Implement-Only Implementation of a Multi Pressure Rail System to an Agricultural Planter

Jacob Lengacher[1], Xiaofan Guo[1], Ryan Jenkins[2], Andrea Vacca[1]

[1] Purdue University, , [2] CNH Industrial

1. Abstract

Tightening emissions regulations and rising fuel costs have driven a desire across many industries for more efficient actuation systems. This is particularly true of the agricultural sector. An extremely common arrangement in this sector is the tractor and implement pairing, in which actuators on an implement are powered by a hydraulic supply system on the towing tractor. This arrangement complicates the development of energy efficient hydraulic systems, as many new system designs require modification of both machines to reap efficiency benefits. Past work by the authors' team has demonstrated great potentials for Multi-Pressure-Rail (MPR) technology involving both the tractor and implement subsystems. However, applicability of this MPR technology in a more realistic scenario where only one vehicle is equipped with such technology was not addressed.

This work proposes an implementation of the MPR technology to an agricultural planter that allows significant savings, while only modifying the implement machine. This is done by manipulating the load sense network of a stock tractor to set system pressures to those required by the MPR system. This greatly reduces the barrier to implementation of MPR technology in agriculture. The work begins by outlining the reference machine for the system, then reviews the MPR system working principle. After this, the proposed expansion to the MPR concept is laid out, and applied to the reference system. Finally, experimental validation is carried out, demonstrating on average 37% reduction in system power consumption.

2. Introduction

A growing world population corresponds naturally with increased demand for food [1]. This increased demand will naturally require more effective agricultural machinery to meet. Simultaneously, however, growing economic, environmental, and social pressures demand a reduction in carbon emissions [2]. These demands can only be reconciled by the development of more efficient agricultural systems capable of meeting the needs of the future in a sustainable way. One particularly common arrangement in existing agricultural systems is the tractor / implement pair, in which a tractor supplies power to a towed working implement. This arrangement is popular for its cost effectiveness; the most expensive components of the system are kept aboard the tractor and can be reused across a variety of operations, such as planting, seeding, baling, and tillage, while the task specific actuators and tools are kept on the less expensive implement. The state of the art for this arrangement is the LS system, in which the tractor supplies flow at a pressure set by the highest load user. While it is very efficient for tightly grouped loads and single actuators, this system often suffers serious inefficiency when supplying multiple actuators at widely spread pressure levels, as demonstrated for the case of an exavator by Zimmerman in [3]. All of this combines to give fluid power systems in agriculture an average efficiency of just 20%, as estimated by Oak Ridge National Laboratory [4].

A wide variety of solutions aiming to improve the efficiency of the LS system, or replace it entirely have been proposed. Madau dynamically minimizes the load-sensing margin of a wheel loader system in [5] to reduce regulation losses. Tian and Stump apply a similar logic to an agricultural system in [6] also varying the margin of the compensator to enable even greater reduction in pump pressure [7]. Independent metering, in which the meter in and meter out valves are controlled independently with the goal of reducing unnecessary metering are also a common method of reducing unwanted losses [8]. Wydra pairs an independent metering LS system with an accumulator rail to allow for some load recovery potential in [9], showing in simulation up to 18.7% reduction in system energy consumption. These solutions are effective in reducing the power consumption of systems with relatively closely grouped actuator loads. They do not address the issue of load imbalance described in [3], however. Solving this problem requires more radical modifications of the system.. The most natural and extreme modification is the addition of more pumps. Grouping actuators together by load and supplying these groups independently allows for reduction in regulation losses due to load imbalance. The natural conclusion of this is primary control hydraulics, in which one actuator is controlled by one pump, either by varying the speed or displacement of the pump. The latter method, displacement control, as implemented in [10] and [11] eliminates the need for throttling speed control, and ensures each actuator is supplied with exactly the pressure and flow required by the user. The former method has seen much interest in recent years as electrification, and thus variable-speed pumps (ePumps) have become a more common part of off-road actuation. Qu proposes an architecture for a small loader using an ePump for primary control of an actuator, reducing system power consumption by greatly reducing throttling losses and recovering energy from the lowering of a boom [12] [13]. All of these solutions have the potential to drastically reduce the power consumption of these hydraulic systems by doing away with regulation losses entirely, and enabling energy recovery from overrunning loads. The limitation of the system is cost, however. The more actuators a system has, the less affordable and plausible primary control methods become. Busquets attempts to resolve this, proposing a pump sharing algorithm that allows for fewer pumps to be used to supply the system’s actuators in [14]. This strategy relies heavily on transient, well-characterized duty cycles, like those present in construction excavators, making them less suited for application to agricultural applications, where there may be many actuators with uncertain drive cycles.

