MEng Report: "Dangle" and Regenerative Braking For Improved Efficiency and Performance in Hydraulic Actuation Systems

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Introduction

Traditional robotic actuation uses large amounts of electric power moving and controlling a series of servo motors to move various parts. As technology moves forward, and robots can become more self-reliant, steps must be taken to conserve small amounts of power in all possible ways to become sustainable. Hydraulic actuation can replace the need for a series of strong and power intensive motors that constantly draw power. Movement of a hydraulic actuation system is also more fluid and life-like than more widely used alternatives.

We have developed two methods of hydraulic powered movement to help reduce the consumption of fluid power, create more lifelike robotic limb movement, and reuse fluid power that would otherwise be wasted. As the world moves towards a sustainable, robotic future, every small bit of power that can be saved is important.

Dangle

Hydraulic cylinders that actuate in two directions are normally controlled by 4/3 directional valves, allowing the cylinder to pressurize in and pressurize out. This requires power for both flexion and extension of a robotic limb. Real human and animal limbs do not behave like this. Instead, muscles use power to pull the limb up in extension, and then release for flexion. The release allows for the limb to be carried by its inertia, or to fall by gravity, depending on the scenario.

A 4/3 directional control valve has four ports and 3 directions. Two of the ports are designated for the two terminals in a hydraulic cylinder, the third port is the input from the pump, and the last goes back to the reservoir. The three directions are; hold, in which the cylinder is frozen in place, pressurize up, and pressurize down.

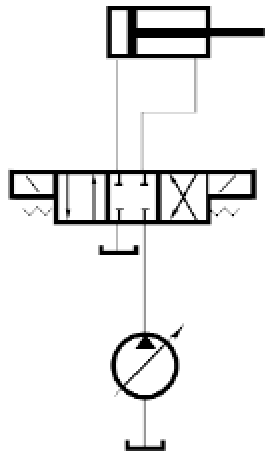


Figure 1: Simple 4/3 directional control valve and cylinder diagram. Clockwise from top left: A: pressurize cylinder up. B: pressurize cylinder down. P: pressure from pump. T: Return to reservoir.
Credit:" The Electric Online" (http://tijarohonline.blogspot.com/2010/11/directional-control-valves.html)

The 4/5 hydraulic valves were designed function as 4/3 valves with additional function. Three of the five directions are identical to those of the 4/3 valve. The two extra are, a second hold position, and the dangle state, allowing fluid to pass between the two terminals of the cylinder across the reservoir. The free passage of fluid allows the natural inertia of the limb, as well as gravity, to take over extension of the limb without the use of fluid power. The natural, free movement of the limb is where "dangle" gets its name.

Two types of dangle valves were prototyped and tested. One, a rotary valve, and the other a linear spool valve. The rotary valve (fig. 2) is the more compact of the two designs, consisting of a spool inside a case which attaches to the pressure source, both cylinder terminals, and the return reservoir. The spool contains 3 ports, 60 degrees apart from each other as shown in the figure below. These three ports match up to the five input ports in the valve housing, and their rotational positioning provides the 5 states that the valve operates in.   Due to the complicated geometry, it was rapid prototyped and assembled after several iterations experimenting with tolerance and technique. This prototyping work was done by another student, Young Bum Hyun. A schematic, created by Michael Meller is pictured below detailing the geometry and function.

