

Control Actuation Reliability and Redundancy for Long Duration Underwater Vehicle Missions with High Value Payloads

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ABSTRACT: The current trend is toward requiring undersea vehicles, manned and unmanned, remotely operated or autonomous, to perform ever longer, more demanding, and increasingly critical missions. Longer duration Unmanned Underwater Vehicle (UUV) missions will depend on highly reliable control actuation to ensure mission success, survivability of high value payloads, and plausible deniability. This paper presents a detailed trade study of various actuation architecture options available for large UUV control systems, examining electro-hydraulic, electro-mechanical, and electro-hydrostatic technologies.

1. Introduction

Future missions for Unmanned Undersea Vehicles (UUVs) may require transiting the open ocean and conducting over-the-horizon operations in littoral waters for 70+ days. In addition to the enabling technologies now under development to provide for autonomy and energy storage, these longer duration UUV missions will demand highly reliable control actuation to ensure mission success, survivability of high value payloads, and plausible deniability. A detailed trade study of various actuation architecture options available for large UUV control systems is presented herein. Technologies examined include electro-hydraulic, electro-mechanical, and electro-hydrostatic systems. Results presented include an evaluation of the advantages and disadvantages of each technology in the undersea domain, analysis of the relative reliability achievable with each, and a discussion of the implications to system redundancy.

2. Assumptions & Scope

This analysis presumes a hypothetical UUV maneuvering and control scheme that uses linear actuators to position some number of control fins or other control surfaces. Further assumed is the premise that loss of control of one or more of these surfaces would represent a meaningful detriment to the ability of the UUV to successfully complete its mission or to return to safety.

For clarity of presentation, several other trade-off elements that are relevant to control actuation architecture design have been consciously omitted from this discussion. These elements include

selection of a dry or free-flooding vehicle type, choice of pressure compensation scheme or schemes where relevant, and the merits of rotary versus linear actuation in a given UUV system. The concepts discussed herein would also have relevance to the design of manned undersea vehicle.



Figure 1 – Notional UUV with Multiple Articulated Fins for Maneuvering

3. ACTUATION TECHNOLOGIES

3.1. Electrohydraulic Technology

Electrohydraulic actuation systems (sometimes referred to as “traditional” hydraulic actuation or abbreviated EH) are the most mature form of automatic motion control for vehicle maneuvering. Enabled by Bill Moog’s development of the electro-hydraulic servo valve (EHSV) in the 1950’s, this type of actuation has been employed in everything from guided missiles, to commercial and military aircraft flight control systems, thrust vector control of rocket engines, as well as numerous industrial applications. EH actuation also finds widespread application in a diverse array of submarine systems from positioning

of rudders and bow planes, to valve actuation, and steam turbine throttle control.

In an EH motion control system, the motive force is produced by a central hydraulic oil pumping station known as a hydraulic power unit (HPU). The HPU includes electric motors, pumps, reservoirs, relief valves, check valves, and associated plumbing. Power is transmitted via hydraulic fluid from the HPU to the individual actuators installed at the point of force application. EH linear actuators incorporate an electro-hydraulic servovalve to convert very low current input signals (on the order of a few milliamps) into very precise changes in fluid flow to the extend and retract ports of a hydraulic cylinder. A piston and rod in the hydraulic cylinder provide the linear motion. The control loop is typically closed by employing some form of linear position sensor (e.g. a linear variable displacement transducer or LVDT).

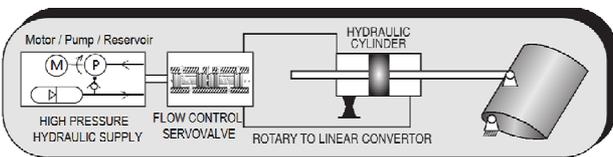


Figure 2 – Typical EH Actuation Architecture

Advantages of an EH control architecture include the relative simplicity of the individual actuators. This technology can also be very efficient in a vehicle or other application where a source of hydraulic pressure is already available. EH actuator designs also lend themselves readily to pressure compensation since they are by necessity oil filled. They tend also to have relatively elegant failure modes, since leaks are typically not catastrophic and can be identified during periodic inspection.



