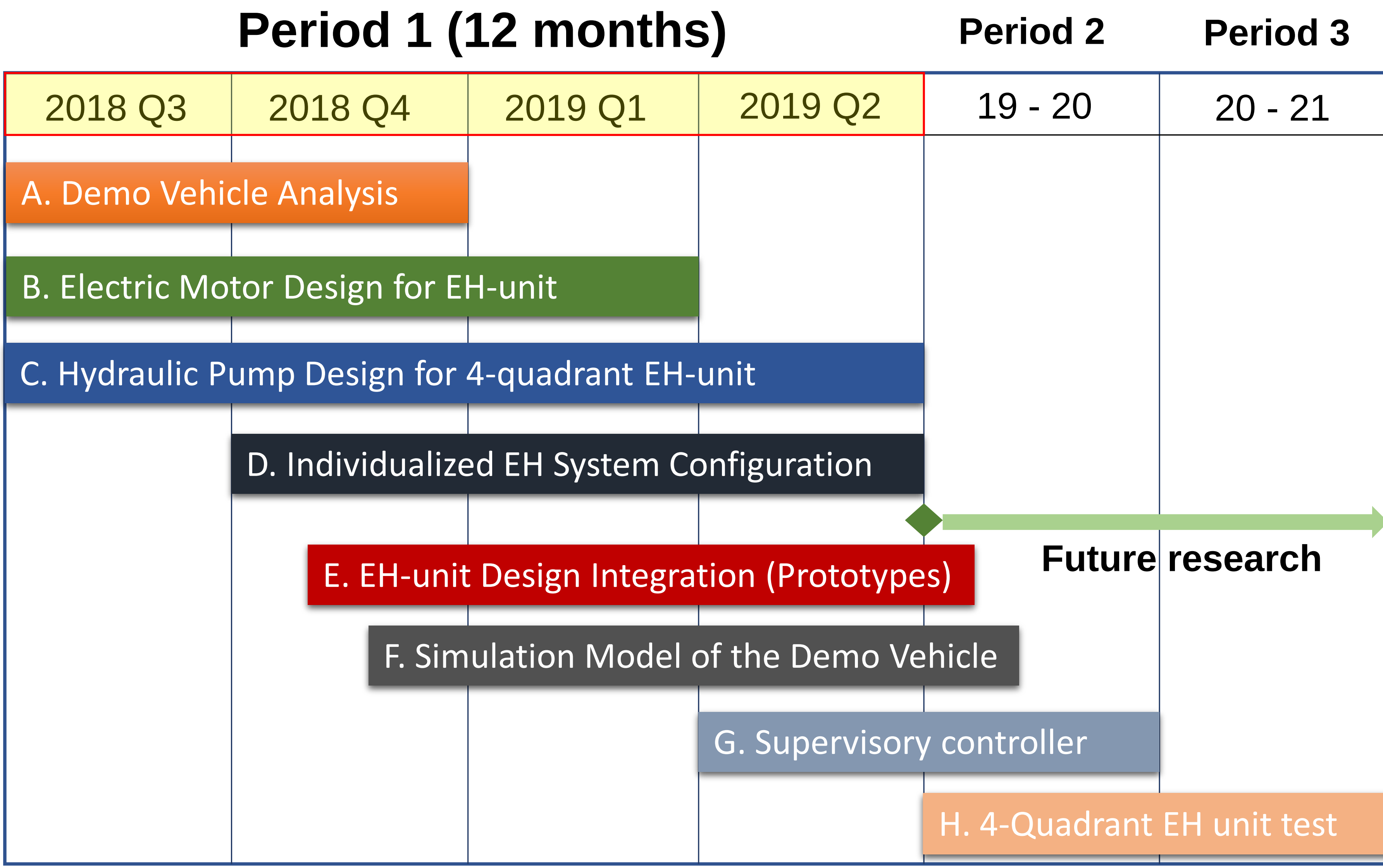


Approach

Period 1 (12 months)	Period 2 (12 months)	Period 3 (12 months)

2018 May

2021 April

EH module design and simulation

Go/ No-Go

Performance above 0.75 at best

Implement the EH unit with the function of EH module

EH unit design and optimization

Go/ No-Go

Efficiency never below 0.6, 0.8 at best points

Implement the pump and motor to the system

4-quadrant EH unit prototype and measurements

Go/ No-Go

Full functionality, efficiency greater than 0.5

Demo vehicle implementation

Baseline measurements and simulation model
Implement of the proposed system on machine

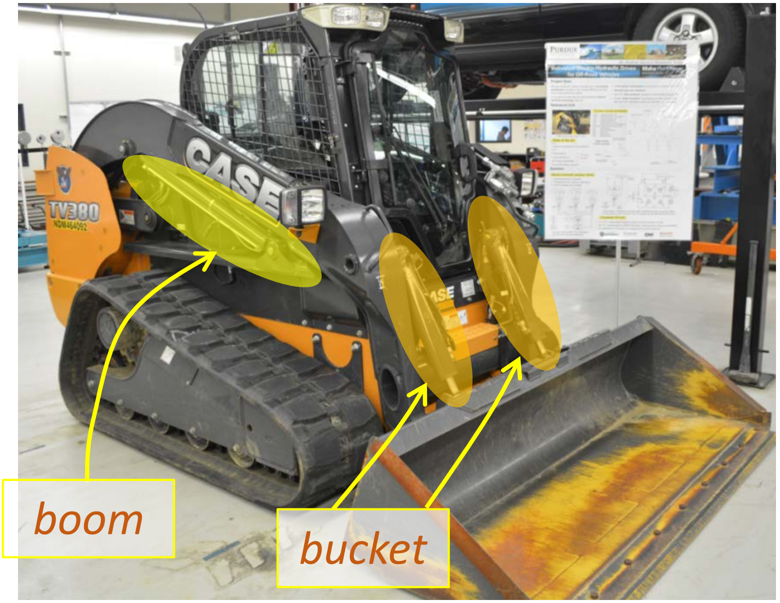
Go/ No-Go

At least 20% higher for efficiency

Market Analysis

Definition of the Demo Vehicle (O3):

