

The 10th International Conference on Axiomatic Design, ICAD 2016
**Application of Axiomatic Design in designing Autonomous Underwater
 photography lighting**

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Abstract

The Biology department of the University of Iceland is using a Gavia Autonomous Underwater Vehicle (AUV) to take high-resolution images of the seabed at various depths for research purposes. However, after a new color camera module was developed for the AUV, obtaining high-quality images has proven to be difficult with the original strobe light. Axiomatic Design was employed to develop a suitable lighting module suitable for still images and video. The performance of different light sources in water was investigated to determine design parameters. The completed design uses LED lights should work with the new camera module at operating depth without compromising AUV dynamics nor significantly impacting mission time.

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Peer-review under responsibility of the scientific committee of The 10th International Conference on Axiomatic Design

Keywords: Axiomatic Design; Autonomous Underwater Vehicle; underwater camera;

Nomenclature

AUV	Autonomous Underwater Vehicle
CA_n	Customer Attribute n
FR_n	Functional Requirement n
DP_n	Design Parameter n

1. Introduction

Teledyne Gavia is an Autonomous Underwater Vehicle (AUV) with a modular design that can be assembled and configured in the field (Fig. 1). It is capable of carrying out a wide range of missions including scientific applications [1] *e.g.* it is currently used to monitor population density of benthic animals in Icelandic coastal waters.

The Sudurnes Science and Learning Center is using a Gavia Scientific AUV both for internal research projects and as a service to other research centers. To obtain high-resolution color images, a new module with Canon 5D mark 3 DSLR camera was designed and built by Reykjavik University in 2013 [2]. However, the Gavia's original strobe light is not sufficiently bright nor the optimal color temperature for the new camera module. The goal of this project is to design a light system



Fig. 1. Gavia AUV [1]

that provides correct and sufficient illumination for the camera without compromising AUV dynamics. of note, there is no currently commercially available solution compatible with the Gavia AUV.

In this paper we will first discuss the background regarding underwater photography on a Gavia AUV, then follow standard Axiomatic Design concepts to develop Customer Attributes (CAs), then Functional Requirements (FRs). Next, Design Parameters (DPs) were rendered into a final design which was then tested. The paper ends with results and discussion of the design.

1.1. Background

The lighting equipment currently installed on the AUV is a strobe that uses Lumiled LEDs (LXHL-PW03). It was intended for use in making images with the original Scorpion SCOR-20CS0 black and white camera [3]. Those LEDs emit

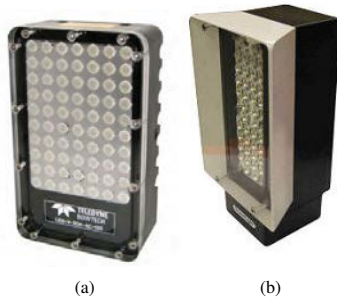


Fig. 2. (a) Teledyne LED-V-SERIES; (b) Deep Sea Systems' Oceanlight LED.

blue-tinted light with a peak intensity at about $430\ \mu\text{m}$ [4], resulting in very blue-shifted images on color photography. The 20 LEDs in the current strobe create a total luminous flux of 2400 lm was discovered to not be powerful enough for the new camera module. In addition, there are software synchronization issues between the camera module and the strobe that were not resolved during the module design, so the strobe often flashes when the shutter is already closed. This results in an unreliable lighting solution.

1.2. Available products

There are commercially available submersible lights available which provide suitable light for the camera. Teledyne's LED-V-SERIES (Fig. 22(a)) is available in various color temperatures [5]. Oceanlight LED (Fig. 22(b)) from Deep Sea Systems comes with 5500 K bright white LEDs [6]. Both products are suitable for a variety of underwater applications at depths down to 6000 m and meet the light needed for this project. However, unlike many submersibles, Gavia's dynamics depend on constant movement in the water, so it requires smaller and more streamlined solutions, even if this sacrifices some operational depth. Our design aims to mimic the shape of the current strobe which has acceptable dynamics, using the same mount points and connectors. The design is Gavia specific, but can be modified for other AUV designs.