Another option is switching to a pressure supplied logic. Pressure supplied systems decouple the flow requirements of the actuator and the pump, having the pump set a rail to a chosen pressure. This arrangement can be inefficient if poorly designed, but with proper design it can be quite efficient [15]. One option to reduce the throttling losses of pressure supplied systems is the use of hydraulic transformers. Proposed by Achten in [16], this concept mimics electrical systems by utilizing a pair of variable displacement hydraulic pump/motors connected in tandem. One serves as the motor, taking flow from a fixed constant pressure rail, to power the second, which pumps up to the pressure and flow required by the actuator. This architecture does away with throttling losses entirely and enables load recovery, but at the cost of somewhat increased component losses. This concept can be implemented in smaller, less dynamic forms as well, to generate multiple fixed rails from one main supply as seen in [17]. Li et al propose an architecture in which a constant pressure system is used, with small ePumps boosting or bucking pressure to that required by the actuators [18] [19], following a similar strategy to this.

A middle ground can be found in multi-pressure rail systems (MPR). These systems split the hydraulic supply into multiple pressure-supplied rails, then use selection valve sets to dynamically adjust the rails attached to each actuator inlet and outlet. In [20], Lumkes proposed this idea with the goal of improving the controllability of pressure supplied systems, though power savings potential and controller design were not considered. It was then utilized to great effect by the STEAM excavator in [21] where the MPR system's decoupling of actuator and prime mover speed enabled not only reduction in throttling losses, but engine management strategies and energy recovery as well.

Relevant to this work, the authors of this work propose an implementation of an MPR architecture specific to the agricultural implement case in [22], using a stationary test rig to assess several options for the hydraulic supply and control logic. Then, in, [23] the proposed architecture was fully fleshed out and demonstrated in simulation. Finally, in [24] the system's functionality and power savings potential were demonstrated on a full-scale prototype machine. This implementation of the architecture takes advantage of the slow dynamics of the agricultural system to further optimize throttling losses by dynamically selecting the rail pressures. This enables the potential for a reduction of up to 48% in system power consumption. However, one limitation of this work, and much of the rest of the prior work done towards improving the efficiency of hydraulic systems, is that it requires the modification of both the hydraulic supply and the valving. As discussed above, one of the fundamental advantages of the tractor / implement system utilized in agriculture is that one tractor can supply and work with a wide range of implements, keeping costs lower. Most of the previously discussed solutions require modifications to both the supply system- the tractor- and the valving – the implement. This represents a significant barrier to adoption of such systems, as the costs of replacing both the tractor and the implement simultaneously is restrictive.

This work aims to address this challenge by proposing an MPR architecture for an agricultural implement that improves system efficiency using only modifications to the implement and can be supplied by an unmodified state of the art tractor. Such a system could serve as a "bridge" implement, capable of working first with existing tractors, and gaining some savings potential, and gaining even further benefits when paired with a purpose-built MPR Tractor. This allows for a staggered adoption of MPR technology, lowering the cost barrier to entry and likely improving adoption rate. To do this, first, the reference tractor/implement system will be outlined, and the MPR architecture proposed in [24] will be briefly reviewed. After this, the working principle of the proposed expansion to the system will be laid out. This principle is applied to the reference case, and then validated via experiments taken on a full-scale prototype machine in real field conditions.

3. Reference System

The reference machine for this work is a Case-IH 2150 Agricultural Planter supplied by a New Holland T8.435 Agricultural Tractor. This implement pairing is representative of the sort of system used across a wide range of North American farms for planting operations on soybeans and corn, and is a worthwhile case for consideration as a result. The tractor is outfitted with a simple pre-compensated load-sensing circuit able to supply implements via two different types of connections. The primary method is the Remote Valves, which are pre-compensated load-sensing valves with quick connections at the outlet and internal load-sense pickups. The second is the Power Beyond Manifold, which uses a larger quick-connect, no control valve, and an external load-sense connection, relying on the actuator to control the amount of flow required. The hydraulic architecture of the tractor can be seen in Figure 1 below.

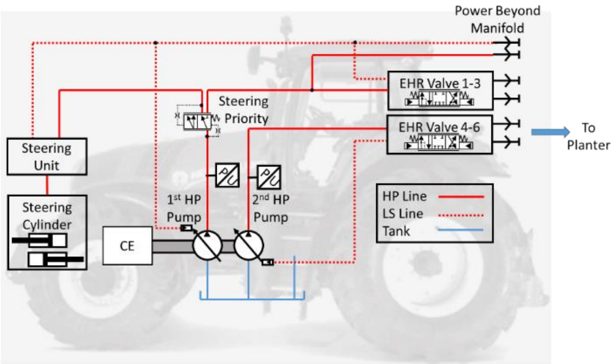

Figure 1: Simplified Tractor Schematic

The planter uses hydraulic motors and cylinders to carry out the majority of the actuations assorted with planting, as shown in Figure 2 below.

