

Hybrid Hydraulic -Electric Architecture for Mobile Machines

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OVERVIEW

Timeline

- Project start: 9.1.2018
- Project end: 8.31.2021
- Percent complete: 20%

Budget

- Total project funding:
 - DOE share \$ 150M
 - Contractor share \$ 386k
- Funding for FY 2018:
- Funding for FY 2019:

Barriers :

- System efficiency
 - Currently only 20%
- Cost of electrification
 - Expensive for high power app.
- Control performance
 - Improve or maintain

Partners :

- U Minnesota (Lead, ME,EE)
 - Li, Van de Ven, Mohan
- U Wisconsin, Madison (EE)
 - Severson
- Eaton Corporate R&D
 - Wang
- OEMs: Bobcat, CNH, JCB, Toro



Relevance

- Off-road vehicles (construction, agriculture, turf, mining, forestry, etc.) use **hydraulics** for high power
- Efficiency from engine output to load only 20%
 - E.g. 20-30ton excavators alone consume 300 trillions BTU/ yr
 - Throttling control – precise but inefficient
 - Hydraulic components – low efficiency at partial load
- **Electrification** can improve efficiency but costly, bulky for high power – high torque applications (limit ~20kW)

Hydraulics and **Electric** actuations are complementary:

- Hydraulic + **unsurpassed power/ force density; robust; familiar**
 - **inefficient; poor energy storage density**
- Electric + **good efficiency, control perf., storage density**
 - **Low power/ torque density; high cost**



Project objective:

Demonstrate a target efficiency of $\geq 65\%$ in off-highway vehicles through development of an **integrated hydraulic and electric system architecture** applicable to a wide range of multi degree-of-freedom mobile machines.

Benefits : High power, high efficiency at low cost; keep electric machines at fraction of size; improved component efficiency and power density; increase productivity

Societal Impact:

- > 3x fuel saving, reduction in harmful emission
- Can be deployed in many machines in different sectors



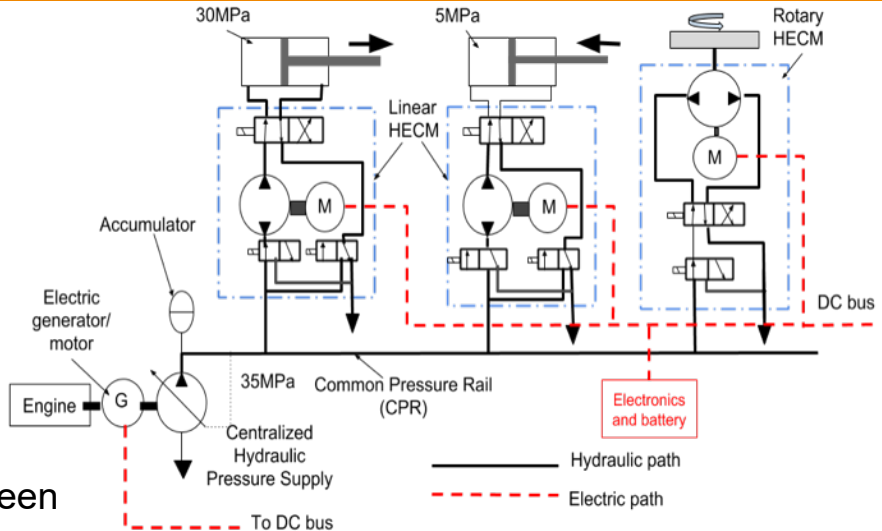
Approach

Develop a novel system architecture that combines hydraulic and electric actuations complementarily

- Hydraulic provides majority power;
- Electric modulates the power, exerts fine control
- Tightly integrated hydraulic-electric energy conversion m/ c

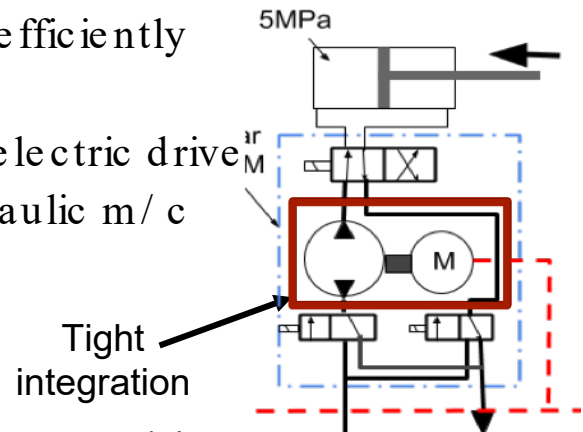
Hybrid Hydraulic - Electric Architecture (HHEA)