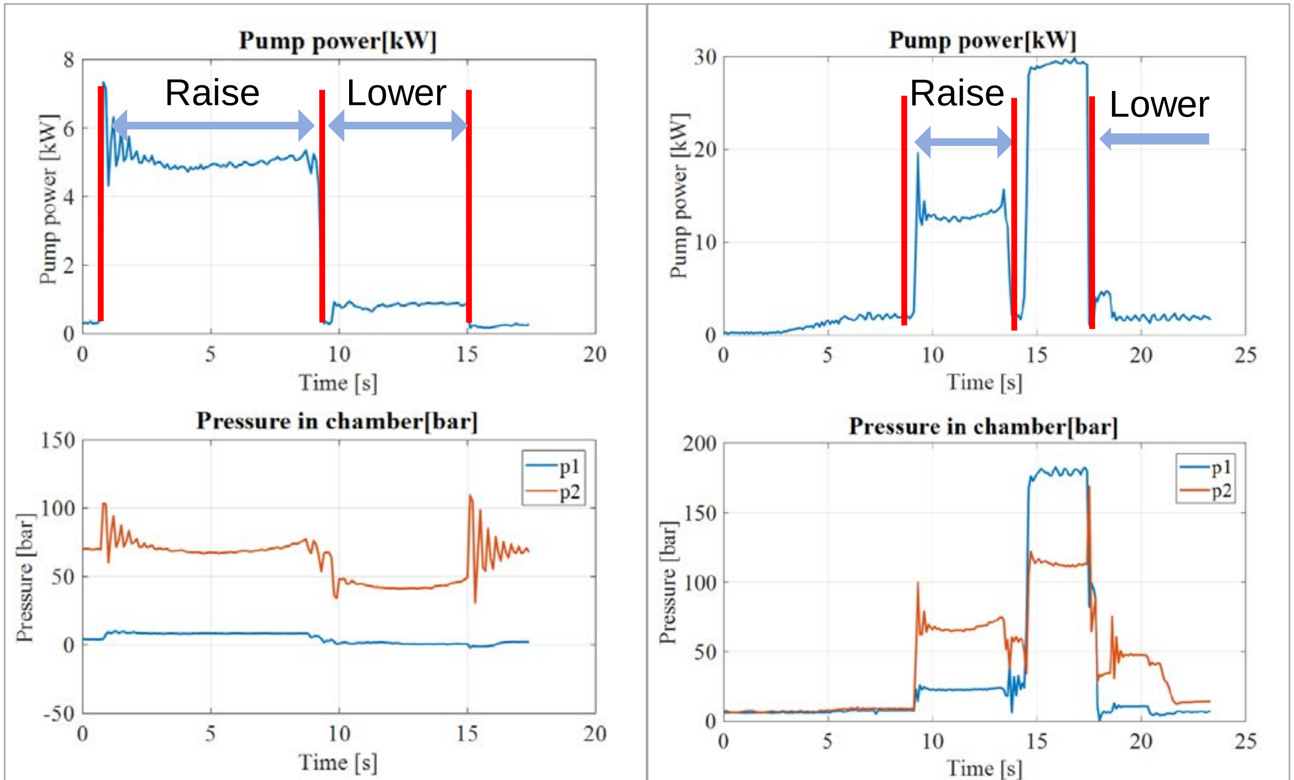
Off-road construction vehicle: skid-steer loader Case TV 380



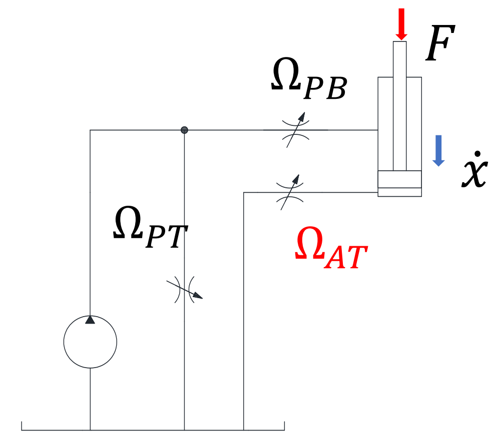
Engine Speed \ Bucket Load		Empty Bucket	Load (1000 lbs)
1140Rpm ~ 2500Rpm	Low Speed	✓	✓
	Middle Speed	✓	✓
	High Speed	✓	✓
Float Lowering		✓	✓

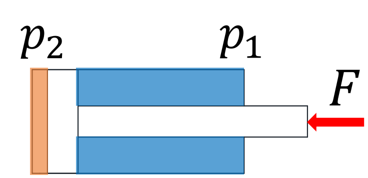
- Two functions (boom, bucket) considered for the technology demonstration
- Machine instrumented for baseline measurements of hydraulic power consumption
- Execution of test plan representative of typical machine duty cycle

Measurements (O3 – O2)



high load – low speed *low load – high speed*





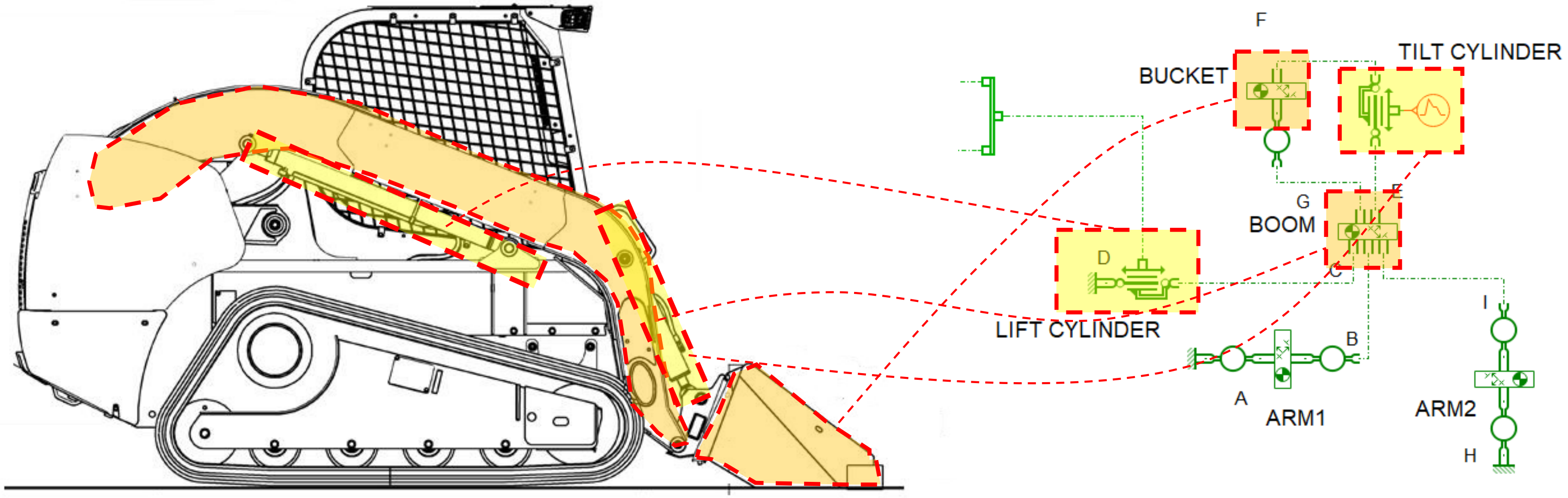
$$F = p_2 A - p_1 a$$

$$F = F_{load} \pm F_{fric}$$

- Tests allowed understanding the sizing choices made for the open center system
- Test permitted verifying modeling assumptions
- Determination of the equivalent loads at the actuators for sizing of the EH system