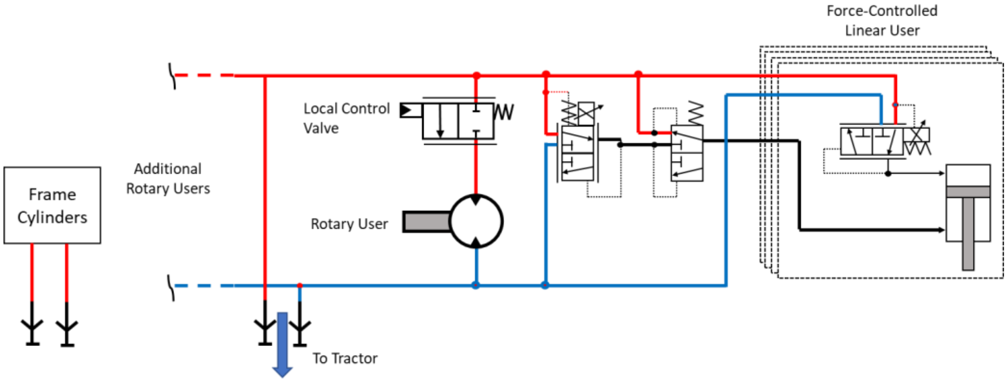

Figure 2: Simplified Planter Schematic

The actuators in use on the planter are outlined below. The steady state rotary and steady state linear functions run continuously during planter operation carrying out a range of operations, such as providing planting material to the planting row units (Bulk and Vacuum fans, Fertilizer pump), powering the row units (compressor and alternator), and ensuring consistent ground contact and planting depth (HDPCs and WMCs). The transient linear functions run far less consistently, serving only to raise and lower the planter toolbar during headland turns, and reconfigure the frame arrangement for transport.

Table 1: Hydraulically Actuated Planter Functions

Steady State Rotary Functions	**Purpose**
Alternator	Power planter electronics
Bulk Fill Fan	Move seed to row units
Compressor	Power planter pneumatics
Fertilizer Pump	Provide fertilizer to row units
Vacuum Fan	Provide suction for planting
Steady State Linear Functions	**Purpose**
Hydraulic Down Force Cylinders (HDPCs)	Maintain consistent planting depth
Weight Management Cylinders (WMCs	Keep wings in contact with ground
Transient Linear Functions	**Purpose**
Frame Cylinders	Raise and lower toolbar to begin / end planting process

The planter has a large number of actuators that must run continuously, so to reduce the number of connections between the tractor and planter, it supplies all of the steady state planting functions via a pair of hydraulic quick connects, connected to the remote valves on the tractor. The remote valves are opened fully, and flow is then controlled via the local flow control valves on the planter. The frame cylinders are then supplied more traditionally using the remote valve for metering control. This arrangement allows for more complex control on the planter and makes the planter largely independent of the control capabilities of the tractor, but it comes at the cost of system efficiency. A conflict in control occurs due to the position of the load-sense pickup between the two control valves. As shown in Figure 3 below, the load-sense pump attempts to maintain a fixed margin across the remote valve, effectively controlling flow through that valve. Simultaneously, the local flow control valves, either via hydraulic compensation or an electronic controller, attempt to control flow to the actuators by throttling from the outlet of the remote valves. This leads to a conflict; the pump upstrokes, increasing flow through the remote valve to try to meet its margin. Simultaneously the control valve compensators close down, trying to maintain their own margins leading to a net increase in the line pressure between the valves. This increase in pressure is passed through the LS network to the pump, causing it to further increase its displacement, and continue the cycle. Equilibrium is reached when the LS pressure reaches the LS pressure for the system. For most applications, pressure saturation is reached first, with the relief valve in the LS line limiting the pump displacement and system pressure. This leads the system to behave not like an LS system, but like a constant pressure system, with the rail pressure set at the pump’s maximum pressure, leading to very low system efficiency but good control characteristics. These control benefits owe to the decoupling of the supply flow rate from the actuator flow rate which allows actuator speed to be controlled entirely by the local flow control valve.

