Buoyancy-Control Apparatus for Autonomous Underwater Vehicle

Dominic Panzino

Design:

The ascent engine is the primary method of changing the net buoyancy of the vessel. This is accomplished through a bladder-type hydraulic accumulator that can be empty or filled with seawater. Bladder-type hydraulic accumulators are pressure vessels with an elastic diaphragm separating them into two chambers, with ports on either side. One side is designated the fluid-side, and generally contains a liquid (seawater, in our case), while the other side is the gas-side, and generally contains a gas. Under normal conditions the accumulator's fluid-side is kept filled with water, which makes the vessel neutrally buoyant, as desired. To increase the buoyancy of the vessel and initiate an ascent to the surface, high pressure gas is admitted to the gas-side of the accumulator, displacing the seawater from the fluid-side. This reduction in weight increases the buoyancy, so the vessel naturally ascends. The ascent engine comprises the accumulator itself and the necessary components to force the water into and out of the accumulator on command.

In a future iteration of the system, DOUG will fill the accumulator with high pressure hydrogen gas, released by reacting Aluminum fuel with seawater. Because this hydrogen system is not included in the current prototype, in order to still use the ascent engine we've added high pressure compressed air storage on-board, and use it in place of the hydrogen. This adaptation of the system was conceived in Fall 2021, and then revised at the beginning of Spring 2022. A P&ID diagram of the revised system is shown in Figure X.2. Note that the three-way solenoid valve at the bottom of the diagram is a two-position valve; in its resting state ports 1 and 2 are joined, and in the actuated state ports 1 and 3 are joined.

To expel the water from the accumulator, the three-way valve at the bottom of the diagram is actuated, allowing high pressure gas from the right to flow into the gas-side of the accumulator, which displaces the bladder and pushes water out of the water vent ports within the wet hull. This process continues until the accumulator's gas-side pressure is about 20psi higher than the ambient water pressure, at which point the internal bladder is fully expanded. When the three-way valve is released (joining ports 1 and 2), the excess pressure on the gas-side of the accumulator is vented back through the valve and out the gas vent, escaping to the environment.

As of the end of Fall 2021, the system did not have any identifiable way to get seawater back into the accumulator after purging, which would make it impossible for the vehicle to dive again after surfacing. To solve this problem, a vacuum pump was added to the accumulator gas vent line, so that a vacuum could be pulled on the gas-side of the accumulator, forcibly drawing water into the fluid-side of the accumulator. A solenoid valve on the fluid-side line from the accumulator was eliminated as unnecessary, which had the added benefit of eliminating two penetrations through the forward bulkhead, so there are now fewer leak paths into the dry hull.

