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Autonomous underwater vehicles powered by fuel cells: Design guidelines

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ABSTRACT

Current commercial Autonomous Underwater Vehicles (AUVs) are powered by conventional batteries. However, such technology has reached a point at which an increase of the endurance and range of operations would require increasing the size of existing AUV designs. Much attention has been paid to fuel cells as they have proven successfully installable in AUV prototypes and have shown good results regarding the increase of range and endurance of AUVs. Nevertheless, no commercial AUV powered by fuel cells has been made yet. In this work, the characteristics of well-known commercial AUVs have been studied using the Principal Components Analysis. Such study allows inferring the requirements and constraints for the implementation of fuel cells in commercial AUVs. Freedom in certain design parameters of both fuel cells and AUVs has been found. Regarding the necessity to store oxidant along with the fuel in underwater applications, a map of achieved energy densities by the combination of different means of storing hydrogen and oxygen has been obtained. Such map reveals the most benefiting combination of storage means for both reactants. Finally, a method for obtaining the initial design parameters of fuel cell powered AUVs is proposed.

1. Introduction

Thanks to the great development achieved in these last years, unmanned vehicles have evolved from the research laboratories into commercial, military, and scientific applications (Vukic, 2013). Although unmanned marine vehicles were developed by the military industry, they are revolutionizing the access to the oceans in the civil industry, as they are allowing to reach depths beyond the limits of scuba divers (Leonard et al., 1998). The main reasons for using underwater unmanned vehicles (UUVs) are that they reduce human presence for safety, costs or acoustic signature reasons, and they increase operational ranges.

Two different types of UUVs can be distinguished, regarding whether UUVs are remotely piloted or not, being both able to develop multitude of missions (Wang et al., 2012):

- Remotely Operated Vehicles (ROVs) are usually employed for deep sea offshore tasks, as substitutes of scuba divers.
- Autonomous Underwater Vehicles (AUVs) are usually employed in offshore industry for obtaining information about subsea environment. They operate without any physical or electronic interaction with human beings, and therefore are able to navigate by themselves (National Oceanic and Atmospheric Administration, 2013; Alam et al., 2014).

Whereas AUVs need media to store energy on board for the propulsion and all the systems, ROVs normally do not need them, as they are connected to a mother ship, although sometimes they might have energy storing media to reduce their cable section (Brown,).

Current commercial AUVs use batteries for storing energy (ECA Group, 2017; Alam et al., 2014; Kongsberg, 2012a, 2012b, 2013, 2015, 2016, 2017a; Elektronik, 2012, 2013; Bluefin Robotics, 2016a, 2016b, 2016c, 2016d, 2017a, 2017b; Gavia, 2016; ECA Group, 2016; ECA Group, 2017a; ECA Group, 2017b; ECA Group, 2017c; ECA Group, 2017d; ECA Group, 2017e). Their main drawback is that current technology has reached a maturity state at which very small improvement is expected regarding their energy densities. This means that at the current state, battery powered AUVs with extended range and endurance are set to be bigger than normal range and endurance AUVs. However, bigger AUVs are less practical as they require heavier duty cranes to put them afloat and need more space to maneuver. The main challenge addressed by this article is to

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increase the endurance and the range of AUVs without increasing too much their size. Therefore, a new power source with higher storage energy density is needed. Such new power source should be able to keep a small acoustic signature, so that sonar readings can still be precise and accurate, whilst keeping a small thermal signature in order not to interfere with other sensors affected by temperature (Kongsberg, 2017b). It is believed that a possible solution might be behind Fuel Cells (FCs) as they have the potential of achieving higher energy densities than those offered by batteries under certain configurations (Evans et al., 2009).

So far, only some prototypes and conceptual designs of AUVs are powered by FCs (Miller et al., 2014; Mendez et al., 2014; Yamamotoet al, 2004; Shih et al., 2014). The reason for the lack of presence of FCs in commercial AUVs is mainly due to the high costs of this technology at its current state. However, this technology can be competitive as it is for AUVs that are to accomplish missions requiring longer ranges and endurances than those powered by batteries. Besides, it is expected that the price of this technology will go down in the following years, as giant car manufacturers have just released the first generation of commercial FC vehicles and are betting for this technology. In the case of watertight AUVs, hybridization of FCs with batteries might reduce even more the cost and volume of final FC power systems (Lane et al., 2017). For flooded AUVs, the cost reduction is yet unclear, as subsea pressure compensated batteries can be even more expensive than fuel cell stacks at current state.

The purpose of this work is to present guidelines for AUV designers at early stages of the designing process of FC powered AUVs, with the aim of saving time and effort.

The first part of the work, as usually done in new projects of naval architecture, focuses in finding existing relations between parameters of different AUVs (Lewis et al., 1988). This is to define the initial design parameters of FC powered AUVs through the regressions obtained from such relations, and to find the FC geometrical constraints that underlie the collected data. The followed method for such aim is based on statistical analysis of well-known commercial AUVs.

The second part of the work discusses the most suitable FC type according to the inferred constraints, and also discusses the different ways to store the reactants. This part culminates with an assessment of the combined storing solutions of reactants, in the form of matrix based maps of achieved energy densities and costs by such combinations.