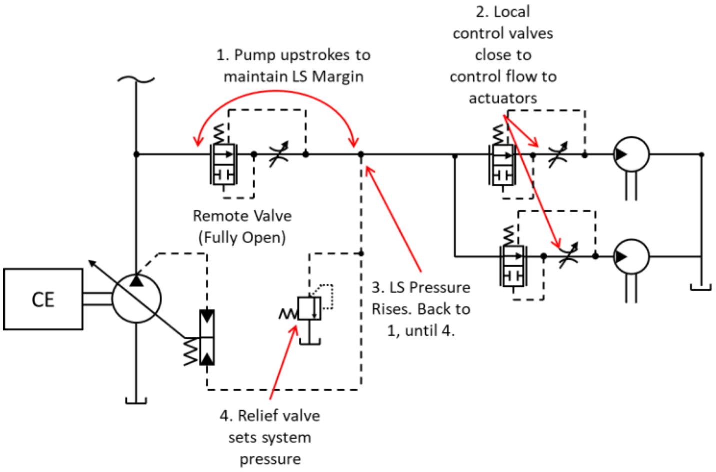

Figure 3: Control Conflict due to Series Control Valves

4. MPR Architecture Review

The MPR Architecture, as presented in [24] aims to improve the system efficiency while maintaining its good controllability by switching from a flow-controlled logic like LS to a pressure-controlled logic. The proposed system, shown in Figure 4 is supplied by 2 pressure rails whose pressure can be controlled by varying the flow provided to them. Thanks to the long lines and large capacitance of the planter case, this can be achieved without the need for accumulators. Rotary actuators are supplied via pressure selection and control valve manifolds which control what rails are connected to the inlet and outlet of each actuator, and then control the speed of the actuator by throttling flow from those rails. The force controlled linear actuators (the HDPCs and WMCs) are connected permanently from HP to LP due to their continuous high load requirements.

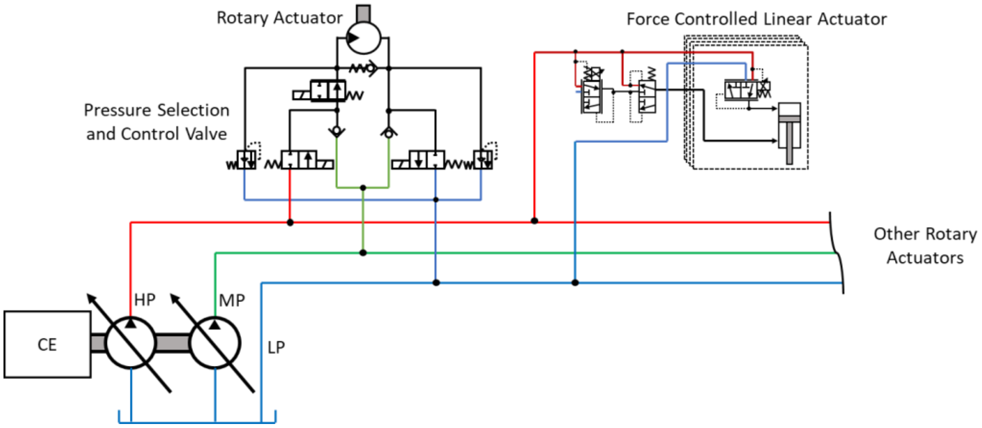

Figure 4: MPR Architecture Overview

The pressure levels of the different rails are optimized to minimize the total system throttling losses while ensuring all actuators get the required flow, following a logic laid out in [24]. In this work, two control logics were proposed. The first varies both the high and medium pressure levels to fully optimize the system throttling losses, called “Variable HP MPR”. The second logic stemmed from the recognition that the downforce system always requires close to maximum pressure, resulting in the high-pressure rail spending most of its time very close to that level. This fact is leveraged by the second control logic, called “Fixed HP MPR” to reduce control effort and improve system stability by locking the high-pressure rail at the maximum system pressure and only optimizing the medium pressure rail. [24] demonstrates that this logic improves dynamic behavior at only a slight cost in terms of reduced savings. To optimize the pressure levels and operating modes of the system a controller was devised. It assigned the HP rail to either a pressure just exceeding the required pressure of the highest load user (for Variable HP MPR), or to the system maximum pressure (for Fixed HP MPR). The medium pressure rail was then selected by calculating the system losses at key points based on the pressure requirements of the actuators and discontinuities in the loss cost function. After the rail pressures were selected, each actuator was assigned to the rail combination that minimized system loss. The previously proposed architecture required modification to both the tractor and the implement, with the control logic and switching being carried out on the planter, and the tractor being relied upon to provide the required pressures. This represents a substantial barrier to potential implementation, due to requiring changes to both systems. This work proposes an alternative method of achieving the Fixed HP MPR control logic on an implement that can be achieved using an unmodified, state-of-the-art tractor.

5. Compatible MPR System

There are some requirements for this unmodified tractor. Principally, it must have remote valves, a power beyond manifold, and a two-pump, divided LS system. This is true of the reference tractor for this work, and a wide range of other machines currently on the market within the 300-400 hp size range of the reference system, and in larger vehicles. The pressure control is then implemented by “tricking” the tractor’s LS system into enacting MPR logic. The high-pressure level is set by exploiting the control conflict discussed previously; the HP rail is connected to one of the LS circuits via the remote valves, and the remote valves are opened fully. The control conflict drives the LS pump to maximum pressure, giving the HP rail its desired pressure level. The MP rail still requires variable control, however, which is achieved using the power-beyond manifold. The MP rail is supplied by the power beyond port, and thus the second LS pump, and uses an electronically regulated pressure to control the LS pressure seen by the power beyond manifold’s LS port. This working principle applied to the reference machine is shown in Figure 5 below.