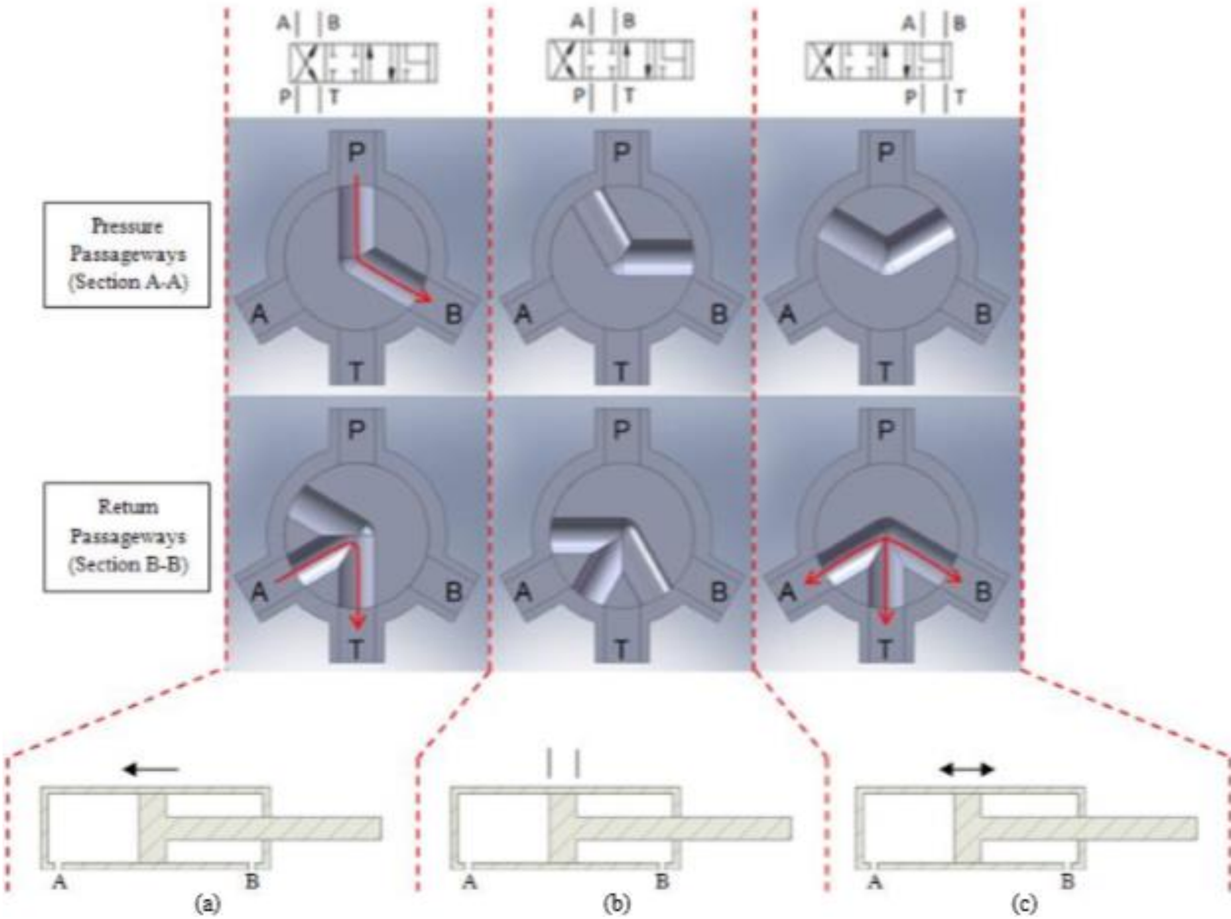


Figure 2: Rotary valve operation. P = pressure source. A = pressurize cylinder up. B = pressurize cylinder down. T = Reservoir return. (a) Pressurizing side B of the cylinder. (b) Holding position. (c) Dangle state enabled. Credit: Michael Meller [1].

The linear dangle valve consisted of a block and spool design. The valve block has five ports, three on top for pressurization and reservoir return, and two on the bottom for the cylinder ports. The spool has three lands, with widths the size of each port, and positioned specifically so that when the top middle pressurization port is covered, the flanges extend past the A and B terminal ports, allowing free flow between the ports in the cylinder and the reservoir. This design had a simple geometry, which allowed it to be machined conventionally. However, the need for linear actuation requires a much larger footprint. For the prototype, the spool was also difficult to seal at the end while maintaining little enough friction to slide into position with accuracy and without the need for excessive force. If the valve was made by industry standards, these problems would be easy to overcome using methods to solve similar problems in other valves.