2. Requirements for a revised design

Following the methodology of Axiomatic Design [7], the first step is to investigate all known customer needs and describe them as a list of Customer Attributes (CAs). Through communication with Hermann Dreki Guls at Sudurnes Science and Learning Center, it became clear that their primary desire is to fully exploit the potential of the new high-performance camera unit on the AUV. It is capable of taking images and recording videos, so it is important to provide adequate lighting for both modes. This means that the top level CA_0 is "Use full potential of the new camera module." The lower level CAs are omitted for brevity and their similarity to the following Functional Requirements (FR).

In still image mode, the lighting essentially only needs to be on at the moment in which the image is captured. For this reason, a strobe light would be preferable: strobe lighting has

a higher intensity for the same average power consumption. In addition, a strobe's intense pulse makes it easier to use a slow shutter by effectively freezing motion. However, in video mode the camera is taking pictures from 25–60 times per second [8]. Therefore, the AUV requires continuous lighting or pulses that are perfectly synchronized with the camera. The image sampling rate must be compatible with LED Pulse Width Modulation (PWM) drivers if they are used.

2.1. Functional Requirements

The next step is to translate CAs to FRs in order to create a definitive base for product development. As Suh states: "FRs are defined to be the minimum set of independent requirements that completely characterize the design objective for a specific need" [7, page 38]. Choosing the right FRs simplifies the whole design process.

The best practice in creating FRs is to start with an action or transformative verb. It requires a designer to put some thought in defining each requirement which leads to a set of FRs that describe the important project objectives from a first iteration. Failure to do so results in a variety of issues as further described by Thompson [9]. FRs do not have to be unchanging through the project since an acceptable set of FRs is not necessarily unique for each need [7]. The number of FRs does not necessarily have to be the same as the number of CAs. One reason for this is that designers have to be able to read between the lines of what customer has asked to see what he really wants. It is important to avoid taking the CAs from the customer and immediately converting them into FRs as discussed in Bragason et al. [10] To ensure that each phase of requirements and design generation is properly done, we "zig-zag"¹.

The top-level primary FR_0 is "Take high-resolution images and videos of seabed". From this top-level FR_0 , the top level guiding concept arose: DP_0 "Streamlined continuous LED illuminator." A light system that provides enough light for the new camera without disturbing dynamics fulfills FR_0 and satisfies the customer.

We then continue our zig-zag process to fully express the requirements in detail as shown below.

- FR_1 Attach to Gavia AUV.
- FR_2 Illuminate seabed at 2.5 meters distance.
- FR_3 Support color still photography and video on Canon 5D Mark 3 module.
- FR_4 Operate at AUV water depth range.
- FR_5 Power for 4 hours.
- FR_6 Preserve AUV dynamics.
- FR_7 Show image scale.

3. Design process

3.1. First concept

A preliminary design was based on a concept from the customer and was inspired by a headlamp. The idea was to have a

¹Complete cycles of mapping and decomposition before returning to the previous domain.

light unit that would be strapped on AUV hull with a separate battery. The associated design matrix is in Equation 1.

FRs describe what we want to achieve without saying how to accomplish it *i.e.* solution neutrality. The design process lies in finding a way of reaching those requirements and describing it in terms of Design Parameters (DPs). DPs describe physical solutions to the desires stated in FRs [7]. A good design will have quantitative measures in the DPs. The values for DP₅ and DP₇ were not known during this phase of the design, so the variables *P* and *d* were used as placeholders.

- DP₁ Straps to attach to the hull
- DP₂ Light intensity of xx lumen.
- DP₃ Visible light around 550 μm.
- DP₄ Seal and structural elements withstand pressure up to 51 bar.
- DP₅ Power consumption of *P* watts.
- DP₆ Housing is neutrally buoyant and streamlined.
- DP₇ Parallel lasers *d* mm apart.