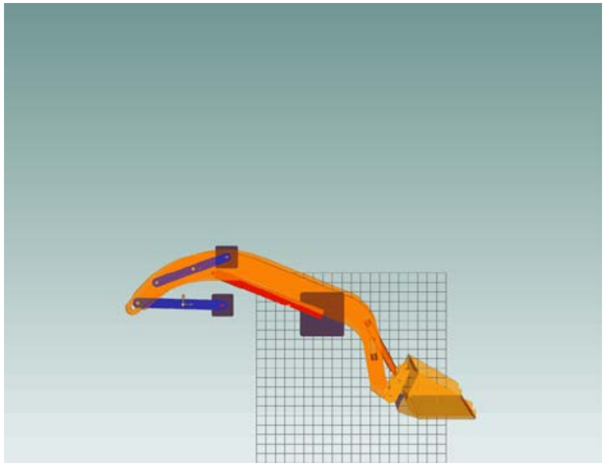
Simulation of hydraulic functions (O2)

A simulation model in Siemens PLM Amesim was created to reproduce the interaction between the mechanical system and the hydraulic circuit



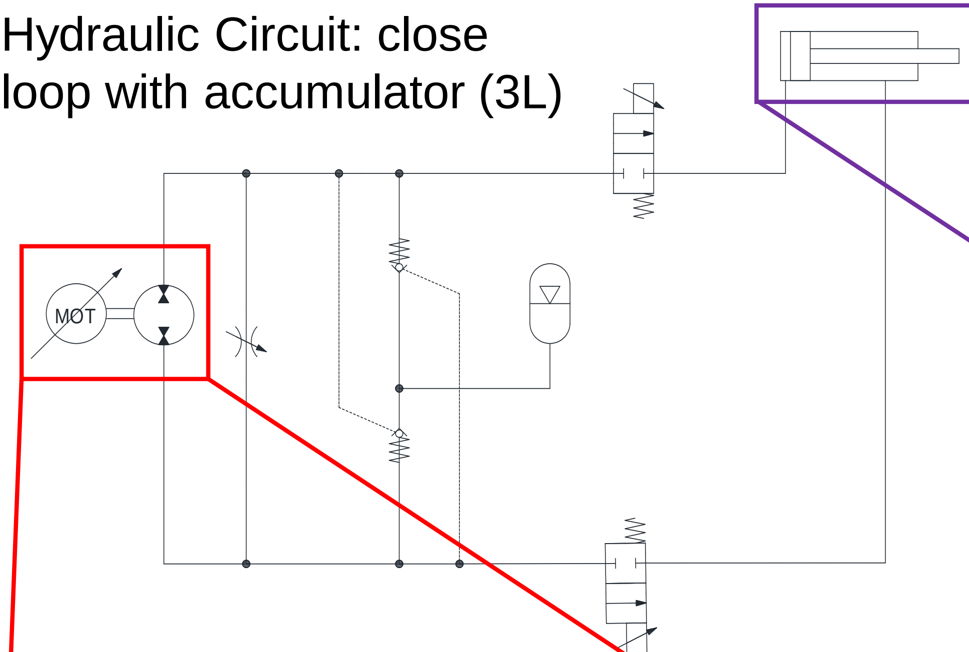
Excellent motion match

Load match error < 5%

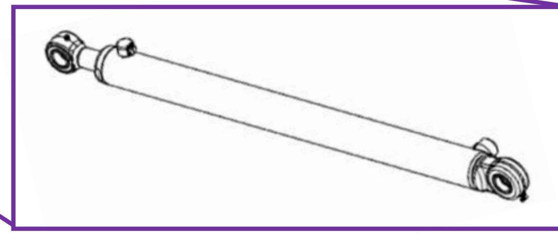


Proposed Electro-Hydraulic System (O2)

Hydraulic Circuit: close loop with accumulator (3L)

