Milwaukee School of Engineering

Rearin' Raiders

MSOE's ¼ Scale Tractor Pull Team

X-Team Design Report

2014

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Overview

It was an inauspicious start for the 2011 model of the Rearin' Raiders Electrohydraulic Performance Puller (EHPP). The EHPP placed 20th out of 21 teams in the tractor pull competition at the 2011 ASABE International Quarter Scale Tractor Student Design Competition (IQS). While placing in the top third for design judging, written design, and the maneuverability contest, the EHPP placed 17th overall in the competition. These results clearly indicated there was room for improvement in the design of the Rearin' Raiders EHPP, especially since the 2011 Rearin' Raiders model was designed primarily as a competition pulling machine geared exclusively toward the recreational tractor puller. Moreover, despite being marketed as a pure competition pulling machine, the prospective owner may find certain design refinements in terms of improved serviceability, driver comfort, and ease of operation. Not least of which includes added performance, especially with the nearly endless possibilities associated with the on-board hydraulic system.

2011 Tractor Design Analysis

Figure 1: 2014 Rearin' Raiders design team members pictured behind stripped down version of 2011 EHPP. Team members pictured from left: Chris Amble, Ethan Ensign, Steven Shaffroth, and Steve DiGrazia.

Research into the results and feedback from the judges of the 2011 IQS competition provided useful information on the strengths and weaknesses of the 2011 EHPP. Most of the shortcomings indicated by the judges pertained to safety, ergonomics, and serviceability. The need for improved pulling performance and refined utilization of the hydraulic system programming software was manifested by the 20th place finish (out of 21 teams) in the tractor pull contest. Placing sixth in the maneuverability contest also indicated that there was ample room for improvement in the steering and controllability of the tractor.

To better understand the goals and outcome of the original design process and prototyping effort of the 2011 EHPP, the 2014 Rearin' Raiders design team met with two members of the 2011 Rearin' Raiders team. During this meeting, limitations and shortfalls discovered during testing and the debut of the 2011 EHPP model were discussed, revealing that there was insufficient time to test and fully develop the control programming to utilize the potential of the Woodward hydraulic control module and MotoHawk development suite. One unresolved issue connected to this was oversensitivity of the motion control pedal. Other related topics included potential design improvements in the steering and hydraulic systems as well as the fuel tank location. After the meeting it was decided that the best way to fully understand some of the limitations and solutions needed for control improvements would be to return the 2011 EHPP model tractor to its original form as an operational vehicle. The tractor had been dismantled and on display for over two years. Restoring the tractor was time-consuming as broken steering components needed repair. Testing produced first-hand experience of the sensitivity of the motion control pedal and its associated safety issues regarding unwanted rapid/sudden acceleration and deceleration when maneuvering the tractor.

By mid-April there was an opportunity to test the early version of the 2014 model EHPP. This version incorporated improvements to the steering and hydraulic systems, instrumentation and controls layout, as well as the initial version of the control software programming. The testing provided feedback on issues associated with these design improvements. Engine-related issues prevented multiple pull attempts to refine programming parameters and systematically adjust weight distribution using ballast to achieve a maximized pulling distance. After numerous complications from traversing uneven terrain, it was discovered that the conservative placement of the wheelie bars by the 2011 Rearin' Raiders design team could be raised to the maximum height allowed per section 13 of the IQS competition rules [1] to ensure ease of travel over uneven terrain and maximum pulling performance.

Figure 2: Test pulling at UW-Madison's testing facilities on April 12, 2014, to test the initial iteration of control programming and redesigned operator interface and control/instrumentation layout.

Areas for Design Improvement

Figure 3: Picture of 2011 EHPP model at 2011 IQS competition in Peoria, IL. One can notice the unsafe location of the fuel tank behind the right front wheel as well as the single-piece fiberglass body.

The steering system of the 2011 EHPP design relied on the operator for providing both the input and force to manipulate the front wheels. The system was a manually operated (unpowered) hydraulic steering system utilizing a hydraulic rotary actuator for driver input from the steering wheel and two dual acting cylinders for controlled movement of the front linkages. This system required the driver to apply a considerable amount of force, roughly 30 pounds, to turn the front wheels when on a rough, hard, dry surface (i.e. concrete). This caused driver fatigue and failure of the mechanical linkage between the steering wheel and the hydraulic rotary actuator. The limited displacement of the hydraulic rotary actuator prevented the use of the full lock (45 degree) steering angle. These steering system shortcomings limited the mobility and ease of operation of the 2011 EHPP.