At this stage, the design can be evaluated using the Independence Axiom (Axiom 1) which states that it should be possible to adjust any given DP to satisfy the corresponding FR without affecting other FRs. The tool for assessing whether the design satisfies Axiom 1 is a design matrix (DM). It is a visual representation of how much each FR is affected by each DP. The DM is represented in a Cartesian product form and it is important that it remains diagonal. A purely diagonal matrix is “uncoupled” and can easily be optimized because each DP only affects one FR. A triangular matrix, either upper or lower, can be optimized by choosing the right order of parameter selection. This situation is “decoupled” or “path-dependent” due to this additional step. Any other matrix is classified as “coupled” with no guarantee that the solution can be optimized. If a design is coupled, one strategy is to increase the number of DPs. While it may be less effective than keeping the design uncoupled, more DPs may benefit the design [7]. Eq. 1 shows the decoupled DM for first iteration.

$$\begin{pmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \\ FR_5 \\ FR_6 \\ FR_7 \end{pmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & X & 0 & 0 & 0 & 0 & 0 \\ 0 & X & X & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & X & 0 & 0 & 0 \\ 0 & X & 0 & 0 & X & 0 & 0 \\ X & 0 & 0 & 0 & X & X & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & X \end{bmatrix} \begin{pmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_5 \\ DP_6 \\ DP_7 \end{pmatrix} \quad (1)$$

When the AUV unit was delivered to the university it turned out that original strobe was held by four bolts and used a commercially communication plug from MacArtney (SubConn Micro Circular 8-pin) for easy removal.

FRs were reviewed again and modified with original CAs in mind. It was decided that the new design would preserve the existing strobe’s shape and layout as much as possible. This made it possible to uncouple some of the elements of the design. Note that primary FR₀ and DP₀ stay the same throughout this process.

- FR₁ Attach to Gavia AUV.
- FR₂ Illuminate seabed at 2.5 meters distance.
- FR₃ Consume little energy.
- FR₄ Operate with light for 4 hours.
- FR₅ Operate at AUV water depth range.
- FR₆ Preserve AUV balance.
- FR₇ Preserve current AUV profile.
- FR₈ Remove for maintenance.
- FR₉ Project image scale.

A new set of FRs requires new set of DPs and consequently a new design as described in Suh’s Theorem 5 [7, page 62].

- DP₁ Bolts used at mount points for the original strobe.
- DP₂ Light intensity of at least 6000 lm.
- DP₃ Efficient LEDs and drivers.
- DP₄ AUV internal battery used to power the light.
- DP₅ Seals and structural elements withstand pressure up to 51 bar.
- DP₆ Dry weight ≈ 1 kg
- DP₇ streamlined housing profile/
- DP₈ Aluminum housing and bolts
- DP₉ Parallel laser 55 mm apart.

A new decoupled design matrix (Eq. 2) was constructed based on updated FRs and DPs. The second matrix is less coupled than the previous one, so most DPs can be modified without having any effect on non-associated FRs. Less coupled design can be broken down into more manageable steps. The coupled elements, FR₃ power consumption and FR₄ operation time, will be further investigated later in this article.

$$\begin{pmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \\ FR_5 \\ FR_6 \\ FR_7 \\ FR_8 \\ FR_9 \end{pmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & X & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & X & X & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & X & 0 & X & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & X & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & X & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & X & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & X & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & X \end{bmatrix} \begin{pmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_5 \\ DP_6 \\ DP_7 \\ DP_8 \\ DP_9 \end{pmatrix} \quad (2)$$

DP₁: Use mount points for original strobe.

By using bolts at the mount points for the original strobe, the coupling between DP₁ and FR₆ was resolved. The new light would be replacing the old one so FR₆ was no longer coupled to DP₁.

DP₂: Light intensity at least 6000 lm.