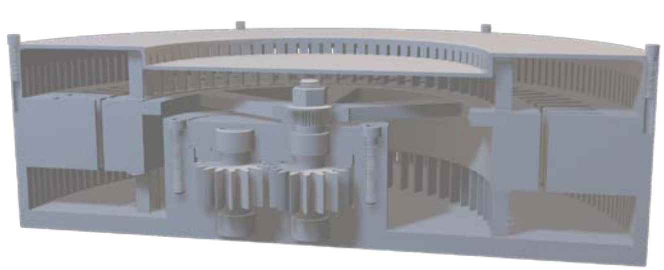


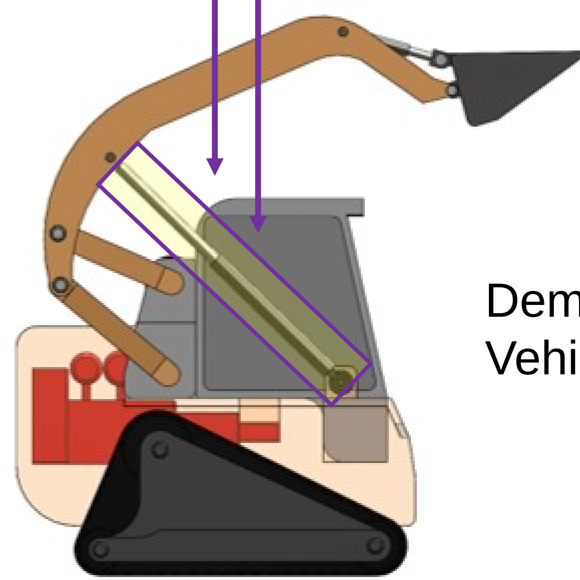
Actuator: max pressure 210 bar



Length: 0.89m

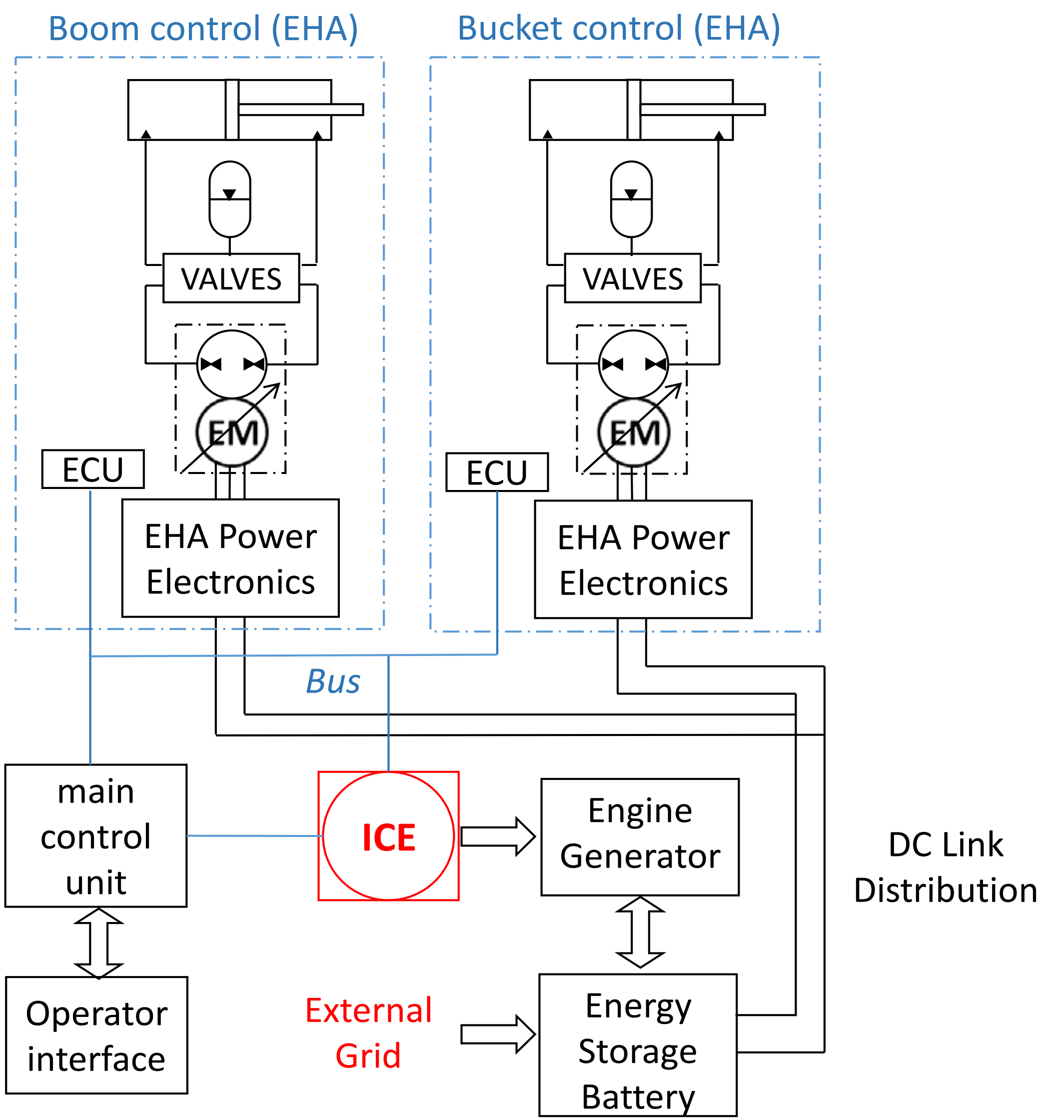
EH-Unit





Demo Vehicle

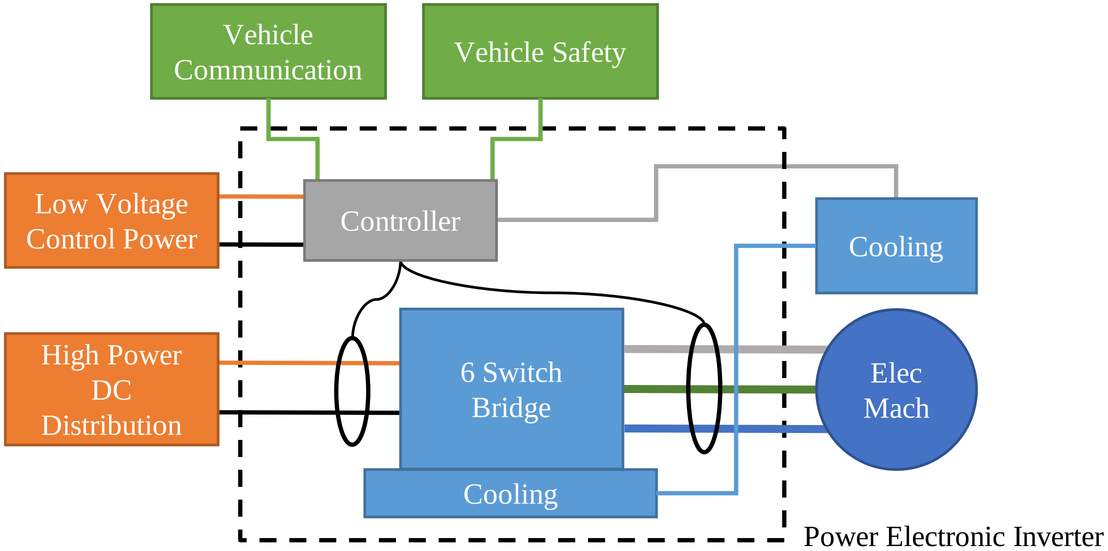
Vehicle integration concept (O2)



- Vehicle will be retrofitted with a hybrid electric hydraulic system
- EHA units are powered by a vehicle DC power distribution network
- Power electronics convert DC voltage into three-phase AC currents to regulate electric machine torque, and thus pump output

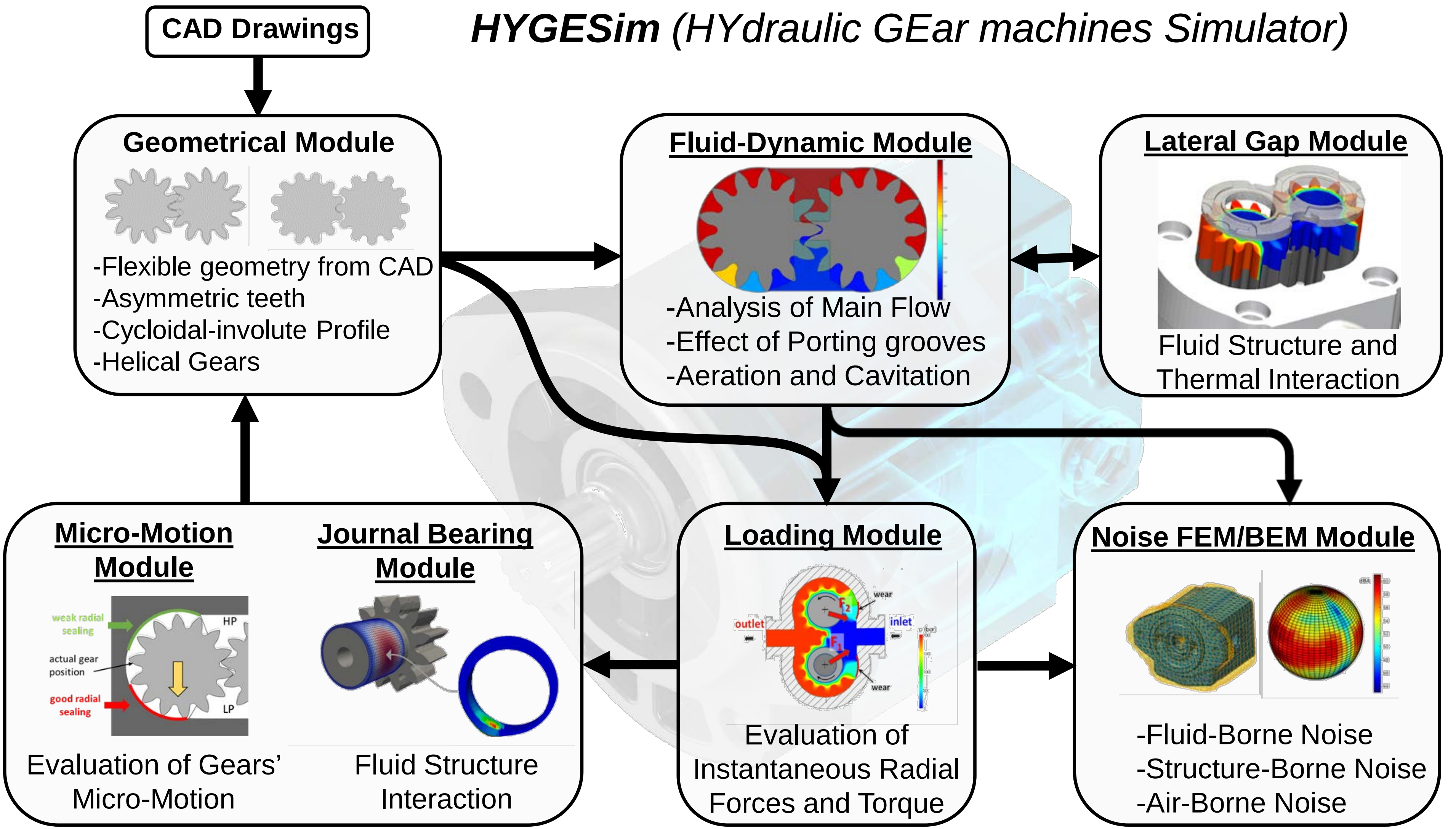
Vehicle integration concept (O2)