The 2011 EHPP featured a hydraulic drivetrain to deliver power from the engine to the rear wheels. The drivetrain incorporated two tandem pumps in closed hydrostatic loops with two hydraulic motors, one operating at each rear wheel location. Initial testing of the 2011 EHPP model design and control programming proved that controllability was a challenge due to the lack of electrical and hydraulic dampening in the circuit to control the pump displacement which in turn controlled the overall tractor acceleration and deceleration.

To achieve improved pulling performance for the 2014 EHPP model, certain items needed analysis: the efficiencies of the main hydraulic components (i.e. pumps and motors), and system parameters to determine whether maximum power was being transmitted to the rear wheels based on available system pressure and motor displacement.

At the 2011 IQS competition, the 2011 EHPP recorded a weight of 795 pounds. The various components of the hydraulic system accounted for a majority of the tractor’s overall weight. To meet the 800 pound weight limit to allow for design modifications in other areas for the 2014 EHPP model, all hydraulic components on the 2011 EHPP had to be reviewed for possible weight reductions to optimize or maintain overall performance.

The 2011 EHPP’s hydraulic system did not incorporate a direct means of dissipating heat energy generated from the various hydraulic components during normal tractor operation. Along with the potential for thermal damage to components within the system, if the hydraulic oil was to overheat, the viscosity of the oil would drop below the normal operating range. This would prevent adequate lubrication for the various moving hydraulic components, possibly resulting in seizing of moving parts and/or actual contact between metal parts in the pumps or motors.

Figure 4: Picture showing poor control labeling and layout along with lack of instrumentation on 2011 EHPP.

Limited service capability of the 2011 EHPP model was due to the one-piece fiberglass body which required loosening of nine sheet metal fasteners for complete removal. Adding difficulty in removal, the body incorporated the dash panel with various switches that were fully wired and permanently mounted. All covered components were difficult to access for service on the 2011 EHPP model. The underside location of the battery made access difficult for external charging or removal. Poor serviceability access of fuses of the electrical system was a result of their location within the web of the frame rail. Checking the hydraulic oil level was hampered by the placement of the reservoir for the hydraulic system. The engine mount prevented efficient oil changing as engine oil would drain over the engine mount before draining into an oil pan.

2014

In terms of safety, the 2011 EHPP model design had few shortcomings as determined by the 2011 IQS judges; one being the fuel tank placed low to the ground and outside the right frame rail, just behind the right front wheel. Relocation of the fuel tank inside the frame rails would reduce the chance for impact on the gas tank, preventing rupture and splashing of fuel on hot engine parts. The 2011 IQS judges also indicated a need for improved labeling of all control functions as the orientation of the motion control toggle switches could cause confusion and lead to incorrect selection of desired motion direction/range. This accompanied the suggestion for added instrumentation to communicate performance and position of certain motion control functions to the operator, making it apparent for the need for safety decals warning of all potential operation hazards (i.e. pinch points, hot surfaces, risk of roll-over on uneven terrain, etc.).

Beneficial Design Modifications

The new design of the 2014 EHPP model incorporates a powered hydraulic steering system that consists of the same front end components and linkage system, except the lines which were changed to hydraulic hoses per section 19 of the IQS competition rules [1]. This system utilizes a commercial, off-the-shelf steering control unit (SCU) produced by Eaton to route pressurized hydraulic fluid to the appropriate front cylinder ports during steering operations. This SCU design also provides a means to turn the tractor in the event of a pressure source loss. The pressure source for this system is the existing charge pump which, through the use of a relief valve, will provide 250 psi of pressure to the system for the continued use of the lightweight front cylinders. This relatively low pressure will allow for steering of the front wheels when the tractor is at its maximum operating weight (1500 pounds) and on a surface with an effective *Mu* of up to 0.9 in a dry steer situation.

By continuing to utilize the original front end linkages and cylinders, the impact and cost of any required changes to the steering system are minimized while providing a more versatile and easy to operate system. The powered steering system helps to minimize operator fatigue by reducing the required force input by the operator to turn the front wheels. The new system requires 10 pounds of input force from the operator under normal tractor operation (with hydraulic pressure supplied by the charge pump). In the emergency steering mode, more force is required because the operator is both powering and controlling the system. This mode will allow for directional control of the tractor in the event of a hydraulic pump failure or engine stall.