Figure 3 – Linear Electro-Hydraulic Actuator for UUV Fin Control

Major disadvantages include the size, noise, and expense of an HPU, the fact that the HPU typically needs to be run continuously whether the actuators are moving or just holding position, and the expense and difficulty associated with routing and then maintaining high pressure hydraulic plumbing.

3.2. Electro-mechanical Technology

In an electro-mechanical actuation (EMA) system power is transmitted to individual actuators in the

form of electricity. Motive force is developed by an electric motor, typically a permanent magnet synchronous machine (PMSM), also known as a brushless DC motor (BLDC). Typical in marine applications are 24, 135, 270, or 440 volt systems. For a linear actuator, the rotational output of the motor is converted to linear motion by a power screw, either ACME, ball, or roller type.

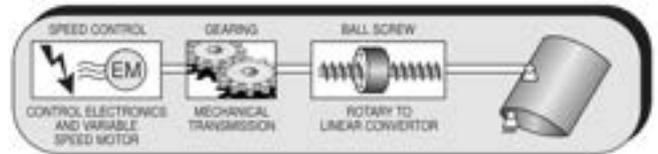


Figure 4 – Typical EMA Architecture

The primary advantage of an EMA system is the elimination of maintenance-intensive hydraulics and the associated cost advantages of routing power through electric wires in lieu of hydraulic plumbing. Disadvantages include the complex control electronics required to drive a brushless DC motor and the associated obsolescence issues, which are of particular concern in applications with very long service lives (such as on submarines).



Figure 5 – Pressure Compensated Linear Electro-Mechanical Actuator for Fin Control

3.3. Electro-hydrostatic Technology

An electro-hydrostatic actuation (EHA) system uses a hybrid of EH and EMA technologies. As with an EMA-based system, power is transmitted electrically to the point of application, avoiding the need for a central HPU and long runs of hydraulic plumbing associated with an EH system. Electricity is used to run a relatively small hydraulic pump, integrated into the actuator housing. The system can typically be designed such that the pump need only run when the actuator is moving a load, ensuring maximum energy efficiency.

The actuator itself in an EHA system closely resembles a traditional EH actuator, linear motion being created by the movement of a piston through a hydraulic cylinder.

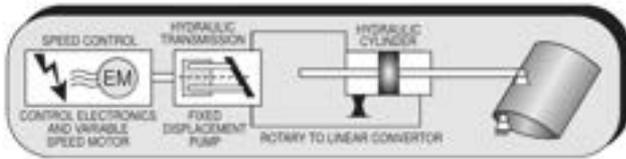


Figure 6 – Typical EHA Architecture

Advantages of an EHA system include the same ease of installation and maintenance that comes with EMA technology; and the more elegant failure modes and ease of pressure compensation that are found with a traditional EH system. Disadvantages include added complexity of each actuator assembly and relatively complex control electronics.

Another important consideration is the unique redundancy arrangements enabled by EHA technology, which will be explored later in this paper.



Figure 7 – Electro-Hydrostatic Flight Control Actuator with Integrated Controller

4. Reliability Comparison

Reliability of an actuation system can be quantitatively evaluated through a calculation of expected mean time between failures (MTBF). System reliability is calculated as a composite of empirically derived failures-per-million-hours data for each component that makes up the system. For this study component failure data was extracted from the Nonelectric Parts Reliability Data (NPRD) maintained by the Reliability Information Analysis Center (RIAC). RIAC is a service of the US Defense Technical Information Center. The 2011 edition of NPRD was used in all the calculations reported below.

This data should not be interpreted as the highest level of reliability achievable with a given technology type. Rather, it approximates the average level of reliability that would be expected with industrial or commercial off-the-shelf type components. In practice, significantly longer times between failures are achievable with custom engineered, military type components. However, despite that limitation, this

data provides an accurate portrayal of the relative merits of different technologies and architectures.