- Each EHA will employ a dedicated self contained power electronics package
- This package contains all operating electrical components, including an inverter power block, controller, cooling system, electrical sensors, and vehicle communications
- Targeting prototype for compactness and ease of debugging
- First year inverter prototype designed to be as highly flexible as exact system parameters are not known until completion of Year 1



EH unit design method (O1)

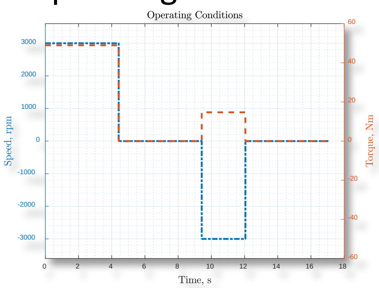
Model integration – hydraulic unit



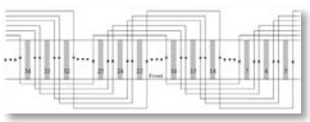
EH unit design method (O1)

Model integration – electric machine

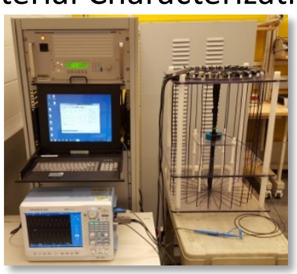
Operating Conditions



Winding Configuration



Magnetic Material Characterization

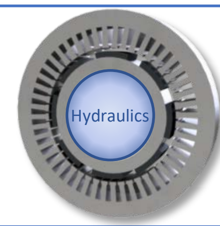


Vehicle power requirements; EHA requirements; manufacturability constraints; …

Electric Drive Optimization

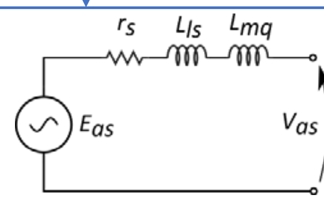
Geometry Candidate

Create feasible geometry



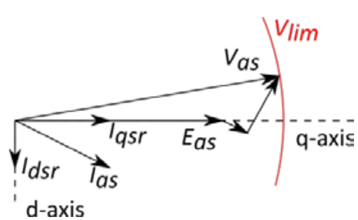
Mass, volume, …

Electric Analysis



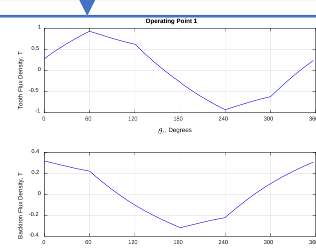
Leakage and magnetizing inductances, Ohmic resistance, proximity effect,…

Control



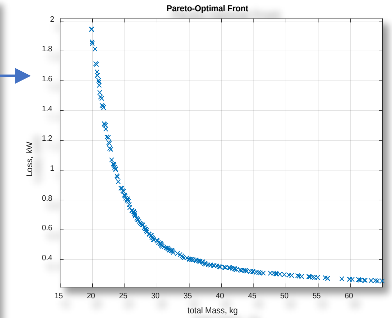
Select current commands, winding and semiconductor losses, …