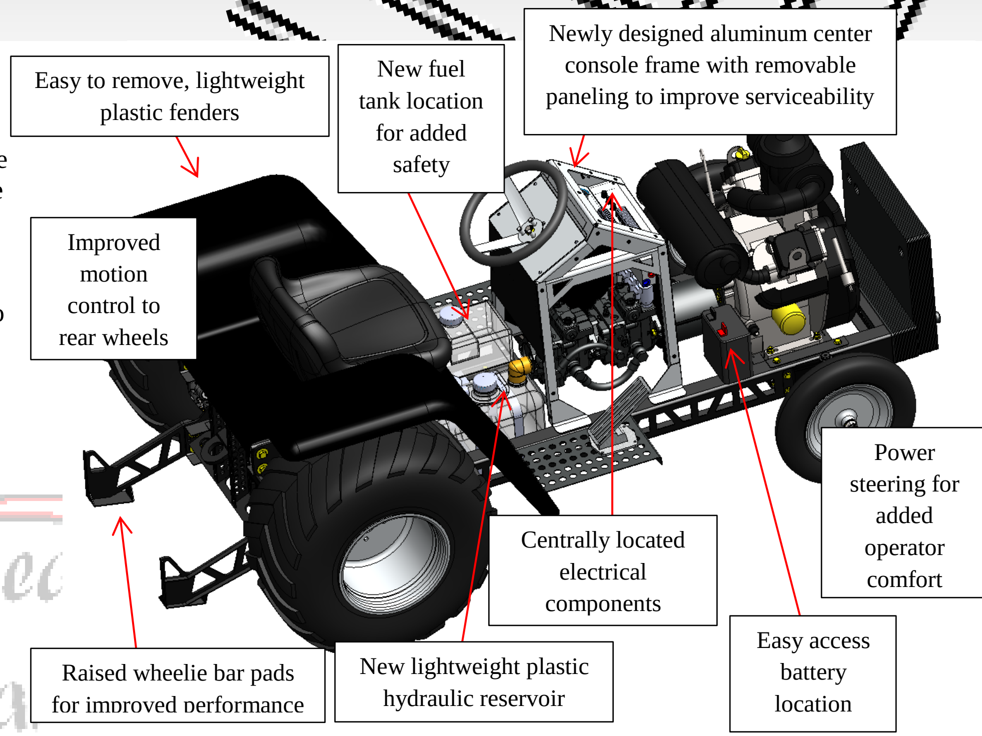

Figure 5: SolidWorks model of 2014 EHPP showcasing design improvements (with some ABS plastic paneling removed). One can notice the relocation of the fuel tank to a location inside the frame rails along with relocation of the battery to provide easy access for installation, removal, and external charging.

In order to improve the robustness and reliability of the steering system in transitioning from the 2011 to the 2014 EHPP model, the front spindle of the tractor will be re-manufactured using a stronger material. Prior to the 2011 competition the spindles yielded when the tractor was accidentally driven off a curb and emergency repairs were made to prevent further problems. By increasing the yield strength of the spindles from 36,000 psi (A-36 steel) to 70,000 psi (1018 cold rolled steel), the 2014 Rearin' Raiders design team plans to mitigate the risk of the spindles yielding while still maintaining the weldability required to manufacture the spindles.

The control system for the 2014 EHPP utilizes additional inputs from the operator to increase drivability and performance. Investigation into the 2011 EHPP design emphasized the need to differentiate between competition pulling and basic maneuvering through control selection options available to the operator. Fortunately, the variable output hydraulic system does not force the operator to sacrifice either of these options for the other. The redesigned controller will recognize the operator's desired mode of operation, engine speed, and ground speed to limit the rate of fluid flow to the motors and eliminate excessive wheel slip. This would help to eliminate the wheel slippage and negative controllability issues that occurred at low speed under sudden/rapid accelerations during initial testing of the 2011 EHPP. For this reason the new control system will limit the amount of torque that can be transmitted to the rear wheels through the use of a designer set value. In addition to the modifications to improve the tractor's performance during the pulling competition, electronically controlled variable engine speed and differential rear wheel speeds will be utilized to increase the overall drivability and maneuverability of the system. The operator will then be able to optimize the tractor's performance based on the task.

In order to optimize the hydraulic drivetrain, communication between the electrical controls and the hydraulic system had to be improved, and the hydraulic and electrical input signals had to be dampened. To dampen out the response of the hydraulic pumps, orifices were added at the inlet to the swash plate control housing. This causes a slight pressure drop in the control housing which dampens out the swash plate rotation and effectively slows the acceleration and deceleration rate of the rear wheels.

