

An Evolutionary Approach for the Design of Autonomous Underwater Vehicles

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Abstract. Autonomous underwater vehicles (AUVs) are becoming an attractive option for increasingly complex and challenging underwater search and survey operations. To meet the emerging demands of AUV mission requirements, design and tradeoff complexities, there is an increasing interest in the use of multidisciplinary design optimization (MDO) strategies. While optimization techniques have been applied successfully to a wide range of applications spanning various fields of science and engineering, there is very limited literature on optimization of AUV designs. Presented in this paper is an evolutionary approach for the design optimization of AUVs using two stochastic, population based optimization algorithms. The proposed approach is capable of modelling and solving single and multi-objective constrained formulations of the AUV design problems based on different user and mission requirements. Two formulations of the AUV design problem are considered to identify designs with minimum drag and internal clash-free assembly. The flexibility of the proposed scheme and its ability to identify optimum preliminary designs are highlighted in this paper.

Keywords: AUV, MDO, evolutionary algorithm.

1 Introduction

Autonomous underwater vehicles (AUVs) are robotic mobile instrument carriers that have self-contained propulsion, sensors, and ‘intelligence’, allowing them to successfully complete sampling and survey tasks with little or no human intervention. With significant developments in artificial intelligence, control theory, and computer hardware, totally autonomous underwater vehicles have become a reality [6]. Being untethered and independent, AUVs provide a platform for ocean exploration and fill in the gap left by existing manned submersibles and remotely operated vehicles (ROVs) [14].

Hundreds of different AUVs have been designed over the past 50 or so years [3] to meet the challenges of oceanographic exploration and exploitation programs, but to the best of our knowledge, very limited in-depth systematic study has been

done with regards to optimum design, or to use any evolutionary algorithm(s) to find the optimum design of an AUV for specific mission requirements. Most of the previous attempts on AUV designs have focused primarily on functional designs with limited attention directed towards identifying optimum designs.

State-of-the-art evolutionary algorithms for design optimization of AUVs are rarely used in naval architecture because existing design tools are not sufficiently robust and/or fast to be used within an optimization scheme [2]. For this reason, the AUV design process is typically based on previous experience non-optimal designs are often adopted and accepted as an option. However, some recent works have considered the problem of finding the optimum hull form for AUVs that include the works of [2, 5, 11, 12] to minimize drag. Small improvement in drag can result in a substantial saving in thrust requirement. Therefore, much work still needs to be done in terms of optimizing the hull form design to minimize drag and increase propulsion efficiency [10].

While hydrodynamic hull optimization has gained momentum over the years, there is very limited literature on the arrangement strategies within the hull items, i.e. how to optimally place the internal on-board components in a ‘clash-free’ state while maintaining appropriate clearance among them, and other factors that affect controllability, like the centre of gravity (CG) and the centre of buoyancy (CB) effects. This establishes the need for the development of a framework that is capable of generating optimum design of AUVs by simultaneously considering both internal clash-free arrangement of components and external size and shape for a given design requirements.

This paper presents an optimization framework that is capable of modelling and solving single and multi-objective constrained formulations of the AUV design problems based on user requirements through the use of two population based evolutionary algorithms. Subsequently the algorithms are used to identify optimal AUV designs. The proposed optimization framework is described in Section 2 where the aspects of geometry representation, arrangement strategy, optimization algorithms and hydrodynamic performance estimation methods are discussed. In Section 3, the details of the numerical experiments are given, followed by a discussion of results (optimum designs) obtained. Finally, the findings of this study are summarized in Section 4.

2 Optimization Framework

This work presents an optimization framework for the design of AUVs with minimum drag consideration. The framework incorporates geometry and configuration modules, a hydrodynamics module, several accepted maritime performance and characteristics estimation methods of AUVs and a suite of optimization algorithms. Shown in Fig. 1 is the flowchart of the optimization framework. The framework facilitates the communication of data from one application to the next, producing an automated multidisciplinary design environment.