Magnetic Analysis

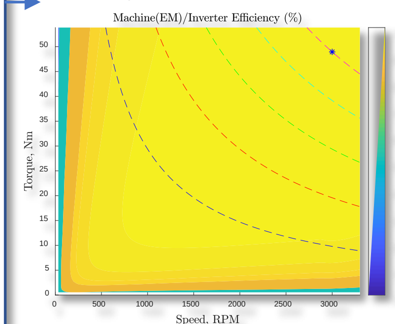


Core losses, torque, …

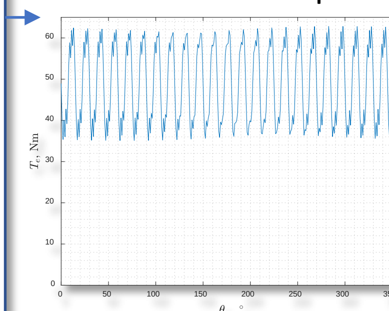
Set of optimal design solutions



Electric drive performance



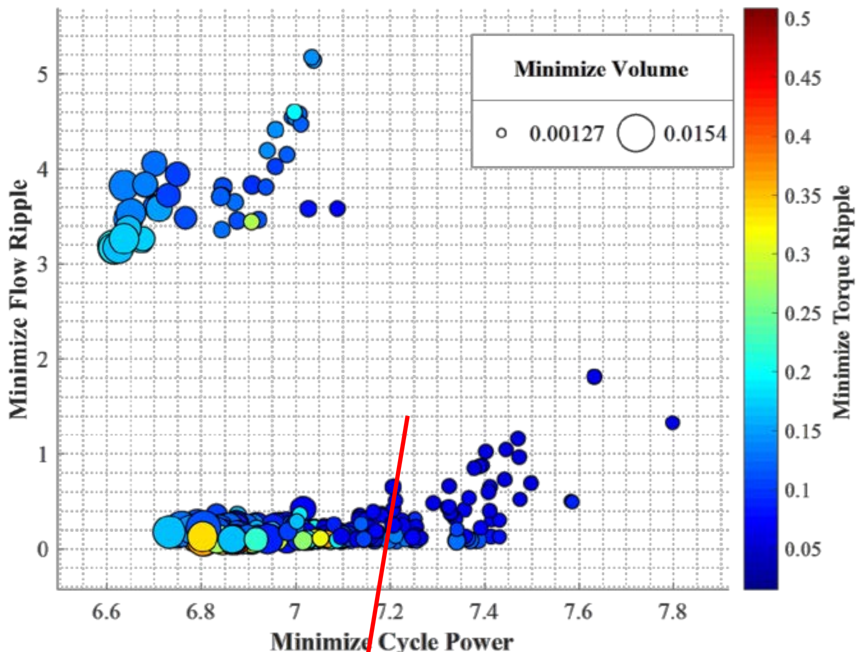
Mechanical output



Technical Accomplishments *#15*

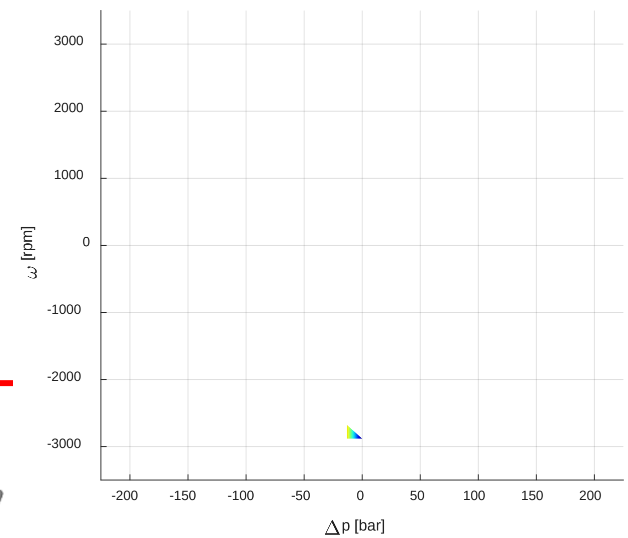
EH unit design method (O1)

Combined Pump-Motor Design Optimization

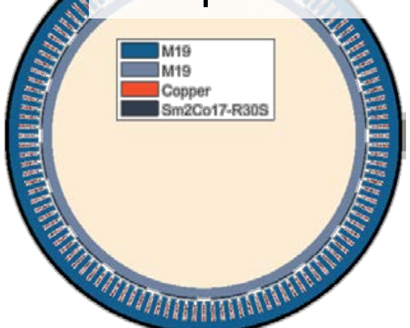


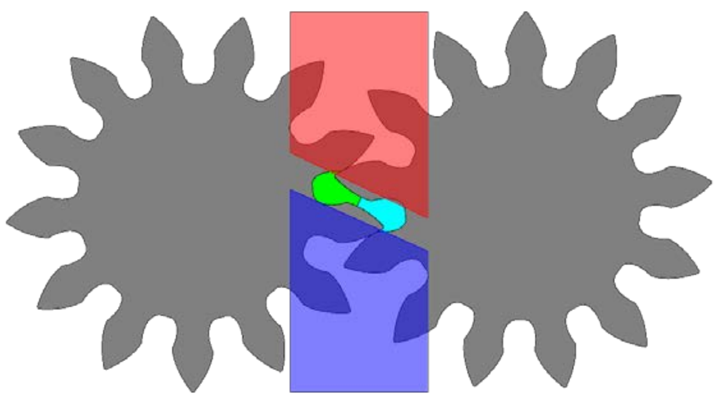
Objective functions

1. Minimize Cycle Power
2. Minimize EHA Volume
3. Minimize Flow Ripple
4. Minimize Torque Ripple



select EHA components





efficiency map

Hydraulic unit always above 85% efficiency

EH unit design method (O1)

EH unit integration

Main specifications:

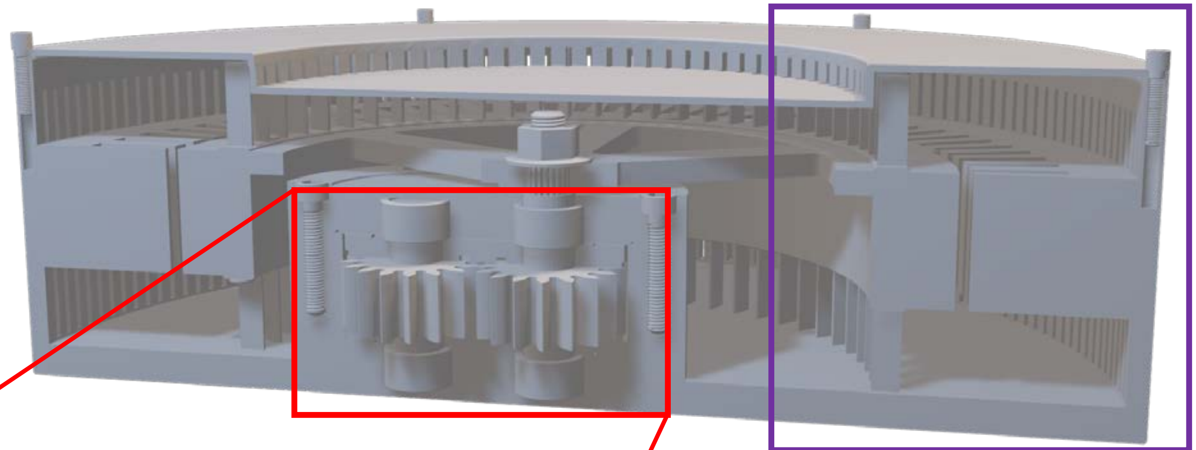
Power: 16 kW

Max flow: 45 L/min

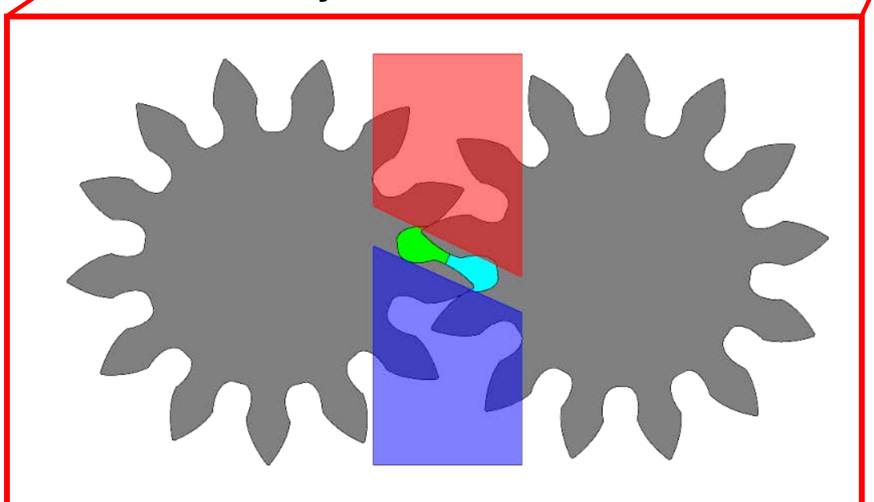
Max pressure: 210 bar

Diameter: 362 mm

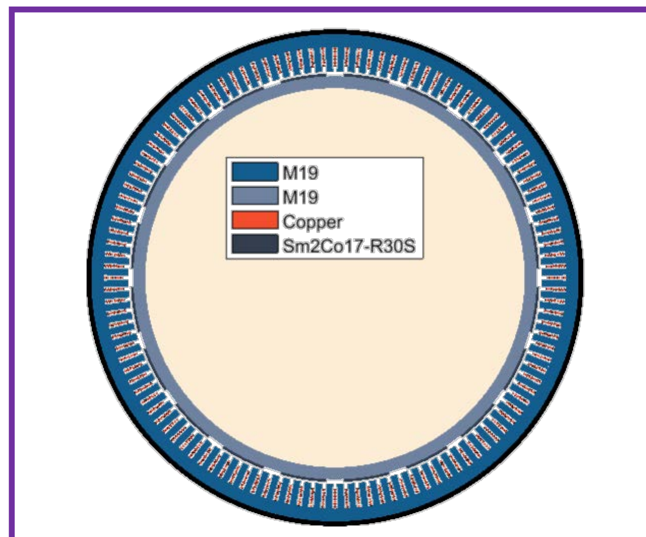
Thickness: 100 mm



Hydraulic unit



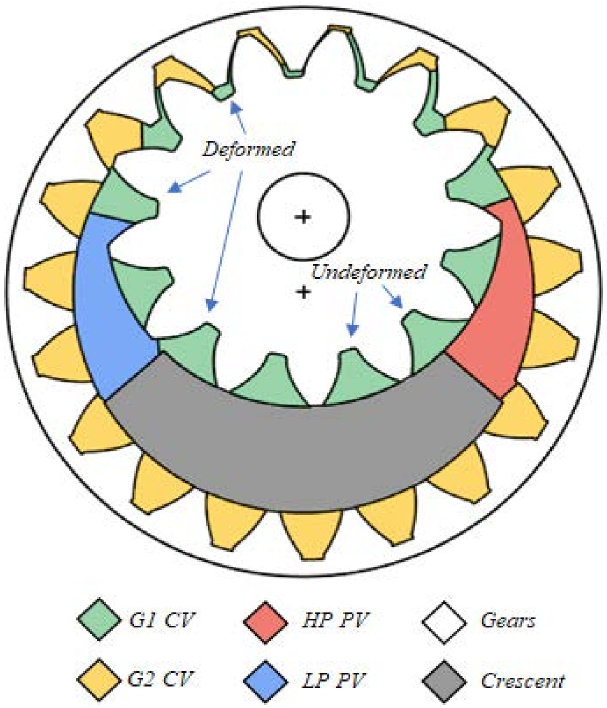
Electric Motor



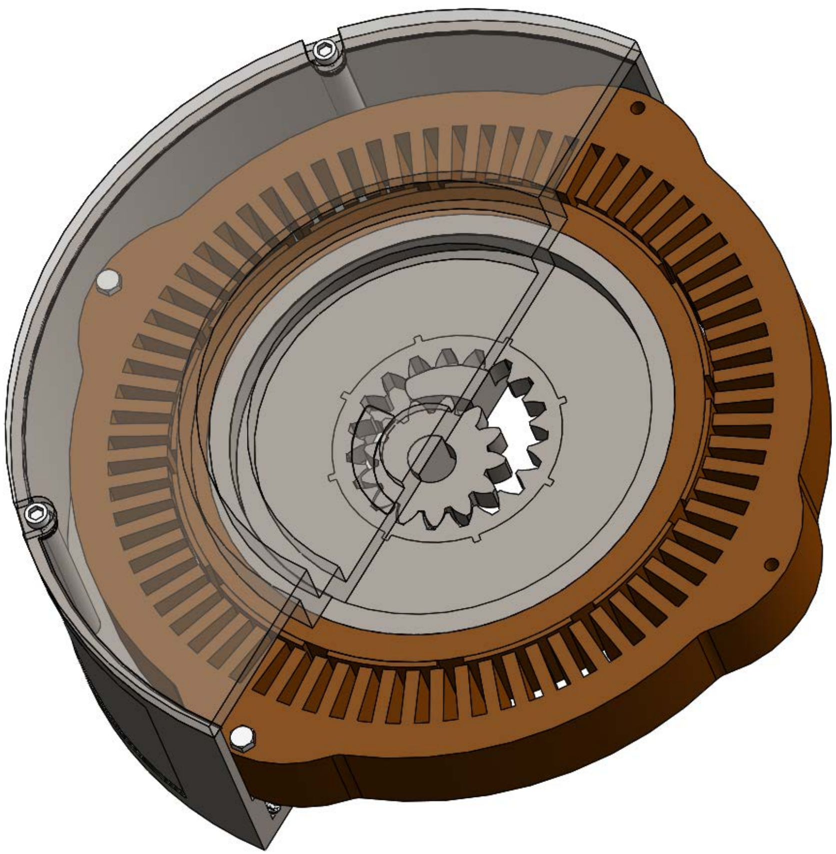
Extension to Internal gear machines (O1)

Simulation model for the hydraulic machine (previously not existing at Purdue)

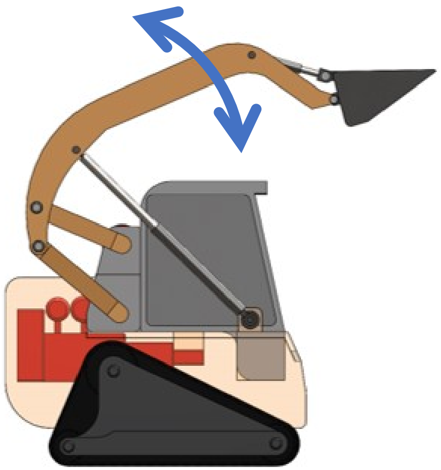
Geometry Definitions:



System Integration preview:

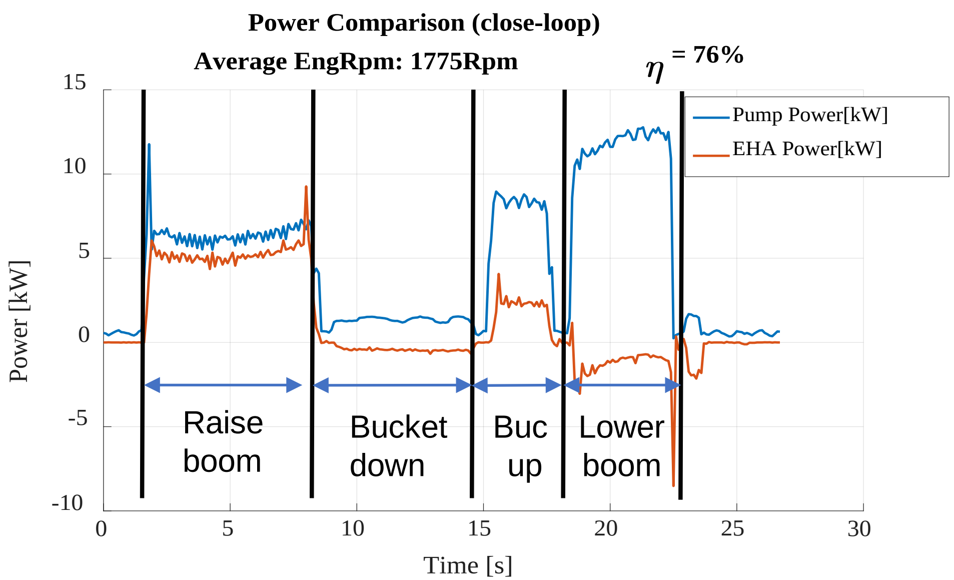


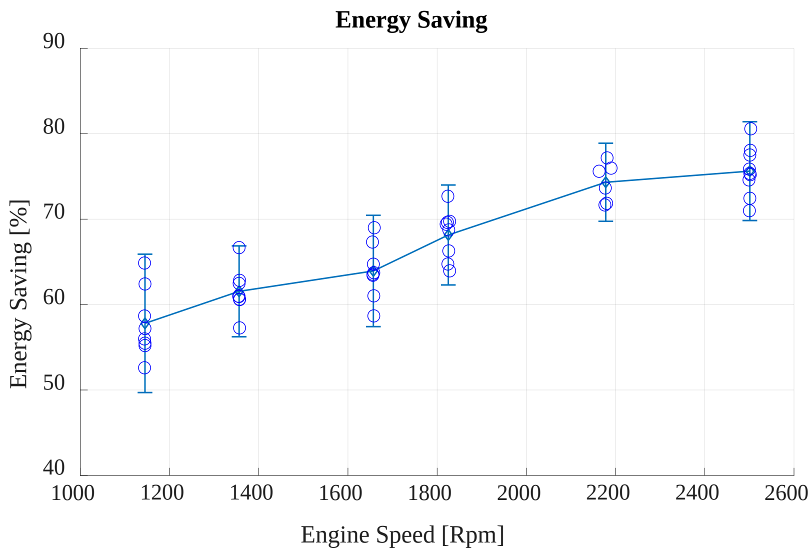
Simulated performance – boom cycle



proposed EH module vs current system

- Simulations based on measured cycles
- The proposed systems avoid over-pressurizations
- Different handling of overrunning condition
- Total energy saving in one cycle: up to 80%





PURDUE UNIVERSITY

Dr. Vacca (PI), Dr. Sudhoff (co-PI)

- Performs the core simulation and experimental activities of the research, involving both the EH unit and the EH module, as well as the implementation on the demo-vehicle

rexroth A Bosch Company

Uwe Neumann, Enrique Busquets

- Provides the key inputs on both the EH unit and EHA design and packaging. Rexroth will also provide hydraulic components and some components of the overall electric-hydraulic hybrid system.

CNH INDUSTRIAL

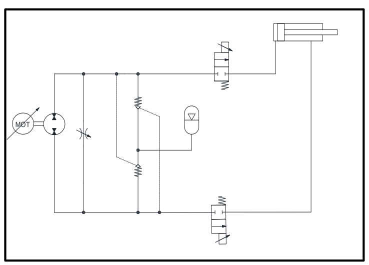
Gary Kassen, Roman Plaszewski

- Case New Holland (CNH) provided the reference vehicle, the basic instrumentation and insights on the vehicle utilization. CNH will also advising on the vehicle control and support on the vehicle testing.

Remaining Challenges

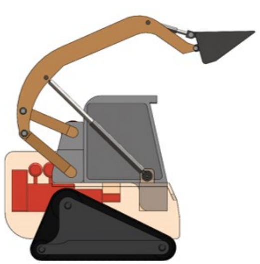
O1. EH unit

- Design integration including alternative cooling solutions
- Performance evaluation internal gear vs external gear desig
- Identification of tolerances and fabrication process
- EH Testing and verification of performance



O2. EH module

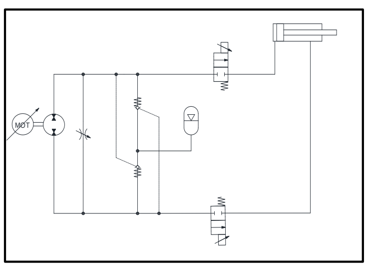
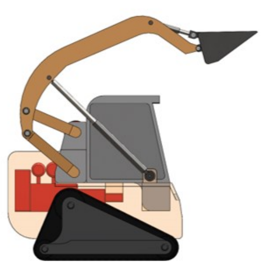
- Space limitation on the demo vehicle for applications
- Simultaneous actuation of multiple actuators
- Control considerations and design for unsteady operation
- Prototype implementation and testing



O3. Technology Demonstration

- Supervisory controller for energy management
- Zero emission mode of operation
- Integration of energy generator and power electronics
- Performance measurements

Period 1 - *Preliminary design*

		Period 2 *Initial implementation*	**Period 3** *Technology demonstration*
O1		EH unit cooling EH unit prototyping EH unit testing	EH unit design - final generation EH unit fabrication and testing General design rules
O2		Component selection Component packaging Prototyping Testing	Design finalization Diagnostic functionality Integrated power electronics
O3		Supervisory controller EHA installation Single actuator testing	Boom / Bucket controller Expert operator testing energy consumption tests Cost analysis

any proposed future work is subject to change based on funding levels

Relevance

The project proposes a new technology for off-road vehicles that merges advantages of fluid power and electric technology

Approach

- Novel four-quadrant EH unit (O1)
- Novel module for EH actuation (O2)
- Integration in a EH hybrid off-road vehicle (O3)

Team

- Largest fluid power research center
- Electric machine expert
- Industry partners leaders in off-road vehicle (OEM) and EH systems/components

Technical accomplishments

- Optimized EH unit able to perform above 85% efficiency (hydraulic unit) and 70% (overall)
- Proposed layout for individual EH modules able to recover energy during overrunning loads
- Instrumented wheel loader for baseline efficiency measurements
- Simulated performance with the proposed EH module estimated to provide energy savings in the order of 70%

Technical accomplishments

- fabrication and testing of both the EH unit and EH module
- Supervisory controller for energy management
- Implementation and testing of the hybrid architecture for two actuators (boom/bucket)