* A provisional patent has been filed on this architecture



Features of HHEA approach

- Marries benefits of hydraulic power (power density) with electric power (control performance)
- Avoids large expensive electric components
- Efficiency benefits:
 - Throttle-less;
 - Captures regenerative energy
 - Components operate more efficiently
- Control performance benefits:
 - High bandwidth control via electric drive
- Tight integration of electric/ hydraulic m/ c
 - Increase power-density
 - Reduce losses
 - Reduce size & cost
- Module --> applicable to many machines



Research Plan

- **Thrust A** : Analyze energy saving potentials of proposed hybrid hydraulic-electric architecture for mobile machines in different sectors
- **Thrust B** : Develop control algorithm for proposed system architecture to achieve both efficiency and fast & precise control performance
- **Thrust C** : Develop a tightly integrated electric-hydraulic conversion machine with high efficiency and power density

BP1: Feasibility:

- Establish feasibility and determine initial designs and target platforms.

BP2: Preliminary validation

- Preliminary validation of efficiency and design approach
- Hardware-in-loop test

BP3: Refined validation

- Further experiments; test interactions between outcomes of the 3 thrusts.



BP1 (feasibility) Tasks:

Thrust A: Energy saving

- Identify 3+ platforms from various sectors for analysis; → **Milestone 1**
- Develop energy saving evaluation tool → **Milestone 2**
- Estimate energy saving potentials for identified platforms

Thrust B: Control performance

- Develop control oriented system model
- Identify appropriate control strategy → **Milestone 3**

Thrust C: Compact integration

- Develop models for key electrical/ hydraulic components
- Identify electric and hydraulic topologies for integration → **Milestone 4**

Go /
NoGo:

Analysis predicts: 1) At least 1 platform $>65\%$ efficiency or $>40\%$ energy saving; 2) Integrated Elect/ Hydraulic M/ C: $>5\text{kW/kg}$ energy density and conversion efficiency $>85\%$



Milestones

Budget Period	Description	Scheduled Completion Date	Status
1	Initial platforms selected.	12/1/18	Target platforms selected.
1	Optimal design tool established.	3/1/19	Optimal design tool selected.
1	Nominal HECM control strategy developed.	6/1/19	Nominal control strategy studies underway. Verbal progress update will be provided during review.
1	Select integration topology (rotary or linear).	9/1/19	Both linear and rotary topologies under study with the rotary concept being identified as the leading candidate.
Go/No Go	At least one platform with potentials of reaching 65% efficiency or 40% energy saving ; HECM control strategy verified in simulation; preliminary analysis shows selected integration topology has the desired power density of 5kW/kg and conversion efficiency of 85%.	9/1/19	tbd
2	Pareto optimal analysis tool	12/1/19	tbd
2	Subsystem model analysis	3/1/20	tbd
2	Design space explored within the multi-physics optimization framework.	6/1/20	
2	integration prototype created	9/1/20	tbd
Go/No Go	At least one target platform verified with high fidelity simulation; control verified on HIL setup; detailed analysis of integrated HECM predicts gravimetric power density 5kW/kg and conversion efficiency of 85%.	9/1/20	tbd

Technical Accomplishments & Progress

- A1: Identify >3 platforms for analysis

- Survey of different off-road vehicle sectors complete
- **5 platforms with good potentials identified for study:**
 - Construction: JCB 26ton excavator; CNH wheel Loader;
 - Agriculture: CNH Early Riser Planter
 - Turf: Toro Wide Area Mower
 - Material handling: JCB telehandler



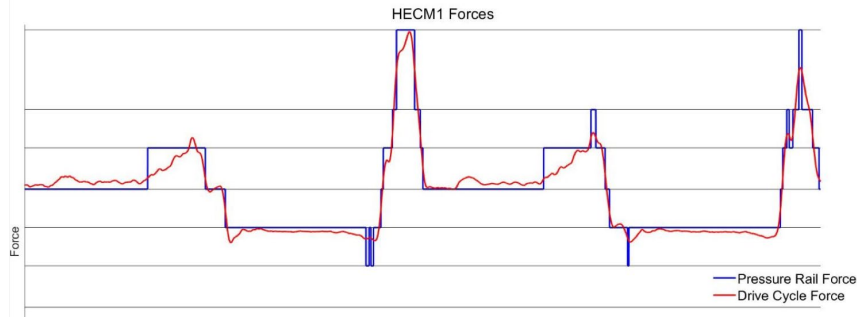
Technical Accomplishments & Progress

- A2: Develop energy saving evaluation tool

Motivation: Energy saving evaluation of system architecture requires a) designing and b) controlling system optimally.