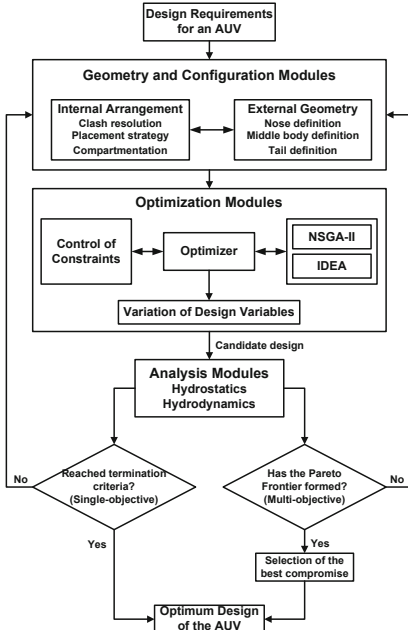


Fig. 1. Detail flowchart of the optimization framework

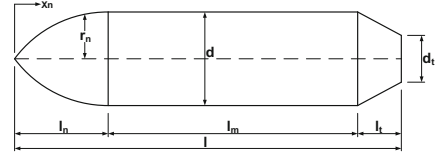


Fig. 2. Parameterization of the hull geometry

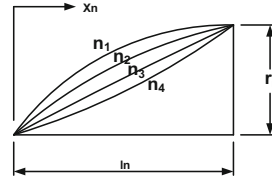


Fig. 3. Parameterization of the nose geometry

2.1 Design Requirements

The basic design concept of the AUV employed herein is based on the development of a small vehicle that can be easily launched, recovered and operated without special handling equipments capable of working at shallow water depth and relies heavily on the use of commercial-off-the-shelf components in an attempt to contain cost. The design requirements used in this study are:

- Operating speed of the AUV is 1 m/s;
- AUV should be able to house a 150 mm cube payload of weighing 10 kg;
- Length of the AUV must be no more than 1.3 m;
- Total weight (including payload) must be less than or equal to 30 kg;
- The AUV is to be propelled by 3 rear jets and 2 jets each for vertical and lateral movements.

2.2 Geometry and Configuration Module

Hull Geometry. The hull size of an AUV is constrained by the space for the on-board instruments that need to be carried, while the hull shape is constrained by the hydrodynamic characteristics. A ‘torpedo body’ that has a nose cone followed by a parallel cylindrical mid-section and a tapered tail section is considered in this study. The torpedo body exhibits low drag compared to other geometries of

similar length to diameter ratios [16]. Illustrations of the family chosen for this study are presented in Fig. 2, where the body is seen to comprise a nose-section of variable length l_n , a mid-section of variable length l_m , and a tail-section of variable length l_t , making up the total body length of l units.

The curve shape of the nose is determined from the Eq. (1).

$$r_n = \frac{1}{2}d \left[1 - \left(\frac{l_n - x_n}{l_n} \right)^n \right] \quad (1)$$

where r_n is the nose radius in m, d is the maximum body diameter in m, which may be varied, and n is the shape variation coefficient of the nose which may also be varied to give different shapes, as shown in Fig. 3.

When it comes to maximizing thrust, there is a requirement to optimize a tail cone shape to direct the three pump nozzle outflows into one single mass flow. While shaped tail cones are a possibility, for ease of fabrication and to direct the three pump nozzle outflows into one single mass flow, a tapered tail cone is more suitable and therefore used in this study. The illustration of the parameterization for the tail geometry is also shown in Fig. 2, where d_t is the smaller diameter of the tail in m and l_t is the length of the tail in m.

Geometry of the Payload Section. The AUVs use on-board computers, power packs, sensors and vehicle payloads for automatic control, navigation and guidance. Therefore, adequate free space should be allocated while designing the AUV hull form. Figure 4 shows the parameterization of the payload section, where a is the edge width and height, and b is the length of the payload box.

Subject to preliminary design requirements, the optimization framework developed herein produces AUV hull shape in a way that can accommodate a variable position payload. Being a relatively heavy system, the capability of adjusting the position of the payload is an important design consideration to account for CG-CB distance manipulations.