In order to provide enough light for the camera to take pictures in dark waters at 500 m depth, the light output was required to be at least 6000 lm.

DP₃: Use efficient LEDs and drivers.

The LEDs chosen for the project are DURIS S10 from OS-RAM. Each diode is 7×7 mm and is able to deliver up to

1100 lm with typical efficacy of 131 lm W⁻¹ [11]. Powering up LEDs from a battery requires controlling the current passing through them. This control is traditionally done in one of two ways:

1. A DC/DC converter and a resistor which loses some energy into heat (See Section 6.6).
2. A specialized LED Pulse Width Modulation (PWM) driver monitors and controls the current directly.

The driver is more efficient and can provide LED status, but designing custom printed circuit board requires a skilled electrical engineer. The current team did not have access to such resources; an EE firm called Boston Embedded was consulted and online vendors were consulted. A custom LED board was estimated to cost 8000–12000 USD, compared to a DC/DC converter found online for 2 USD. The DC/DC converter was chosen; details on implementation can be found in Section 6.6.

DP₄: Powered by AUV internal battery.

Using the internal AUV battery as a power supply solves two coupling problems at a time. It ensures light operating time matches the AUV mission time. An external battery would make it harder to preserve the AUV's balance and profile. One disadvantage is that the light will always cause a reduction in mission time. Based on communication with the customer, a reduction of 20% is the maximum allowed.

DP₅: Seal and structural elements withstand pressure up to 51 bar.

For the transparent part of the system 6 mm Plexiglas should withstand the water pressure at operating depth and sudden impact in case of a mild collision. To make it even more robust, the housing is filled with oil to balance internal and external pressure. Plexiglas is convenient in terms of machining and can be done in-house using a laser cutter. No specialized tools or out-sourcing are necessary. O-rings will be used to form a robust seal without applying large compression forces on structural elements.

DP₆: Dry weight ≈ 1 kg.

Since the unit cannot compromise the buoyancy of the AUV, it has to match that of the original strobe which is 1 kg.

DP₇: Streamlined housing.

The new light's shape will be as close as possible to original acceptable strobe shape. Flow around the AUV should change very little which preserves AUV balance and drag. This matter is investigated further in Section 6.4.

DP₈: Use 6061 aluminum and aluminum bolts.

When choosing the right material for the new AUV light unit, both weight and corrosion need to be accounted for. The Gavia is made out of aluminum 6061 [2] so any metallic items in contact with the UAV should be made of similar aluminum. Galvanic corrosion occurs when two dissimilar metals are in

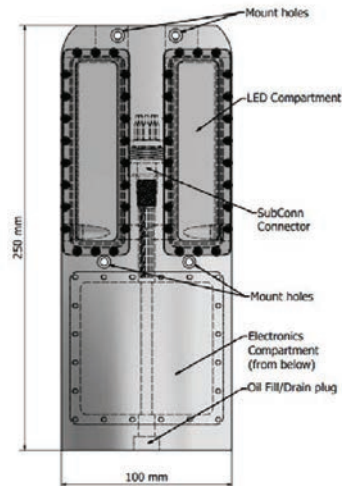


Fig. 3. Final light enclosure design with compartment for electronics, SubConn connector and two compartments for LEDs.

Table 1. Refraction index [2]

Refractive index	Air	Water	Oil	Plexi
n	1.00	1.33	1.47	1.49

contact with one another in the presence of an electrolyte² creating an electronic pathway for the movement of electrons. The potential difference between the metals is the driving force behind the corrosive reaction [12]. “In a marine environment, severe localized pitting corrosion to the aluminum tread has been observed where uninsulated stainless steel bolts were used to secure the treads in place” [13].

6061 aluminum was chosen due to these corrosion concerns. The other alternative was plastic, but its high thermal resistance would have created coupling due to heat generated by the LEDs and power supply.