To conclude, a method for obtaining the initial design parameters of FC powered AUVs is described. The followed approach throughout this work is numerical. This has been done with the intention of adding objectivity in the decision making at early stages of the designing process, especially when there is lack of data to support decisions.

2. Analysis of commercial AUVs

The aim of this Section is to obtain the existing relations among parameters of commercial AUVs. Therefore, a data analysis is performed in a group of existing AUVs. Although all of these are powered by batteries, this will help to set the initial dimensions of the FC powered AUV by prefixing as few parameters as possible (Lewis et al., 1988), and will also help to unveil the geometrical constraints of the FC to be fitted in the AUV.

There are two additional constraints for AUV designs that cannot be found in the data analysis, and must be always considered during the designing process. Such two constraints are known due to the similarities of AUVs with submarines (Kormilitsin and Khalizev, 2001), being the first one that they must be able to stay in upright position, and the second one, that they must have neutral buoyancy when no thrust is applied in immersion. The first one is fulfilled in designs with lower center of gravity than center of buoyancy, and the second one is fulfilled in designs with overall density equal to the one of the seawater. One exception to the second constraint is found in glider-type AUVs, as they propel themselves by varying their own buoyancy (overall density) (Zhang et al., 2014).

Table 1 collects data of 21 well-known commercial AUVs (Kongsberg, 2017a; Kongsberg, 2012a, 2012b, 2013, 2015, 2016; Elektronik, 2012, 2013; Bluefin Robotics, 2016a, 2016b, 2016c, 2016d, 2017a, 2017b; Gavia, 2016; ECA Group, 2016; ECA Group, 2017a; ECA Group, 2017b; ECA Group, 2017c; ECA Group, 2017d; ECA Group, 2017e) that have proved cost effectiveness. Such table contains information about the main AUV parameters: length L, diameter D, mass displacement Δ, maximum depth h, maximum speed v, stored energy E, endurance T, mean power output $\dot{W}$, and length to diameter ratio L/D. The information shown in Table 1 has been extracted directly from the datasheets of the corresponding manufacturers, except for $\dot{W}$ and L/D, which have been calculated by dividing E by T, and L by D, respectively.

All the AUVs gathered in Table 1 are powered by batteries, and are propelled by mechanical means, typically propellers or pump-jets, except for the Seaglider, whose means of propulsion stem from the gliding caused by changes in the overall density of the AUV. Thanks to the small power consumption of the glider-type propulsion, very long endurances can be achieved, up to 10 months.

Before starting with the data analysis process, the original data structure shown in Table 1 is checked by using a procedure capable of explaining the variability of such data. The most common procedure used for this purpose is the Principal Component Analysis (PCA). This procedure not only allows to explain the variability of the data, but also reduces the dimension of the problem as it reveals simpler data structures that underlie the original one as it implies obtaining the covariance matrix (Abdi and Williams, 2010). As the method works with matrixes, it requires full information of the involved parameters; therefore, all the AUVs collected in Table 1 with missing information are eliminated during the PCA. In this work, the PCA rotates the original data structure, defined as the reference vectors or parameters $L, D, \Delta, h, v, E, T, \dot{W}, L/D$, to new reference vectors that are linear combinations of the original ones. Such new reference vectors, also known as Principal Components (PCs) are the eigenvectors of the covariance matrix of the original data, meaning that they are linearly independent amongst themselves (Martens and Naes, 1992). For that reason, L/D and $\dot{W}$ are also omitted as they are dependent on other parameters, allowing a reduction of the problem to 7 dimensions: L, D, Δ, h, v, E, T.

The covariance matrix obtained from a first PCA on the data in Table 1 indicates that most of the variability of the data is determined by a linear combination of the parameters related to the size of the system (L, D, Δ, E). As it will be discussed later, a numerical correlation between them can be verified, that allows using only one as a representation of a global variable that will be named "*SizePC*". The mass displacement has been chosen to represent this global variable, as it is the most related factor with size, then a new PCA has been carried out, using only four variables, namely, Δ, h, v and T.

At this point, the problem is down to 4 dimensions (Δ, h, v and T), allowing a second PCA with satisfactory results. Table 2 shows the 4 new rotated vectors or PCs, obtained by the second PCA, ordered in decreasing degree of information they contain on the variability of the data. Each PC is represented as a composition of the original parameters Δ, h, v and T. Here is a brief discussion on the PCs obtained:

- The first PC summarizes the AUV information given by Δ, h, v and T, containing a 52.9% of it. Such PC has great influence of all the four parameters, but as it is mainly defined by Δ with a factor of 0.654, the chosen alias for the first PC is *SizePC*.
- The accumulated percentage of AUV information represented by the first two PCs, accounts for the 78.4%. As the second PC is mainly defined by h, and v, with factors of 0.793 and 0.584, respectively, its chosen alias could be *PerformancePC*, but as it can be seen as well in the third PC, the second PC is not the only one clearly defined by two parameters, therefore the alias *DepthPC* is considered better suited in this case.