4.1. Electrohydraulic Reliability Drivers

The data in Table 1 show the failures-per-million-hours predicted by NPRD 2011 for each component of a typical EH actuation system. Calculated total system failure rate is also reported.

Table 1 – Predicted Reliability of Typical EH System and Components

Part Name	Total λ (FPMH)
ECU (low voltage)	10.7673
Check Valve	5.3266
EHSV	4.2896
LVDT	4.2896
Hydraulic Supply/Return Line	3.4921
Piston & Cylinder Assembly	3.0675
Accumulator	2.7362
Pressure Transducers (ΔP)	2.3947
Relief Valve	2.2005
Structure & Miscellaneous	2.045
Electric or Shaft-Driven Pump	1.497
Hydraulic Reservoir	1.023
Fill/Drain Port	0.144
Filter	0.1299
Total (FPMH):	43.4031
MTBF (hours):	23,040

Despite the relatively simple, low voltage, circuitry involved, this analysis predicts the largest single contributor to failure probability of an EH system to be the electronic control unit or ECU. The check valve and electro hydraulic servovalve (EHSV) also factor prominently in the MTBF. Overall, reliability is driven primarily by the relatively large number of components involved.

4.2. Electro-mechanical Reliability Drivers

The data in Table 2 show the failures-per-million-hours predicted by NPRD 2011 for each component of a typical EMA system. Calculated total system failure rate is also reported.

Table 2 – Predicted Reliability of Typical EMA System and Components

Part Name	Total λ (FPMH)
Controller Assy	23.3623
Ballscrew Assy	10.7673
Cables	4.5455
LVDT	4.2896
Batteries or BUS connection	4.1953
Gearbox Assy	2.175
Structure & Miscellaneous	2.045
Resolver	2.02
DC Motor Assy	1.5595
Total (FPMH):	54.9595
MTBF (hours):	18,195

As in the EH evaluation, the control electronics are the largest single contributor to failure rate. The increased complexity of the controller relative to an EH system is manifested in a greater than twofold increase in controller failure rate with EMA. Reliability of the ball screw assembly is also a significant factor. This analysis predicts a mean time between failures of the typical EMA system at approximately 80% of a comparable EH system. Again, much higher reliability may be achievable in a system custom engineered for a given application.

4.3. Electro-hydrostatic Reliability Drivers

The data in Table 3 show the failures-per-million-hours predicted by NPRD 2011 for each component of a typical EHA system. Calculated total system failure rate is also reported.

Table 3 – Predicted Reliability of Typical EHA System and Components

Part Name	Total λ (FPMH)
Controller Assy	23.3623
Pump Assembly	9.3449
Cables	4.5455
LVDT	4.2896
Batteries or BUS connection	4.1953
Piston & Cylinder Assembly	3.0675
Structure & Miscellaneous	2.045
Resolver	2.02
DC Motor Assy	1.5595
Hydraulic Manifold	1.0724
Total (FPMH):	55.502
MTBF (hours):	18,017

The analysis shows that a typical EHA system has a controller with reliability comparable to a similar EMA alternative. With the absence of a ball screw in an EHA arrangement, the pump assembly is

the largest mechanical contributor to MTBF. Overall system reliability is shown in this study as comparable to a similar EMA system.

5. Redundancy Architecture

Reliability and redundancy are separate but related concepts in designing a control surface actuation system to maximize the probability of mission success. Adding redundant components will generally reduce the calculated MTBF of a system, since MTBF is tightly coupled with part count (i.e. more parts means a higher probability of a part failure occurring). However, the presence of a redundant component can mitigate the consequences of a component failure, thereby increasing overall system reliability. Therefore, selection of redundancy architecture requires a detailed understanding of the overall undersea vehicle design and concept of operations (CONOPS).