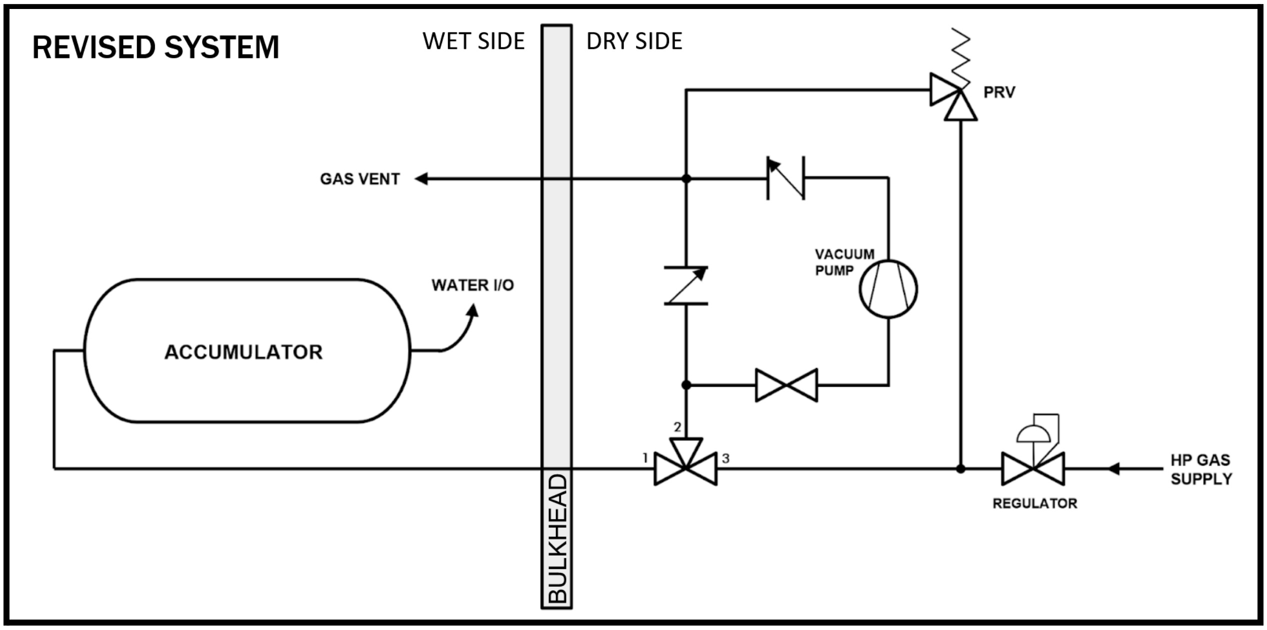


Figure X.2: The revised ascent engine plumbing, showing the vacuum system. The forward end of the vessel is to the left.

Fabrication:

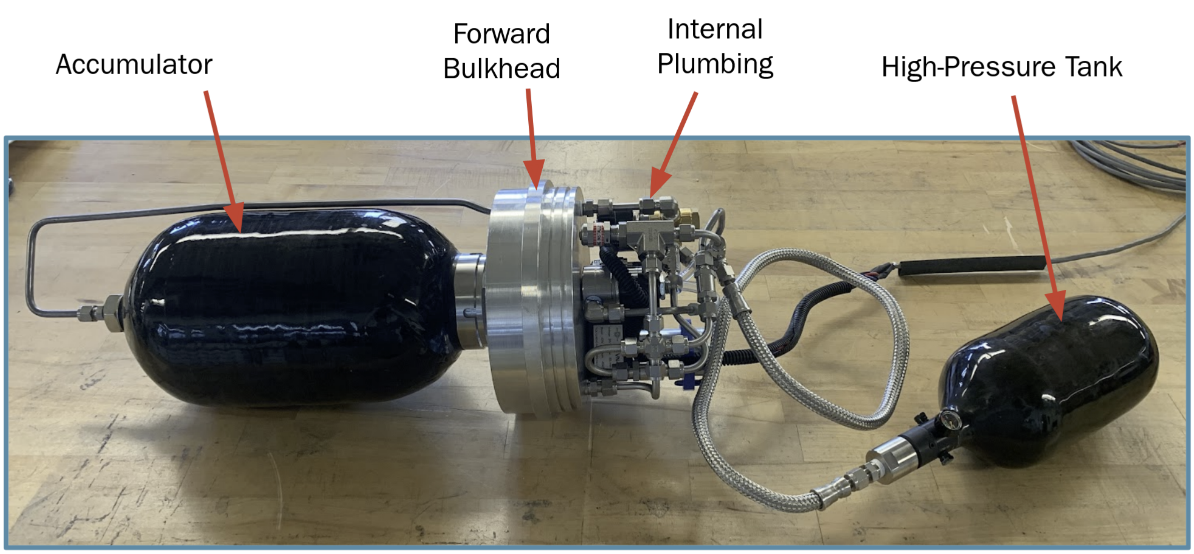


Figure X.3: The whole ascent engine, showing major components

Implementation and fabrication of the ascent engine was fairly straightforward once an acceptable arrangement of the components was decided on. This was worked out by hand, moving components around, trying to minimize the amount of space the system occupies along the axis of the vessel, without requiring exceptionally complex tubing bends. Almost all piping in the system is 316 stainless steel Swagelok tubing and fittings, rated for over 3000psi. The three-way solenoid is the only high-pressure component rated at a lower rating, of only 600psi. This maximum pressure corresponds to roughly 400m depth, which is far deeper than the current prototype will go. The lines to and from the vacuum pump are not considered high-pressure, as they will only operate at the surface, and so will only see pressures between vacuum and 1 atmosphere. Accordingly, those two lines are simply made from flexible vinyl tubing. This internal plumbing is shown in figure X.4.

The assembly of the tubes and components is rigid and so does not require any mounting brackets or other mechanical supports beyond the mechanical connection afforded by the Swagelok fittings themselves. The vacuum pump does require a simple mounting bracket to secure it to the bulkhead. The bracket is 3D-printed, but was designed to also be machined from solid material if desired. The somewhat flexible plastic bracket is advantageous, however, as it does a good job of isolating the vibration of the vacuum pump from the rest of the system.