Accomplishments:

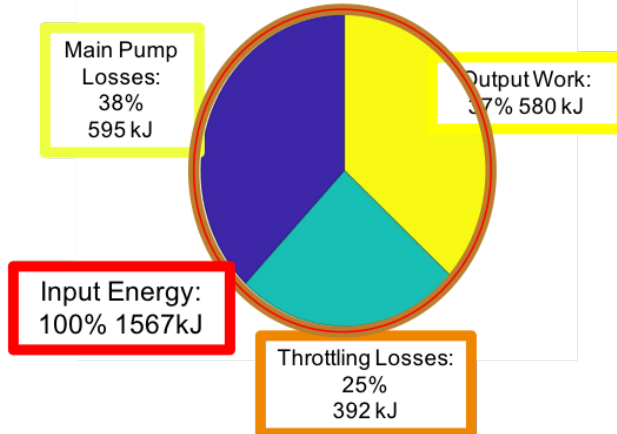
1. Created rapid inner loop algorithm (via Lagrange multiplier method) to determine optimal control to minimize energy use
2. Coupled with outer loop outer design (sizing, system parameters, etc.)
3. Compare results with a base line load-sensing architecture and direct electrification for a pilot system



Technical Accomplishments & Progress

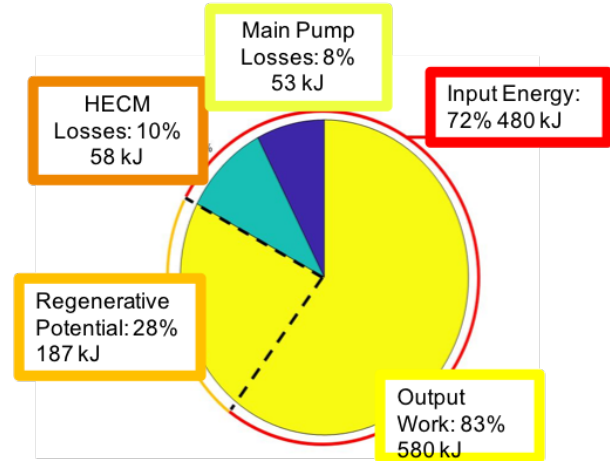
- A2: Develop energy saving evaluation tool (Sample results)

Load Sensing



- HHEA consumes 70% less energy than baseline load sensing
- HHEA requires 66% smaller e-machines

HHEA



E-motor requirements:

- Direct Electrification 48kW, 420Nm
- Proposed HHEA: 15kW, 135Nm



Technical Accomplishments & Progress

- B1: Identify nominal control strategy

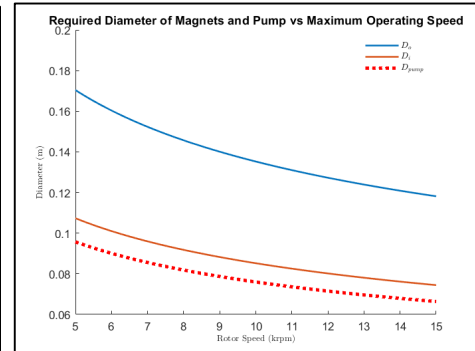
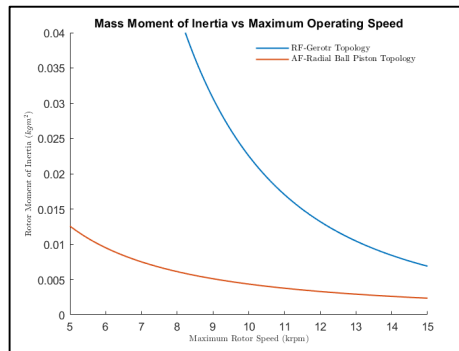
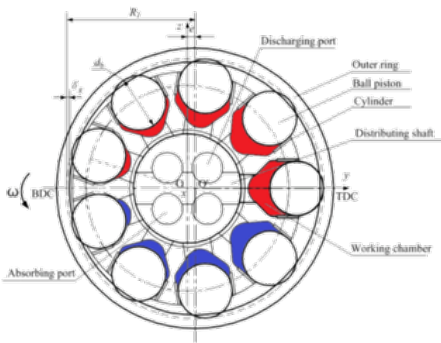
- The nonlinear passivity based backstepping control approach using the natural compressibility energy in the fluid has been identified as the basic control strategy
- **Advantages:** robust and high performance; has been applied with other system architectures