In terms of improving the overall pulling performance of the 2014 EHPP through hydraulic system modifications, a few design aspects were analyzed. Since IQS competition rules limit engine modifications and hydraulic system operating pressure to 4000+50 psi (section 5 and 19, respectively, of [1]), the only possible modification intended to increase the output power to the rear wheels was to increase the displacement of the motors. This idea was investigated, and new motors were selected that would directly replace current motors so design changes would not be needed for the mounting plate or frame. However, this idea was determined unfeasible because too much torque would be produced at the rear wheels, effectively causing too much breakaway wheel spin as the torque would exceed the available traction forces.

Research of hydraulic system components that could be changed or modified on the 2011 EHPP showed that one of the major sources of possible weight reduction was in the hydraulic reservoir. The 2011 EHPP incorporated a 4-gallon steel reservoir that weighed 57.8 pounds when completely full with oil. Two options were analyzed as possibilities for the new lightweight design: a 2.6 gallon aluminum reservoir or a 2.5 gallon plastic reservoir. Each design offered a significant weight savings, but the plastic reservoir design was chosen as the best alternative because it had a total weight of 20.19 pounds when completely full of oil and a total weight savings of 37.61 pounds. In addition to being a lighter, more effective design, at $14.51 it cost much less than the steel ($275.00) and aluminum ($250.00) reservoirs. The selection of the plastic reservoir resulted in significant cost and weight savings, but the thermal capacitance of the hydraulic oil was diminished since the overall volume of oil decreased from 4 to 2.5 gallons.

A thermodynamic analysis was completed to determine the thermal load of the 2014 EHPP and its hydraulic system. A worst-case scenario was analyzed in which it was assumed that all input power to the hydraulic system (from the engine) was converted to heat, meaning that all hydraulic fluid flow was over the relief valve resulting with the input power being converted almost entirely to thermal energy. In addition, it was assumed that the hydraulic system was a completely adiabatic system under which no thermal energy would be lost to the environment. Under these extreme/implausible conditions, the tractor operated for roughly 6.5 minutes before reaching hydraulic oil temperatures that would begin to damage hydraulic components. This analysis proved that the 2014 EHPP can operate safely without another means of heat dissipation under IQS competition run time requirements. However, to help ensure zero component failure in the hydraulic system due to overheating and to allow for flexibility in a longer run time, an oil to air heat exchanger was selected for the tractor based on an overall thermal load of 6.7 hp. The oil to air heat exchanger will be installed on the 2014 EHPP if space and weight allow, as the 2014 EHPP must meet the IQS competition gross vehicle weight limit of 800 pounds (as stated in section 2 of [1]). Incorporation of the oil to air heat exchanger will help to maintain the hydraulic oil at a desirable operating temperature and prevent thermal damage to the system, but it will add 8.8 pounds to the overall weight and cost $334.00, effectively increasing the cost of the tractor.

Another oversized hydraulic component for the 2011 EHPP was the hydraulic filter housing which handles flows up to 15 GPM when a maximum flow rate of 8 GPM would flow through the filter. The new filter housing selected for the 2014 EHPP is an MP Filtri MPT-024 series tank-mounted filter. The filter assembly was rated to 8 GPM, as well as being 1.2 pounds lighter and costing $50.00 less than the Schroeder Industries filter on the 2011 EHPP model. The filter for the 2014 EHPP also has a finer filtration specification than the previous filter, resulting in cleaner, more efficient oil and increasing the life expectancy of the respective hydraulic components.

To increase serviceability of the 2014 EHPP, a new center console was designed out of tubular and bent sheet metal aluminum components in order to closely match the weight of the smaller 7 pound steel center console frame of the 2011 EHPP while simultaneously trying to reduce manufacturing costs associated with the forming and welding of the sheet metal components. This console design incorporates removable

ABS plastic paneling that is fastened on using simple thumb screws for easy removal without tools. This allows for easy access to all covered hydraulic components and hoses located around the tandem pumps, including the hydraulic manifold and SCU. The new console design also features a sealed compartment for the location of the hydraulic control module and all related wiring, terminal blocks, and fuses located on the tractor. The location of this compartment is easy to access and allows for easy service of all electrical components.

The rear fender portion of the body was also redesigned as an individual piece for the 2014 EHPP. The design is made of lightweight ABS plastic which allows for easy removal in order to access the covered hydraulic hoses running to the individual rear wheel motors. The battery for the tractor has also been relocated from this location to an area adjacent to the engine, allowing for easy installation and removal as well as easy access for external charging. The middle body section is also made of lightweight ABS plastic material to provide covering for the relocated fuel tank and smaller plastic hydraulic reservoir while still allowing for easy fill of the fuel tank using the Briggs and Stratton Smart-Fil fuel can without the need to removing any body components. This section of the body also features viewing cutouts that allows the operator to easily check the level of the hydraulic oil and fuel contained within the respective transparent tanks. With relocation of the fuel tank to a place inside the frame rails, the risk of fuel tank rupture resulting from accidental impact has been greatly reduced over the 2011 EHPP model design, thus improving safe operation of the tractor.