The electrical connections of the solenoid valves and the vacuum pump are routed to a small 3D-printed connection box, where the soldered connections are made to a multi-conductor cable. That cable provides a short lead, terminated by an M12 connector.

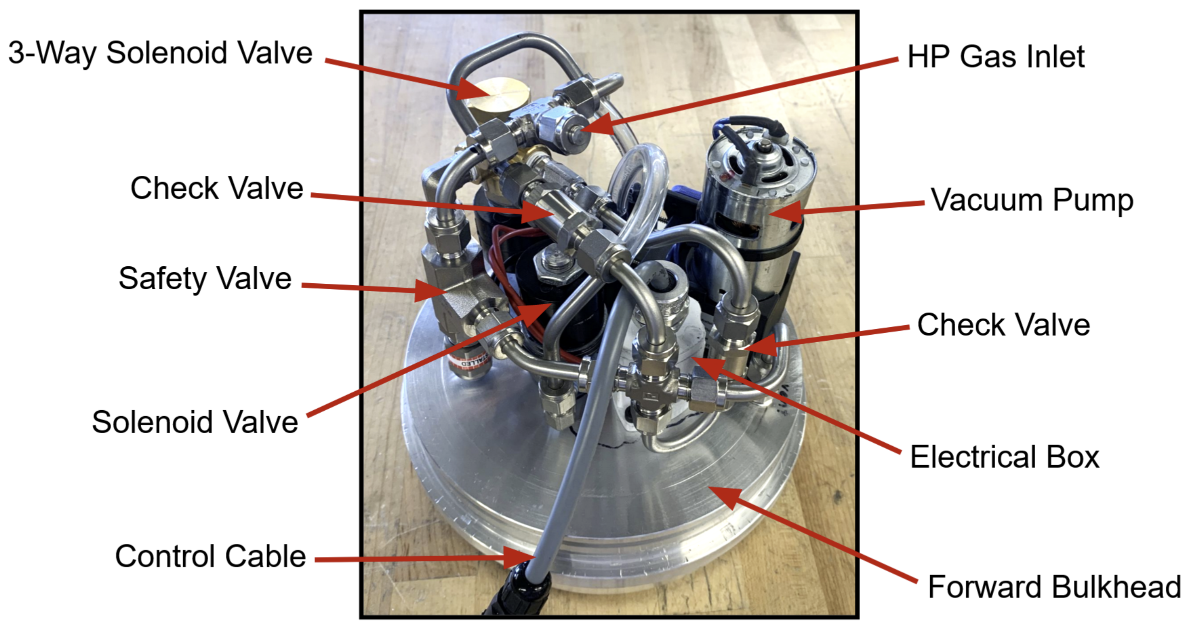
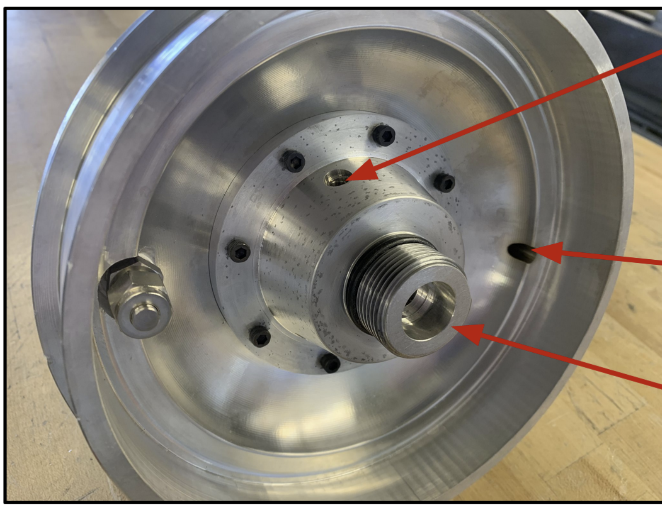


Figure X.4: The dry-side of the ascent engine, showing the somewhat complex plumbing and large number of components.

Moving to the wet-side of the bulkhead, the accumulator has a female ORB-16 fitting on the fluid-side, so an aluminum flange was made that could mount to the wet-side face of the bulkhead and presents a male ORB-16 fitting that the accumulator screws onto. Ports were drilled in the side of the flange radially to allow the water in and out of the accumulator. This makes for a very easy, strong, and rigid method of mounting the accumulator, and does not require any connections to the inside of the wet hull itself, allowing for the wet hull to be removed easily without interfering with the ascent engine. This flange and attachment method is shown in figure X.5.