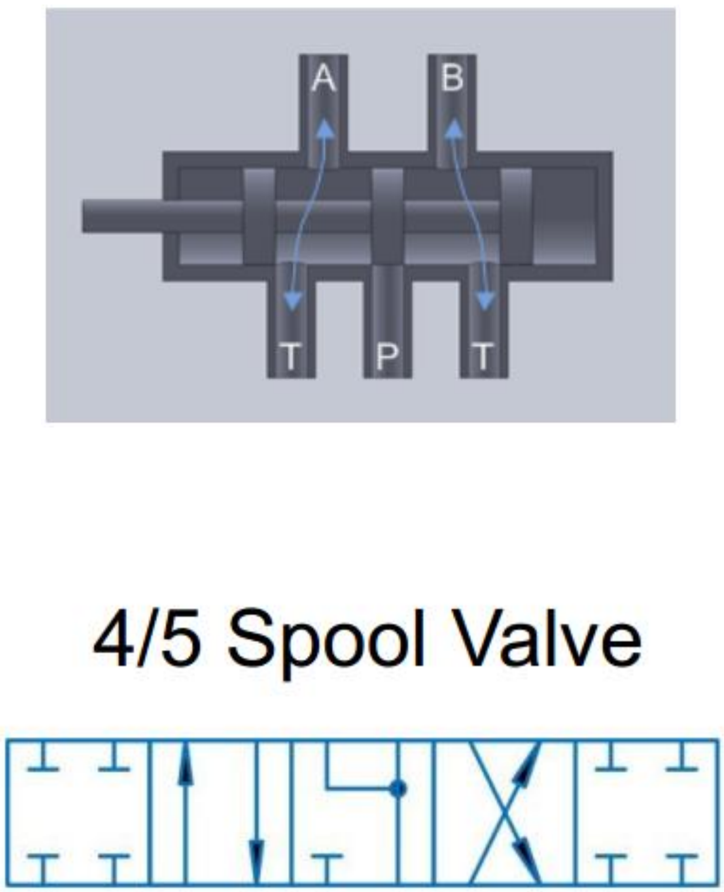


Figure 3: (Top) CAD design of linear valve in dangle position, with free fluid flow between A & B terminals and the return reservoir. (Bottom) Directional representation of the linear dangle valve. Credit: Michael Meller [2]

Both valves were tested on a small scale leg with one cylinder, and both successfully pressurized both terminals of the cylinder as well as enabled the dangle state. Each valve was able to successfully pressurize the cylinder and achieve dangle. However, being prototypes, they were not reliable enough to use in our experimental setup. Instead, we used two 3/2 valves in series, as shown in the circuit diagram below. These valves were able to create the dangle effect successfully with commercial hydraulic valves to operate at the pressures the system calls for (around 100 psi).

Figure 4: Linear dangle valve prototype with small-scale dangle test leg.

We built a simple hydraulic circuit to test the effectiveness of both dangle and regenerative braking in a controlled manner. It consisted of one diaphragm pump, two cylinders (one large and one small) and four solenoid actuated 3/2 valves. These valves were controlled with an ardunio nano microcontroller.

Regenerative Braking

Regenerative braking systems have been used in large scale construction equipment and automotive applications to reuse power otherwise dissipated when halting motion is necessary. One way that this is done is by using the lost torque of a car's engine to turn an electric generator to reclaim power, a technique used in many hybrid cars. In hydraulic systems, the backpressure from stopping motion can be stored in an accumulator. Then the fluid power can be released back into the system to assist the pump or power an actuator.

Our system is being designed on a smaller scale, with the end goal of being implemented into a bipedal robot, so a large hydroelectric generator is not ideal. Instead we investigated what kind of power we could get from charging an accumulator and releasing it back into a system to power another cylinder.

At first, we chose a small accumulator in an effort to move towards a compact system. Later we found that in order to store a significant amount of fluid pressure to move the cylinder as much as we wanted, we would need to be able to store a larger volume of fluid. We upgraded to a much larger accumulator, which could store enough fluid pressure for our application, but may be too cumbersome to implement into a bipedal robot.