DP₉: Parallel lasers 55 mm apart

Two laser diodes on the light unit with parallel beams are used to give reference points in the images. The distance between them will always be the same which provides a reliable scale for objects in the images.

4. View angle

The light beam coming from the LEDs is 120° wide. It first travels through oil, then Plexiglas, and at last through the sea water. When the light hits a new material the refractive angle of the beam changes according to Snell's law from [14, page 1084]. By using refractive index for each material the light travels through (Table 1) and applying using Snells law: $n_1 \sin \theta_1 = n_2 \sin \theta_2$, we can determine the final angle.

²such as seawater

Table 2. Light intensity test data.

	3 LEDs	2 LEDs	1 LED
lux	990	670	339
lumen	3110	2105	1065
ISO-Speed	12800	f/4	f/3.5
Exposure	1/500	Good	Good
ISO	12800	f/2.8	f/2.5
Exposure	1/1000	Good	Good
			Average

Based on those calculations, the beam angle in water will be 146°. We can calibrate how much effect that will have on the light intensity in water. By using $I_{air}A_{air} = I_{water}A_{water}$ we can calculate that the light intensity in water will be about 52% of the light intensity in the air.

Therefore we can estimate how much more light intensity is needed underwater due to spreading. As the calculations state, the light needs to be twice as powerful in water as it is in the air.

5. Experiment

An experiment was performed to determine how many lumens the camera needs to take properly lit pictures of the seabed. From this information, the number of new LEDs could be determined. The test was performed by setting up the camera and the light separated by 1.2 m pointing on a gray wall at the distance of 3 m. A light intensity sensor, Hagner EC1-X No. 53719, was placed 1 m away from the light source. ISO-Speed on the camera was set to 12800 which has acceptable noise level³.

Two exposure times were tested with this ISO setting. LEDs were powered up by a DC/DC converter (CN6009) with a current-limiting resistor. Tests were performed with 1, 2 and 3 LEDs together.

The test results shown in Table 2 show that 3 LEDs with a combined luminous flux of 3110 lm are enough for taking pictures in the air. Combining this information with the view angle calculation in Section 4 indicates 6 LEDs with a combined flux over 6000 lm should be sufficient to satisfy DP₀.

The power efficiency and draw needed to be determined to see the impact on mission time. 30 W was measured at the laboratory DC power supply which was connected to the DC/DC converter. The power delivered to LEDs was 25 W, resulting in 16% power loss at the DC/DC converter. This value was considered acceptable.

6. Discussion

The following sections discuss implementation details for the lighting modules sub-components.

6.1. Enclosure

Enclosure design is one of the key components of the light system. It fixtures and encapsulates all other elements while protecting them from the harsh underwater environment. Fig. 3, shows a drawing of the final design. Two LEDs compartments

³According to the customer.

Table 3. Values for drag calculation and calculated drag force.

		Original	New	
Length	L	184	290	[mm]
Diameter (approx.)	d	96	110	[mm]
Drag coeff. [17]	C_d	0.854	0.856	—
Salt water density [17]	ρ	1025	1025	[kg m ⁻³]
Drag force	F_d	6.3	8.3	[N]

will be covered with Plexiglas covers and one for electronics will be covered with an aluminum plate. Four smaller holes will be made for wire access between the compartments, one of which is for the underwater communication connector. A hole opposite to that will be used for oil filling and air draining the rest will be closed with a threaded plug.

6.2. Window

The window material is one of the key components in the light design due to its interaction with the water. This material must be compatible with the oil chosen to maintain optical clarity and withstand the pressure at a depth of 500 m. Glass can be a brittle material, shattering under impact. “Glass needs to be very thick and has usually one or more laminated layers to be able to bear water pressure. It has a greenish tint. Plexiglas/Acrylic is optically superior and has no visible tint” [15]. Based upon this suggestion, Plexiglas was chosen.