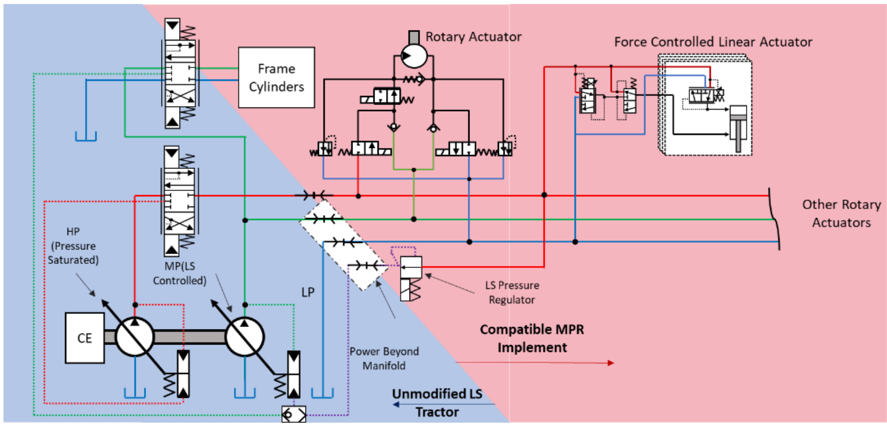

Figure 5: Implement-Only MPR Working Principle

As can be seen, the HP and MP rails are connected and controlled as outlined above. Notably, the transient linear functions are connected to the same pump as the MP system, ensuring their LS functionality is maintained. With this supply arrangement, the MPR implement can be left largely unchanged from that previously outlined, using pressure selection and control valves to handle speed control and mode switching for the rotary functions, while the force controlled linear functions are connected continually from HP to LP.

It is worth noting that this implement architecture also be compatible with an older-model tractor, via an expansion to the onboard control system, switching the system to use only HP and LP rails. Such a system would likely gain very few savings but would still be able to function as usual. This potential is valuable, and represents a direction for further investigation.

6. Experimental Setup

To validate system functionality and savings potential, the proposed architecture was then implemented on the reference machine. This modification was done in addition to the modifications presented in [24]. Figure 6 below shows the ISO schematic of the modified planter, including key sensor locations, along with the structure of the DAQ and control system for both the tractor and planter.

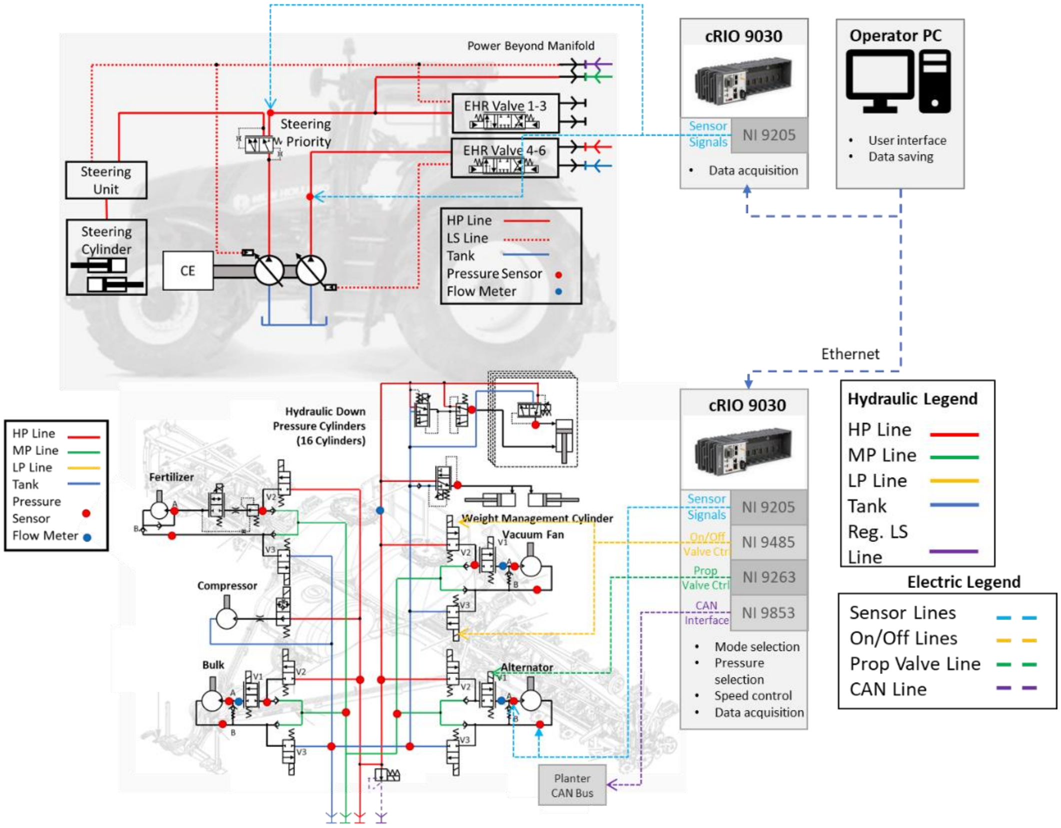

Figure 6: Implement-Only MPR Architecture Applied to Reference Machine

As can be seen above, the control logic was implemented using an NI CRio system. As in previous work, two CRios were used, one on the planter and one on the tractor. For this system, however, all control was carried out on the planter, with the tractor system serving only to monitor the behavior of the tractor hydraulic supply. The hydraulic modifications to the implement, beyond those shown in prior work, are shown in Figure 7 below. The hydraulic modifications made are implemented as a sort of adapter, connecting the MPR implement’s quick connectors to the correct ports on the tractor and siphoning flow from the HP line to run the regulator