Hydraulic Test Circuit

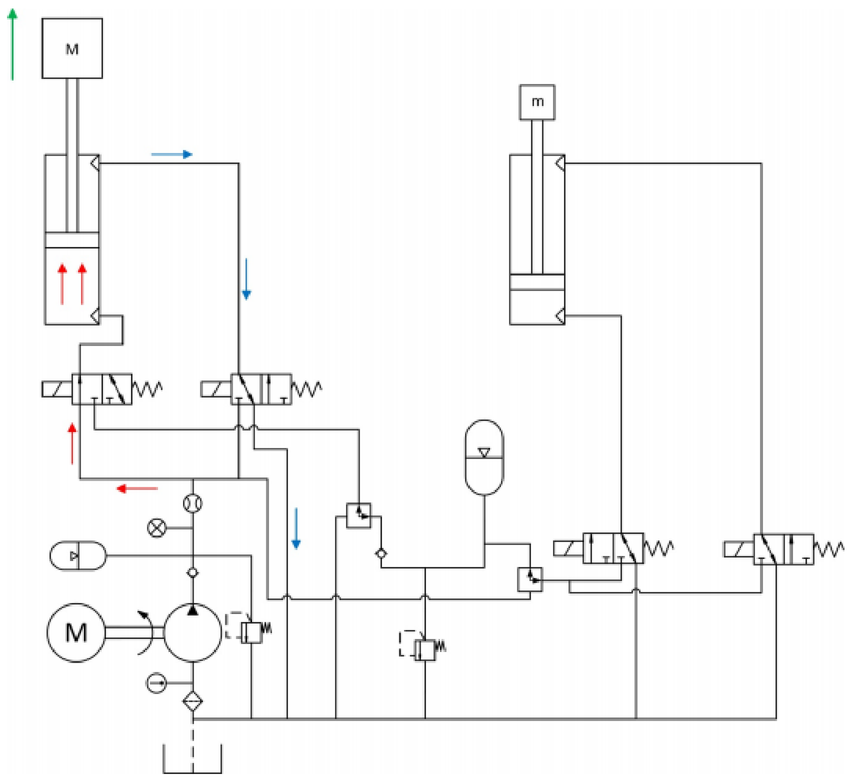


Figure 5: Experimental test circuit raising cylinder in dangle mode. Credit: Michael Meller [2]

Pictured above is a diagram of the test circuit. A diaphragm pump, show in the bottom left corner of the diagram powers the whole system at about 100 psi. The fluid goes from the reservoir, through the pump, into the first set of two valves. Both valves have the same input pressurize, separated by t-joints. Then the two valves were each connected to one of the cylinder's two terminals. This way the pump can pressurize either side of the cylinder, hold, or allow fluid to pass between the two terminals when the dangle state is enabled. The return line of the first valve has can be directed in two different directions, back to the reservoir, or to the accumulator, by a three-way ball valve. If the fluid is directed back to the reservoir, it functions as the closed dangle circuit. The dangle routine is as follows; open valve one (pressurize the cylinder one up), open valves one and two (dangle cylinder one), close both valves, repeat.

The second half of the circuit is for the purposes of testing regenerative braking. The fluid power coming from the cylinder would charge the accumulator while the second set of 3/2 valves are closed. The second valve's return line directs flow straight to the reservoir. The second set of valves function similarly to the first. Both valves are supplied with input pressure directly from the accumulator, and again, each of the valves output lines are connected to the reservoir. The pressure output was connected to the second cylinder identically to the first set of valves, one to each pressure terminal.

The regenerative braking routine was intended to directly follow the dangle routine, opening the pressurize up valve after the accumulator was charged by the first cylinder dangling. However, the weight on the first cylinder was not enough to charge the accumulator. We decided to pressurize the cylinder down to solve this for the purpose of the experiment. Therefore, the regenerative braking routine is as follows; pressurize cylinder one up, pressurize cylinder one down (charging the accumulator), open valve three (pressurize cylinder two with accumulator), open valves three and four (dangle cylinder two).

The closed dangle circuit was tested first. It pressurizes the cylinder up, lifting the weights on top of it, and then after a period of time programmed into the microcontroller, it switches to dangle and the weight moves the cylinder back down without fluid power. Using pressure and flow sensors in the circuit, as shown in the circuit diagram, we monitored how the fluid moved through the process. Another sub-team compared this data to another routine, in which we pressurized the cylinder down using traditional 4/3 actuation. Qualitatively the dangle circuit performed as expected.