The high pressure gas to supply the ascent engine is currently coming from the high-pressure tank. In order to get a reasonably small, lightweight, high pressure COPV on short notice, we chose to use a commercially available tank for paintball guns. The tank is rated for up to 4500psi, and was selected partially because it has an integral regulator set for 800psi, which eliminates the need to find space for a separate regulator in the hull. A special adapter for the tank was fabricated from 316 stainless steel that connects the tank's unusual outlet fitting to Swagelok fittings. The connection between the tank and the ascent engine itself could be either rigid stainless steel tubing, like the rest of the plumbing, or a high-pressure braided stainless steel flexible hose can be used. The latter method can be seen in figure X.3.



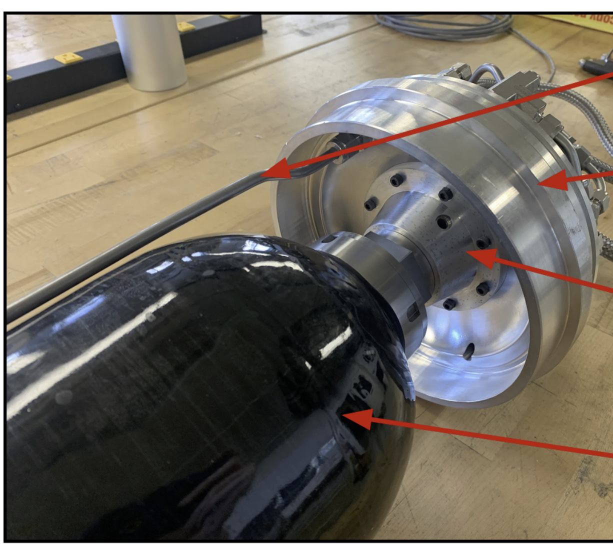


Figure X.5: At top, the mounting flange is attached to the wet-side of the forward bulkhead, showing the fluid ports and the ORB-16 fitting. Below, the accumulator is mounted to the flange.

Testing:

Once the ascent engine was finished, it was necessary to verify that it was operating as intended and could go through multiple cycles of operation reliably. Additionally, we wanted to measure the exact change in buoyancy achieved. To do this, the assembly was suspended in a container of water from an overhead hoist. Because the ascent engine by itself is not net buoyant, it was possible to measure the net buoyancy directly by placing a force gauge on the line supporting the ascent engine. This test setup is shown in figure X.6.