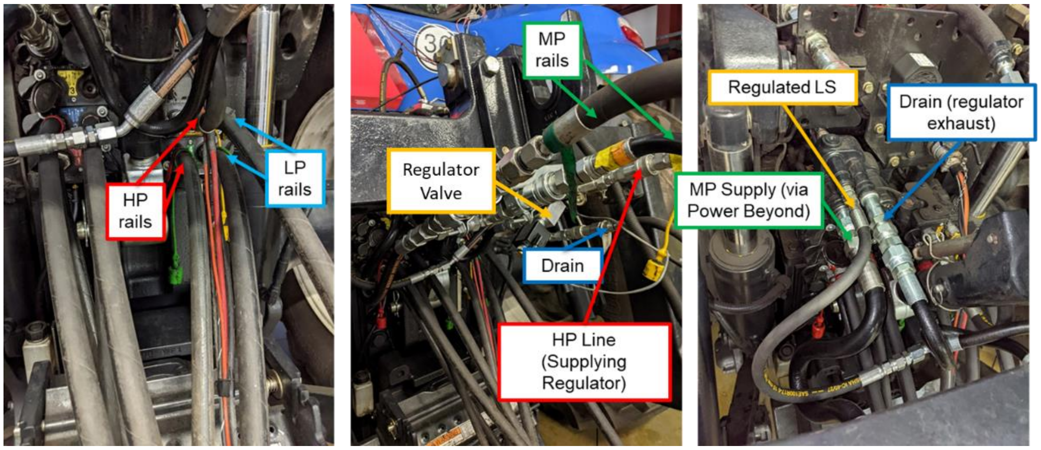

Figure 7: Compatible MPR Adapter Hydraulic Implementation

To assess the effectiveness of the system, and ensure a fair comparison against prior work could be made, the same working cycle as used in [24] was used. This cycle was provided by the vehicle manufacturer and contains two common working conditions; one corresponding to normal planting conditions, and one corresponding to a more aggressive high-speed planting case. Each test case was run at several engine speeds. The overall test set is shown in Table 2 below.

Table 2: Normalized Validation Drive Cycle

Drive Cycle Name	Crop	Vehicle Speed (%)	EngineSpeed (%)	Vacuum (%)	Alternator (%)	HDPC Force (%)	Wing Force (%)	Bulk Fill (rpm)	Liquid Fert. (gal/ac)
Baseline - Popcorn	Popcorn	50%	71%	57%	60%	50%	55%	70%	13%
			86%						
			100%						
High Speed - Popcorn	Popcorn	83%	86%	71%	80%	100%	55%	70%	13%
			100%						

Tests were taken in a similar method to prior work, on a quarter-mile test field strip at a Purdue farm, as shown in Figure 8. Each test was begun by starting the recording software, lowering the planter toolbar, planting for the length of the field, then raising the toolbar before stopping the recording. This ensured that ample steady state regions could be recorded to assess the power savings potential of the system at each condition.

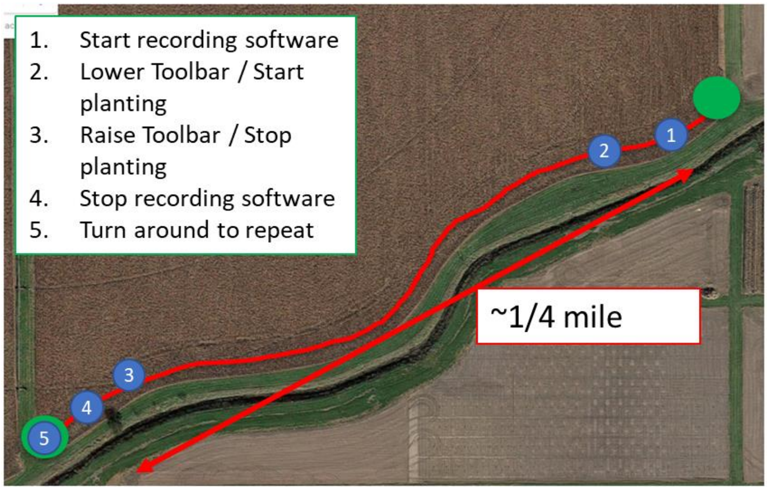

Figure 8: Test Field and Plan

7. Experimental Results

Figure 9 below shows the time series behavior of the MPR system, including several actuator modes and rail pressure levels. The system pressure behavior is as expected, with the HP rail locked at maximum pressure, and the MP rail settling to roughly 50% of the system maximum pressure. Initially, all the rotary actuators connect from MP to LP, however once the fertilizer has reached its target speed, it no longer needs to accelerate, but only to keep spinning, dropping its load enough to switch to connecting from HP to MP. Meanwhile the HDPCs are supplied from HP to LP.