In a traditional EH system, the ECU, being the largest contributor to the probability of a failure, is a relatively simple, small, and inexpensive component that can easily be made redundant. Redundancy options include a pair of ECUs in a primary / back-up arrangement, or systems of three or more ECUs with a voting algorithm (e.g. three ECUs giving commands with majority rules). Similar redundancy of control electronics is also feasible in EMA and EHA systems, but may be more expensive and/or come with greater penalties to weight and envelope due to the more complex electronics involved.

With any of the technology types discussed, one redundancy option is to provide multiple complete actuators per control surface. This can be either multiples of the same type actuator, or use of more than one type. For example, critical flight control systems might have an EMA as the primary actuation and an independent EHA, attached to the same surface and providing passive damping under normal conditions of operation. In the event of an EMA failure, the EHA can be powered up to perform the actuation function.

Another common way to accomplish redundancy in an EMA system is to have multiple motors drive a single actuator. Two motors can be configured in a simple torque summing arrangement where, in the event of a single motor failure, output force from the system is reduced by half. This type of arrangement may require a clutch to remove resistance from the failed motor from the gear train. Alternately, a speed summed gear arrangement can be used, where a failed

motor reduces output speed by half but maintains full torque. The disadvantage of this arrangement is that a brake is required to stop the failed motor or output will become uncontrolled. The probability of failure of the brake itself must then be taken into account.

An EHA system enables a unique redundancy architecture where multiple pumps are used to drive a single actuator. Like an EMA with multiple motors, a reduced amount of force may be provided in the event of one pump failure. In very critical applications sufficient margin can be built into the system to ensure full performance even in the event of a failure (e.g. a quadriplex arrangement, four pumps per actuator, with each pump capable of providing 1/3 of the required pressure and flow, so 100% performance can still be achieved with one pump offline). This type of redundancy does not require the added complexity associated with brake or clutch mechanisms.



Figure 8 – Quad-Redundant Electro-Hydrostatic Actuator

6. Conclusion

The choice of control system actuation technology type and redundancy architecture is a complex task for the underwater vehicle designer. EH, EMA, and EHA technologies each have a unique set of pros and cons that are tightly coupled with other underwater vehicle design tradeoffs. A detailed knowledge of the system architecture and vehicle CONOPS is required to fully evaluate the effectiveness of each system type.

Individual components of an actuation system can be engineered to minimize the probability of a failure occurring. Additionally, redundant components can be introduced to the system to mitigate or eliminate the consequences of a failure. Different options for introducing redundancy into the system bring along their own considerations relative to system complexity and control actuation robustness.

For undersea vehicles that will perform critical missions, engagement of an actuation system designer

early in the vehicle development will maximize the probability of achieving the control requirements in the most efficient manner possible. This type of trade study has been performed numerous times for aircraft applications and much has been learned that may also be relevant for undersea vehicles. However, the undersea domain brings unique challenges, such as the need for pressure compensation, which may lead to a different set of optimum solutions.

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About the Author



Jason Weiss is the chief technologist responsible for design & development programs, internal research & development, and business capture for the Naval System business unit of Moog Inc. Space and Defense Group. The primary operations of the business unit are in Orrville, OH and East Aurora, NY.

The Naval Systems team designs and manufactures high performance electrohydraulic, electro-hydrostatic, and electromechanical motion control devices and control electronics for nuclear submarines, aircraft carriers, surface ships and unmanned underwater vehicles. Moog's motion control solutions comply with stringent naval qualification requirements such as shock, vibration, low acoustic signature, and seawater corrosion resistance.

Prior to joining Moog, Mr. Weiss was an Engineering Manager at the Knolls Atomic Power Laboratory (KAPL) in Schenectady, NY, where he was involved in the design, manufacture, and fleet support of nuclear propulsion plants in LOS ANGELES, OHIO, and VIRGINIA class submarines. He also served as Mechanical Design Manager for the MARF Prototype in West Milton, NY; used in the training of US Navy nuclear operators and testing of nuclear propulsion technologies. Mr Weiss holds Bachelor of Science and Master of Engineering degrees in Mechanical Engineering from the University at Buffalo and Rensselaer Polytechnic Institute.