6.3. Oil

Any oils that could be used to fill the enclosure have to be colorless and not electrically conductive. High thermal conductance is needed as well. After investigating multiple oils, Glycerol was found to be suitable. It is a colorless, odorless, highly viscous liquid that is commonly used to insulate electronics [16].

6.4. Drag

This light is longer than the original light so the frictional force should increase. Change in drag is not proportional to length: it is a nonlinear function of frontal area, drag coefficient, the specific weight of water, and stream velocity. To estimate drag forces on the light housing, it was analyzed as a half cylinder with the flat face facing upstream. The drag force (F_d) for this geometry can be found in [17, page 503] $F_d = \frac{1}{16}C_d\pi d^2\rho V^2$.

Table 3 shows dimensions used for drag calculation along with calculated drag; width of the enclosure was used for diameter approximation. In this case drag increase is 2 N which results in $P = F_d V = 2 \cdot 2 = 4$ W power consumption increase. The power consumption per hour can be calculated from an AUV water speed of 2 m s⁻¹, resulting in an increase in power consumption of $P = 4$ W h⁻¹.

This is a worst case scenario where front and back of the cylinder are flat. In reality, there is less drag on the light unit because of boundary layer development around AUV hull and streamlined shape of front and tale of the light enclosure.

6.5. O-rings

An O-ring seal is used to prevent the loss of a fluid or gas. The seal assembly consists of an elastomer O-ring and a gland and it operates over a wide range of pressures, temperatures, and tolerances. They are easy to service with no extra lubrication or increased tightening needed. There is a large range on allowable tightening, so O-rings are unlikely to cause structural damage for the given application. In many cases, an O-ring can be reused, an advantage over non-elastic flat seals and crush-type gaskets [18].

In order for the O-Ring to guarantee the seal, it is accepted that the compression does not exceed 3% of its circumference value. During the installation for this type of application, the O-Ring undergoes a stretching process that must not exceed 6% of its circumference value [19].

6.6. Electronic components

A DC/DC converter (bought from eBay) was chosen to provide a constant voltage of 28.6 V to the LEDs from the AUV mains. In order to control current in the circuit, each LED will be connected in series with a 2 Ω resistor. Following Ohms Law [14], the voltage drop through the resistor will be 0.6 V for the current of 0.3 A, which is the rated value for DURIS S10 LEDs [11].

This configuration dissipates 0.2 W of the supplied current into heating the current limiting resistor. This power loss is an acceptable trade off to the large cost of getting a custom driver board developed. Total power consumption of the light unit will be about 60 W (based on experiment data) and will reduce mission time by approximately 17%.

7. Conclusion

In the final design, all Functional Requirements were addressed. The new light module produces enough light to make clear and bright underwater images of the seabed from a distance of 25 m. The new modules were suitable for the Gavia AUV, and the power consumption of the unit allowed for a mission time of four hours.

The new design should withstand Gavia's maximum operating depth of 500 m. Since the new light has nearly the same profile as the old light module and a dry weight of one kilogram, the AUV profile and balance is preserved. The new aluminum bolts and 6061 aluminum housing is a good combination to prevent galvanic corrosion, easing maintenance. The Gavia lighting system is ready for further testing and deployment.

8. Future work

Pressure tests need to be performed on the prototype unit to ensure that it is able to meet the operating depth required.

Further work needs to be done on the picture scale system. There is a space in the enclosure for the lasers, but this module was not further developed to focus on other elements.

The angle of the light beam coming from the light unit is much wider than the angle of the camera lens. Lenses might greatly improve the light coverage on the area of interest.

Acknowledgments

Special thanks to Voytek Krajewski at Boston Embedded for advising us on electronic components. Many thanks to the Biology department of the University of Iceland and Hermann Dreki Guls who provided us with the AUV. We give thanks to our French collaborators from Université de Valenciennes at the department of Genie mécanique et productique, Paul-Emile Colot, Floriant Djennadi, and Boubakr Jallow, who made a prototype housing for this project.

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