Technical Accomplishments & Progress

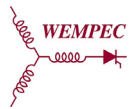
- C1: Hydraulic subsystem modeling / topology selection

- Rank and selected gerotor and radial piston pump/motor as two most promising topologies for integration with electric machine for HHEA
- Constraints for interfacing with electric analyzed:
 - Radial ball piston complements an axial flux electric topology
 - Moment of inertia stays small across a wide speed range
 - Electric motor magnet placement and hydraulic pump diameter scale together
- Modeling of hydraulic topology consider valve timing, pressure dynamics, leakage, friction and scaling effect

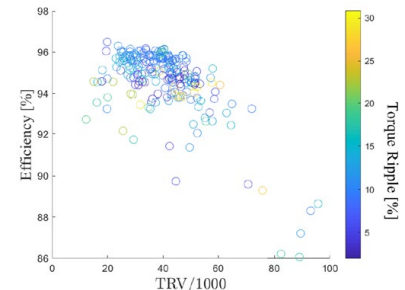
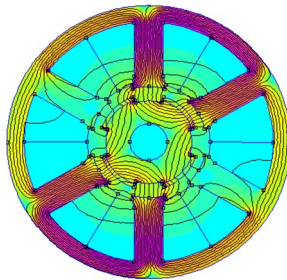
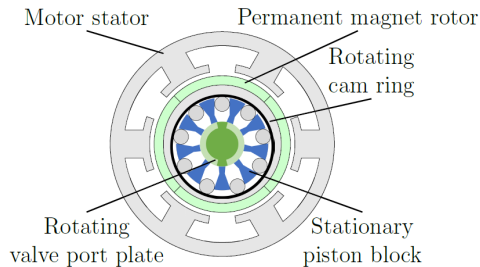


Technical Accomplishments & Progress

- C2: Electric subsystem modeling / topology selection

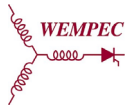


- Modeling and initial design space exploration
 - Electric machine designed and modeled in Finite Element Analysis (FEA)
 - Preliminary multi-objective optimization (efficiency, torque/rotor vol, torque ripple)
 - Design parameters: 4 pole, PMSM motor, 15,000rpm, Arnold Arnon-7 steel, Recoma-35E magnets
 - **Optimal design has efficiency > 96%**



Technical Accomplishments & Progress

- C2: Electric subsystem modeling / topology innovation

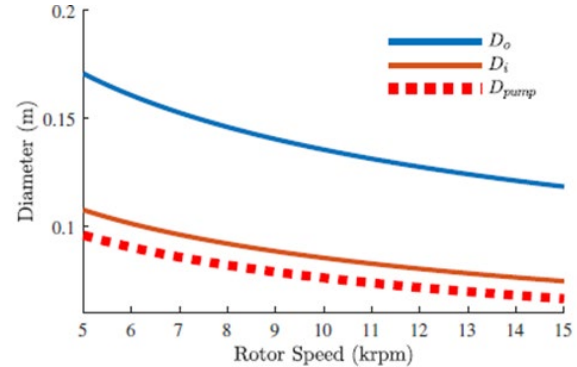


- A novel electric machine topology sized analytically:

- Higher power density
- Lower moment of Inertia

- Design Parameters:

- Type: **8 pole**
- Stator type: **Ironless**
- Max rotational speed: **15,000 RPM**
- Steel used: **Arnold Magnetics Arnon-7**
- Magnets used: **Arnold Recoma-35E**



- Modeled and Finite Element Analysis (FEA) performed
- Very Promising candidate- Exact topology under IP Disclosure process.
- Initial sizing relations for Power Electronics obtained
 - Machine parameters essential for accurate sizing & modeling being obtained from transient FEA.