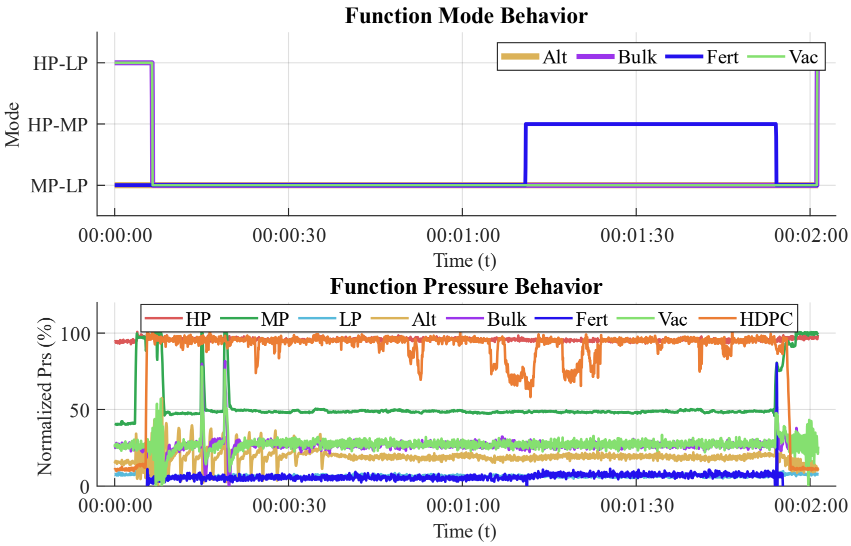

Figure 9: Time Series Results for Implement-only MPR System

All functions switch to be supplied by HP to LP at the beginning (0:00-0:10) and end (1:55-2:00) of the cycle. This coincides with the toolbar of the planter, which is powered by the MP pump (as shown in Figure 5) being lowered and raised, and occurs because the MP pump's LS functionality is maintained. When the bar is moved, the MP pump pressure rises, placing the MP and HP rail pressures close together and leading the system to function at a suboptimal point. This is only a transient region, however, and the system quickly stabilizes and returns to more optimal operation. Table 3 below shows the system's improvement in power consumption over the baseline system, compared with the two-machine, Fixed HP MPR version of the system presented in [24] averaged across the tests taken.

Table 3: Pump Power Consumption Results Compared with Tractor / Implement MPR

Operating Condition	**Pump Power Reduction (%)**	
Solution:	Tractor / Planter MPR [24]	Implement-Only MPR
Normal	*49.9*	*39.3*
High-Speed	*37.1*	*34.5*

As can be seen, the implement-only MPR architecture does not achieve the same level of savings as the two-machine MPR system. There are several reasons for this. The first is that where the implement-only system supplies the HP rail via the remote valves, which have compensators, metering areas, lock check valves, and other features to ensure breadth of usability, the two-machine system uses specially made MPR quick connects which bypass these features. This allows for smaller pressure losses from the pump to the actuator, allowing the two-machine system to operate at a slightly lower pump pressure to maintain equivalent rail pressures. The second source of this loss is the LS regulator, which siphons a small amount of flow from the HP rail continuously. This flow is small, but since it comes from the HP line it does have a noticeable impact on the overall system efficiency.

8. Conclusion

This work set out to design an MPR-based architecture capable of improving the efficiency of a tractor-planter system while only modifying the implement. An expansion to the basic agricultural MPR architecture was proposed allowing the system to function in tandem with a standard LS tractor that met certain requirements. The system working principle was detailed and a schematic presented. This architecture was then implemented on a full-scale prototype planter and tested with an unmodified tractor. Field test results demonstrated an average 37% power savings over the unmodified system. This improvement was less than that demonstrated in [24] for a two-machine MPR system, but still substantial, and its requiring modifications to only one machine represents a significantly smaller barrier to adoption.

9. Acknowledgement

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10. References

[1] D. Wrachien, B. Schultz and M. Goli, "Impacts of population growth and climate change on food production and irrigation and drainage needs: A world-wide view," *Irrigation and Drainage,* pp. 981-995, 2021.

[2] A. Masia, "Greenhouse Gas Emissions-Off Highway Vehicles Solutions and Future Trends," Maha Fluid Power Research Center , Lafayette, IN, 2022.

[3] J. Zimmerman, M. Pelosi, C. Williamson and M. Ivantysynova, "Energy Consumption of an LS Excavator Hydraulic System," in *ASME International Mechanical Engineering Congess and Exposition,* 2009.