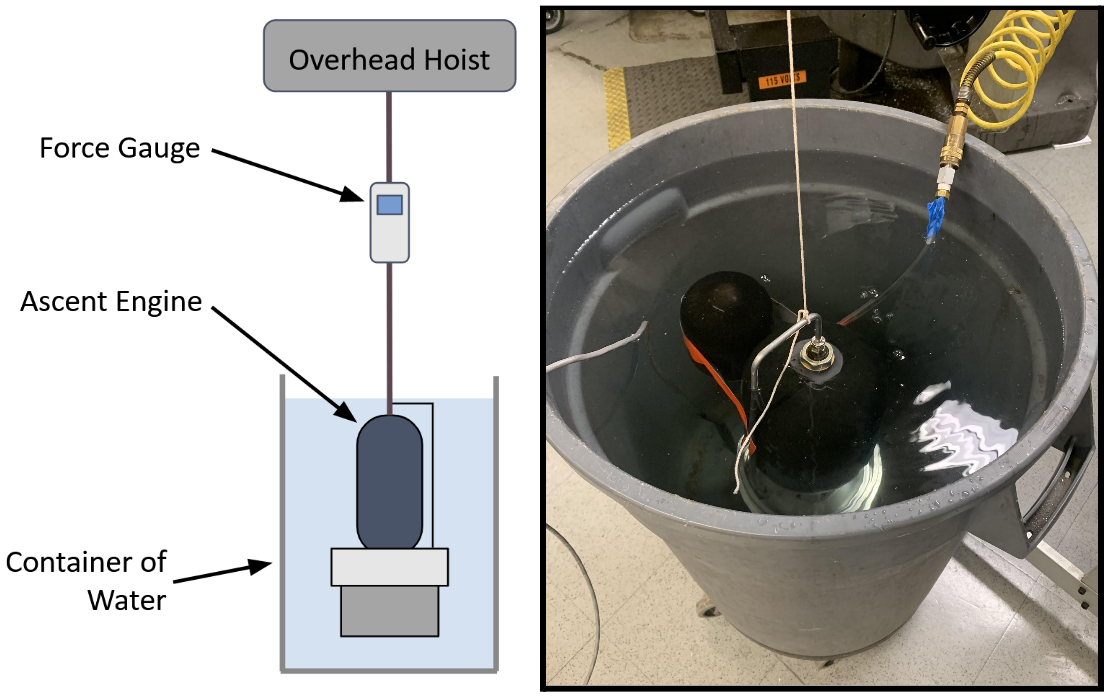


Figure X.6: Left: Pictorial representation of the test setup of the ascent engine, showing the ascent engine assembly suspended in a container of water.
Right: photo of the ascent engine in the water; note the yellow air supply line entering from the upper right, and the gray control cable entering from the left.

It was discovered in testing that the accumulator has three distinct states, rather than the two obvious states of empty and full. The third state is the state where the accumulator bladder has been allowed to relax into its unstressed, relaxed state. When the bladder is fully expanded (and thus the accumulator has no water in it, and is empty), the bladder is stretched elastically, requiring a gas-side pressure about 20psi higher than the ambient sea pressure. When the gas-side is vented back to atmospheric, the elastic forces of the bladder draw a small amount of water back into the accumulator, giving rise to the third state. The buoyancy at each state is shown in table X.1.

Table X.1: Net and Relative Buoyancy of the Ascent Engine Assembly

State	Real Net Buoyancy	Buoyancy Relative to Full State
Full	-13.4 lbs	0 lbs
Empty	-6.3 lbs	+7.1 lbs
Relaxed	-7.5 lbs	+5.9 lbs

As shown in table X.1, testing started with the accumulator full of water, which is the heaviest state of the system. Buoyancy was measured relative to this initial starting point, since this is the state at which the entire vessel should be neutrally buoyant. Actuating the three-way valve to allow gas to flow into the gas-side of the accumulator displaced the water over the course of 30 seconds, adding 7.1 lbs of buoyancy in the process. When the three-way valve was released, the excess gas pressure was vented, which took about 90 seconds. After this venting was complete, the accumulator was in the relaxed state, with a net buoyancy of 5.9 lbs relative to the starting point. Going back to neutral buoyancy, the solenoid valve connecting the vacuum pump to the gas line was opened and then the vacuum pump was run, drawing the water back into the accumulator in about 60 seconds.

Note that while the bladder relaxation draws back 1.2 lbs of water, we do not believe this will be a problem. This is because as the vessel ascends, the hull will expand as sea pressure is reduced, which in turn increases the overall vessel buoyancy. So in effect, the loss of buoyancy from accumulator bladder relaxation is counteracted by the increase in buoyancy caused by the expansion of the hull.

The ascent engine was taken through 4 or 5 full cycles of the states explained above, and the net buoyancies noted at each stage. It was able to reach all the states with approximately the same net buoyancy each time, indicating that the system was completely filling and expelling the water consistently over multiple cycles. The air for these tests was supplied by a regulated 20psi supply from the machine shop where the tests were conducted, rather than from the high pressure paintball gun tank. This is because filling the small high pressure tank to the full 120psi shop air supply only provides enough gas to do one dive cycle, and filling the tank to higher pressures would require access to a specialty compressor that we did not have. Some basic tests were conducted that verified the accumulator could be emptied and filled while using the high-pressure tank, but net buoyancy was not measured in those preliminary tests.

Any additional testing done in the future should include running the ascent engine using the high pressure tank at full pressure, and also verifying that the system operates correctly while horizontal, as the tests above were conducted with the ascent engine oriented vertically. No problems are anticipated for the system when horizontal, provided that the gas vent line is directed away from the fluid intake ports. A potential risk exists when the accumulator is being filled with seawater if the gas vent is oriented such that the bubbles of gas leaving the vent are subsequently sucked into the fluid ports. This would cause the accumulator to not fill completely, leaving the vessel slightly buoyant, preventing descent. The control system could detect this failure, and could respond by emptying the accumulator and trying to fill it again, but this would waste compressed gas. Ideally the gas vent should just be directed out of the wet hull, so that there is no orientation where the bubbles can re-enter through the fluid ports.