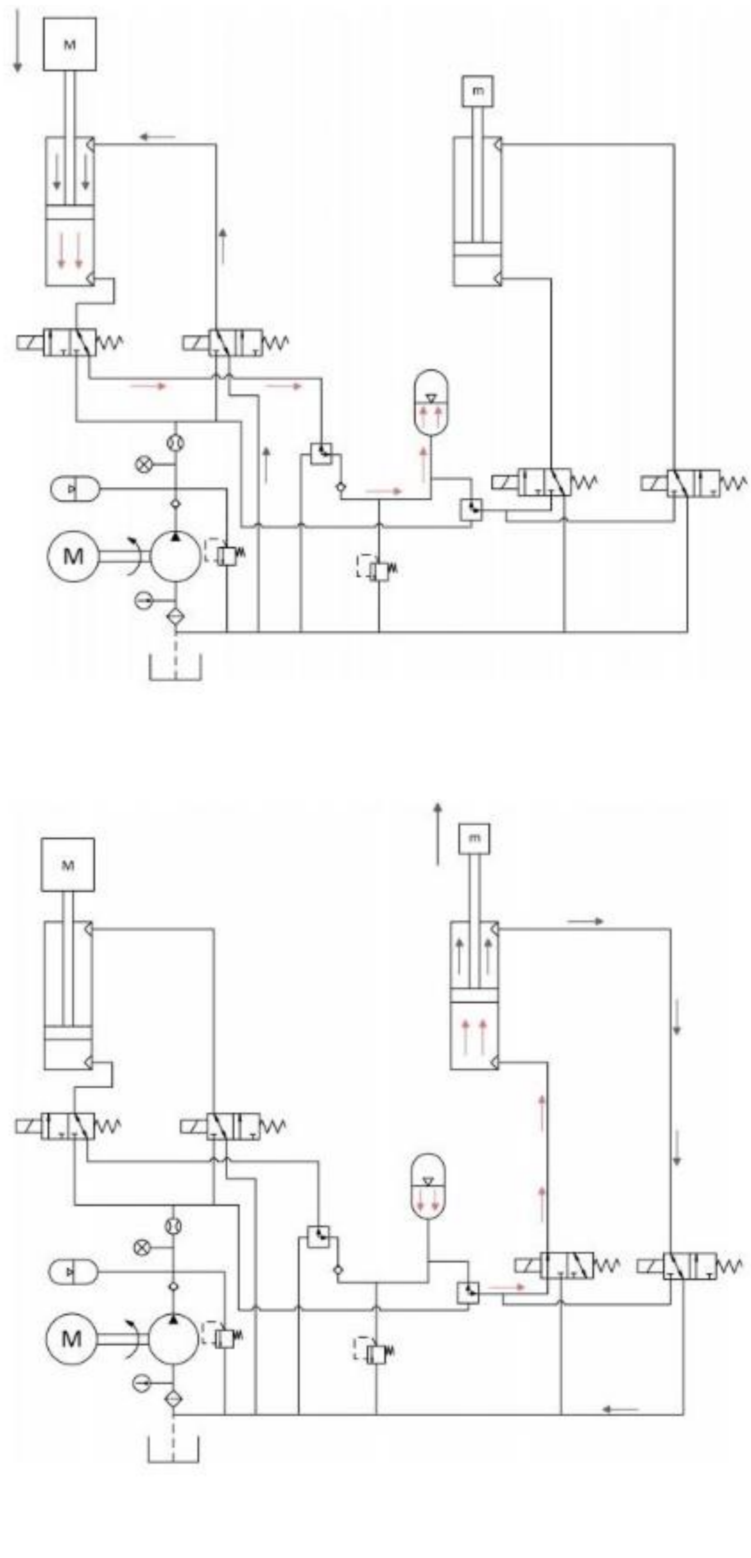
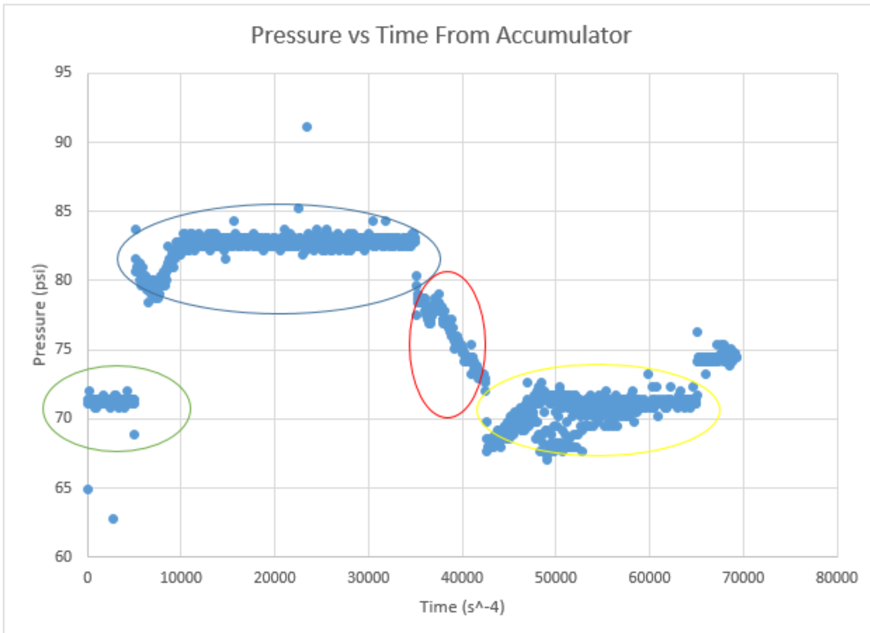