[4] L. J. Love, E. Lanke and P. Alles, ""Estimating the impact (energy, emissions and economics) of the US fluid power industry,"," Oak Ridge National Laboratory, Oak Ridge, TN, 2012.

[5] R. Madau, A. Vacca and F. Pintore, "Energy Saving on a Full-Size Wheel Loader Through Variable Load Sense Margin Contro," *J. Dyn. Sys., Meas., Control.,* 2021.

[6] X. Tian, P. Stump, A. Vacca, S. Fiorati and F. Pintore, "Power-Saving Solutions for Pre-Compensated Load-Sensing Systems on Mobile Machines," in *Transactions of the ASABE. 64(5)*, 2021.

[7] P. Stump, X. Tian, J. Lengacher, R. Jenkins and S. Fiorati, "Combined Pump and Compensator Margin Control for Pre-Compensated Load Sensing Architecture: Implementation and Experiments," in *Fluid Power Systems Technology*, Sarasota, FL. USA, 2023.

[8] Z. e. a. Quan, "A Survey of Powertrain Technologies for Energy-Efficient Heavy-Duty Machinery," *Proceedings of the IEEE*, vol. 109, no. 3, pp. 279-308, 2021.

[9] M. Wydra, G. M. and B. Weiss, "An Approach to Combine an Independent Metering System with an Electro-Hydraulic Flow-on-Demand Hybrid-System," in *The 15th Scandinavian International Conference on Fluid Power*, Linköping, Sweden, 2017.

[10] J. Zimmerman, Toward Optimal Multi-Actuator Displacement Controlled Mobile Hydraulic Systems, West Lafayette: PhD Thesis: Purdue University, 2012.

[11] N. Daher and M. Ivantysynova, "Yaw stability control of articulated frame off-highway vehicles via displacement controlled steer-by-wire," *Control Engineering Practice,* pp. 46-53, 2015.

[12] S. Qu and e. al., "A high-efficient solution for electro-hydraulic actuators with energy regeneration capability.," *Energy,* vol. 216, 2021.

[13] S. Qu, D. Fassbender, E. Busquets and A. Vacca, "Formulation, Design and Experimental Verification of an," in *Global Fluid Power Symposium*, 2020.

[14] E. Busquets, Advanced control algorithms for compact and highly efficient displacement-controlled multi-actuator and hydraulic hybrid systems, West Lafayette: Purdue University: PhD Thesis, 2016.

[15] W. Shen, H. Huang, Y. Pang and X. Su, "Review of the Energy Saving Hydraulic System," *IEEE Access,* pp. 665-669, 2017.

[16] P. Achten, Z. Fu and G. Vael, "Transforming future hydraulics: a new design of a hydraulic transformer," in *The Fifth Scandinavian International Conference on Fluid Power,* Linkoping, Sweden, 1997.

[17] J. Lengacher, P. Stump, A. Vacca, R. Jenkins, F. Pintore and S. Fiorati, "Application of the Hydraulic Transformer Concept to Reduce Throttling Loss in a Multiple-Function Load Sensing System," in *ASME/BATH 2023 Symposium on Fluid Power and Motion Control*, Sarasota, Florida, 2023.

[18] P. Li, J. Siefert and D. Bigelow, "A HYBRID HYDRAULIC-ELECTRIC ARCHITECTURE (HHEA) FOR HIGH POWER OFF-ROAD MOBILE MACHINES," in *Proceedings of the ASME/BATH 2019 Symposium on Fluid Power and Motion Control*, Longboat Key, FL, USA, 2019.

[19] J. Siefert and P. Li, "Optimal Control of the Energy-Saving Hybrid Hydraulic-Electric Architecture (HHEA) for Off-Highway Mobile Machines," *IEEE TRANSACTIONS ON CONTROL SYSTEMS TECHNOLOGY,* 2021.

[20] J. Lumkes and J. Andruch, "Hydraulic Circuit for Reconfigurable and Efficient Fluid Power Systems," in *The 12th Scandinavian International Conference on Fluid Power*, Tampere, Finland, 2011.

[21] M. Vukovic, R. Leifeld and H. Murrenhoff, "STEAM - A hydraulic hybrid architecture for excavators," in *10th Int. Fluid Power Conference*, Dresden, Germany, 2016.

[22] X. Guo, R. Madau, J. Lengacher, A. Vacca and R. Cardosa, "Multi-Pressure Rail System Design with Variable Pressure Control Strategy," in *The 13th International Fluid Power Conference*, Aachen, Germany, 2022.

[23] X. Guo, J. Lengacher and A. Vacca, "A Variable Pressure Multi-Pressure Rail System Design for Agricultural Applications," *Energies,* vol. 15, 2022.

[24] X. Guo, J. Lengacher and A. Vacca, "Quantification of energy savings due to the adoption of of Multi-Pressure Rail technology in an Agricultural Tractor – Implement system through experiments," *Energies*, 2024 (Under review; draft available upon request).