The layout of the newly designed instrument panel for the 2014 EHPP also features added instrumentation including a digital tachometer/hourmeter, voltmeter, as well as indicator lights for range selection and warning lights for hydraulic oil temperature and engine oil pressure. The placement of all instrumentation and control functions have been well thought out and ergonomically placed according to [2] and [3] while ensuring safe operation of the tractor by individuals from the 5^{th} to 95^{th} percentiles. Further reference *included ISO 15077: Tractors and self-propelled machinery for agriculture—Operator controls—Actuating forces, displacement, location and method of operation*. Improved labeling of all control functions will also be added to the 2014 EHPP based on *ISO 3767-1: Tractors, machinery for agriculture and forestry, powered lawn and garden equipment—Symbols for operator controls and other displays—Part 1: Common symbols* and *Part 3: Symbols for powered lawn and garden equipment*. This will help to improve the safety of the 2014 EHPP in addition to featuring safety signs and hazard pictorials warning the operator of all relevant safety hazards associated with operating the tractor based on *ANSI/ASABE AD11684:1995 (APR2011) Tractors, machinery for agriculture and forestry, powered lawn and garden equipment—Safety signs and hazard pictorials—General principles*.

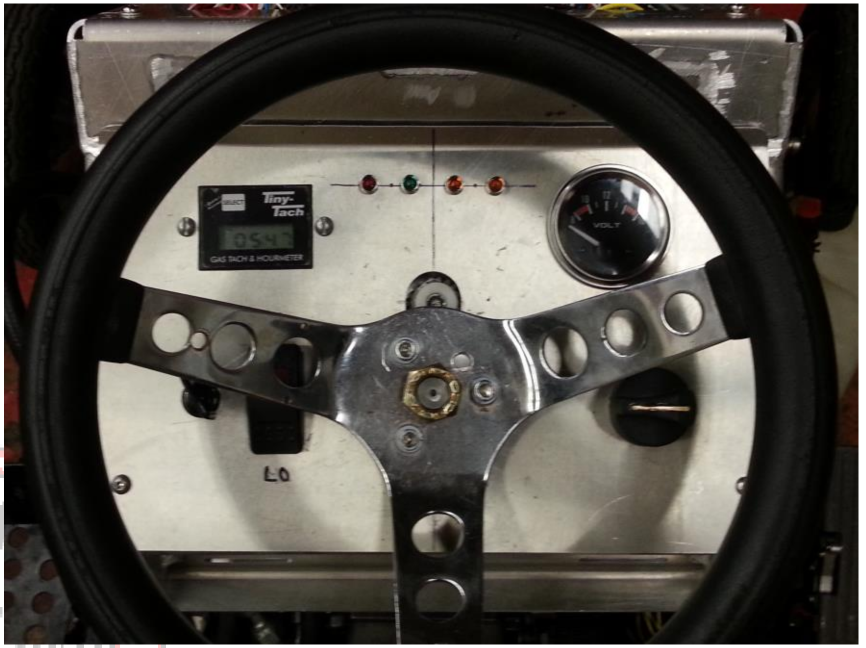

Figure 6: Prototype of instrument/control panel for 2014 EHPP. The range selection indicators are located in the upper center of the dash panel in between the tachometer/hourmeter (left) and the voltmeter (right). The ignition switch is located in the lower right corner while the 4-position range selection rotary switch is located in the far lower left. A performance mode rocker switch is located directly right of the range selection switch. This offers the capability to switch between performance and maneuverability modes by adjusting engine speed and pump displacement. It should be noted that picture does not include control labeling.

References

[1] American Society of Agricultural and Biological Engineers, "ASABE International Quarter-Scale Tractor Student Design Competition: 2014 X-Team Rules and Regulations," 2014. [Online]. Available: http://www.asabe.org/media/153748/2014_asabe_iqs_x-team_rules.pdf.

[2] C. E. Goering, M. L. Stone, D. W. Smith and P. Turnquist, in *Off-Road Vehicle Engieering Principles*, St. Joseph, MI, ASAE, 2003, p. Chap 15.

[3] D. Drakopoulos and D. Mann, "An Ergonomic Analysis of the Controls Present in a Tractor Workstation," CSBE, 2006, pp. 1-14.