Figure 6: Experimental test circuit in regenerative braking. (Above) Circuit charging accumulator. (Below) Raising cylinder with regeneration. Credit: Michael Meller [2]

Next the regenerative braking circuit was tested. First we attempted to dangle the first cylinder to see it would provide enough force to charge the accumulator, but we found it was necessary to pressurize the cylinder down. The dangle method may be effective with more weight, and it would be the most power efficient method of regenerative braking. However, using more weight in the configuration that we were in would make us run the risk of bending the cylinder shaft. Then the second set of valves releases that pressure to raise the second, smaller cylinder.

Figure 7: Photo of dangle and regenerative braking test circuit.

The accumulator was able to charge and move the second cylinder. We estimated that the force charging the accumulator by pushing it down was equal to 36 kg with a stroke length of 35 cm, and it moved 9kg up 51 cm, which gave us a 36% energy capture.



Green – First cylinder actuates up (stable)   Blue – Accumulator charging

Red – Energy released from accumulator   Yellow – Back to stable pressure

Figure 8: Pressure vs time data from pressure sensor in line after accumulator during regenerative braking cycle.

The data pictured above is from a pressure transducer in the fluid line after the accumulator. Each of the four phases of the regenerative braking routine is circled. The pressure starts out at a stable value, and jumps when the accumulator is charging. Then, the fluid is released from the accumulator at a decreasing pressure value, which is expected, as the pressure in the accumulator is directly proportional to the amount of fluid inside the accumulator stretching out the rubber membrane. Finally, the pressure returns to a stable state and the cycle repeats itself.

Conclusion

The hydraulic test circuit experiment proved that these two hydraulic actuation techniques, dangle and regenerative braking, are functional methods to improve efficiency and life-like movement in robotic systems. Of the two, dangle is the most effective, saving energy by conserving fluid power as well as producing smoother robotic limb motion. Both valve prototypes are viable methods of achieving the dangle state, and we hope that they can improve with industrial fabrication techniques. Regenerative braking also demonstrated a significant energy capture, however releasing that power back into the system in a controlled manner presents a new set of problems. For instance, if the braking force is not the same each cycle, the output will be different as well. This makes the complications inherent to the dynamics of a walking robot even more complicated, and presents a new host of control problems. That being said, both technologies show promise, and further integration into a robotic system would provide exciting opportunities for investigation.

I would also like to thank Michael Meller for leading these investigations, among others, and the rest of LIMS M3 team for their work and collaboration with this project.

References

[1] Meller, Michael, Rashi Tiwari and Ephrahim Garcia. "Directional Control Valve with the Ability to 'Dangle.'" Laboratory for Intelligent Machine Systems, Cornell University.

[2] Meller, Michael, Ephrahim Garcia. "4/5 Spool Valve with the Ability to Dangle." Laboratory for Intelligent Machine Systems, Cornell University.

[3] Kumar, Amitesh. "Hydraulic Regenerative Braking System" *International Journal of Scientific & Engineering Research*. Vol 3; Iss 4; April 2012.