Electric Machine Sizing Curves










Response to Previous Year Reviewer Comments

- This project is a new start



Partners/Collaborators

 UNIVERSITY OF MINNESOTA	Lead PI institution. Responsible for system level modeling and control, power electronics modeling and selection and mechanical design aspects of integrated electric motor – pump (EMP).
	Co-PI institution. Responsible for electric motor modeling and design of the EMP.
   	OEM manufacturers. Responsible for vehicle system requirements, duty cycle requirements and voice of the customer.
	Hydraulic components manufacturer. Responsible for providing support to hydraulic component and system modeling, and prototype testing.
Consultant	Retired hydraulic industry expert in product development. Responsible for overall project management and OEM coordination.

Remaining Challenges and Barriers

- Analysis and prediction of performance and energy saving potential of proposed system architecture requires accurate component models and representative duty cycles.
 - **Mitigation:** Team will work closely with OEM and industry partners to obtain accurate models and useful duty cycles.

Proposed Future Research

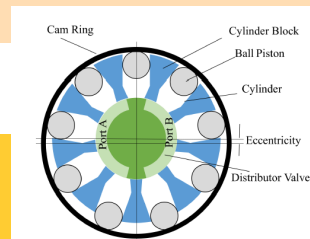
Any proposed future work is subject to change based on funding levels

Ongoing (BP1): FY18/19:

- 1A.3: Evaluate energy saving potential for selected platforms; down-select for analysis in BP2
- 1B.3: Complete nominal control strategy development → **Milestone 3** (nominal control)
- 1B.4: Verify control strategy through simulations under certain and uncertain parameter scenarios
- 1C.1: Refine and integrate hydraulic and electric subsystem models for combined design optimization → **Milestone 4** (select integration topology)

Proposed (BP2): FY19/20:

- 2A.1: Perform optimal trade-off analysis for different design decisions w.r.t. multiple objectives (efficiency, cost, complexity, etc.). BP1 focuses mainly on efficiency.
- 2B.1/2: Experimentally verify control strategy on hardware-in-the-loop setup
- 2C.1: Validate electric and hydraulic subsystems on benchtop experiments
- 2C.2/3/4 Conduct multi-physics hydraulic-electric optimization for combined machine and create detailed design of integrated prototype.



Summary

Relevance:

- Off-road vehicles require hydraulics to provide high power but are inefficient
- Electrification is challenging due to cost of high power/torque electric machines
- Proposed architecture blends hydraulic and electric actuations to provide for significantly improved efficiency; improved control performance; while minimizing need for high power electric machines.

Accomplishments / future work

- Energy saving evaluation tool developed & ready for selected platforms
- Control strategy identified and to be verified on hardware-in-the-loop testbed
- Electric and hydraulic subsystems topologies being analyzed for tight integration.

Technical Backup Slides



Platform Selection Criteria

1. Potential for significant energy savings
2. Requirement for control performance
3. Compatibility of proposed architecture
4. Electrification benefits other than efficiency or control performance
5. Ability to demonstrate architecture's unique potential (E.g. multi-DoF with different pressure requirements)
6. Can benefit from a common prime mover
7. Too high power to be electrified directly
8. Commercial feasibility
9. Availability of information from OEM

Selection Criteria for Hydraulic pump/motor

Topology for integration with e-machine

Criteria	Description
Low Pump displacement scalability	As the pump displacement (size) gets smaller, how does the pump perform
High pump displacement scalability	As the pump displacement (size) gets bigger, how does the pump perform
Maximum speed capability	Does the pump have the potential to run at high speeds
Displacement Density	How much fluid is displaced for a given packaging mass (mass can't become too large for most mobile applications)
Cost	Dollar amount
Volumetric eff @ high pressure	How volumetrically efficient is the system at high pressure
Mechanical eff @ low speed	How mechanically efficient the system is at low speed
Mechanical eff @ high speed	How mechanically efficient the system is at high speed
Ease of integration	How easy can the pump become electrically integrated
Ease of valves	How easy can the pump have active valves
Stick-Slip @ low speed	How noticeable is the stick-slip behavior of the pump at very low speeds
Wear and reliability	How much wear occurs within the pump
Noise	How loud is the pump/motor