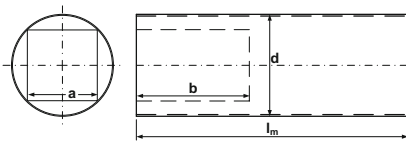


Fig. 4. Parameterization of the payload section

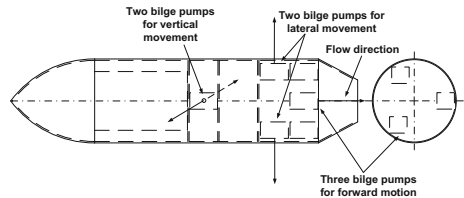


Fig. 5. Configuration of the propulsion system

Propulsion System. Currently available AUVs are predominately propelled by three means: propeller, jet-pump and buoyancy driven (glider) propulsion systems. Although a majority of the current AUVs are equipped with a propeller and rudder mounted at the tail for propulsion and steering, a jet based

propulsion system is used in this study. Jet-pumps are more beneficial than propellers in terms of mechanical design, cost realization, robustness with respect to transportation and safety for occasional swimmers.

The propulsion of the AUV under consideration is achieved through the use of bilge pumps. There are seven pumps of three different types mounted inside the vehicle, three of which are used to propel the vehicle forward in the water. The remaining four pumps are used to steer the vehicle left and right, as well as up and down, as illustrated in Fig. 5.

The positions of the bilge pumps for lateral and vertical movements as shown in Fig. 5, are not fixed, but are rather free to move within the entire mid-section. During the optimization process, the optimizer chooses these pumps from a catalogue of ten off-the-shelf different pumps commonly available and also the optimal positions of those pumps while designing the AUV.

Power Source. Unlike tethered vehicles, AUV operations are limited by the on board power they can carry [14]. The power determines the endurance and operating range, and the mission characteristics of the AUV accordingly. The rechargeable high performance Lithium Polymer (LiPo) batteries with nominal cell voltage 3.8 V and energy density of 193 Whr/kg have been selected in this study. These batteries are attractive as they are light and small.

Placement Strategy for the Internal Components. The design optimization framework presented in this paper not only optimizes the hull shape but also arranges its contents avoiding interference while maintaining workable spaces around the components using ‘clash-free mechanism’. For efficient utilization of the available internal volume, a careful arrangement needs to be achieved. As the current approach utilizes the optimization modules to iterate, the use of clash-free mechanism is an essential part to obtain a clash-free arrangement of the internal components for every valid design. Details of the clash-free mechanism appear in the authors’ earlier work [1].

2.3 Optimization Module

The framework developed here uses two state-of-the-art evolutionary algorithms, NSGA-II and IDEA. It is worth mentioning that any optimization algorithm capable of solving single and multi-objective optimization problems can be used within the framework. The chosen algorithms are written in Matlab and are integrated with CATIA along with VBScript to automate the whole AUV design process. CATIA (Computer Aided Three-dimensional Interactive Application) is a multi-platform computer-aided design (CAD) commercial software suite and widely used for design purposes. VBScript (Visual Basic Scripting Edition) is a tool for scripting the design process of CATIA.

NSGA-II. Non-dominated sorting genetic algorithm II (NSGA-II) was proposed by Deb *et al.* [7], and remains one of the most widely used population based algorithms for evolutionary optimization. It uses Simulated Binary Crossover (SBX)

and polynomial mutation for generating off-spring. The ranking of solutions is first done based on non-dominance, followed by the crowding distance. While non-dominance based rank drives the population towards the Pareto Optimal Front, crowding distance based rank aims to preserve the diversity among solutions. For problems with constraints, the feasible solutions are ranked above infeasible solutions. The infeasible solutions are ranked based on their constraint violations. For the single objective formulation, NSGA-II assumes the form of a real coded EA with SBX and polynomial mutation.

IDEA. Infeasibility Driven Evolutionary Algorithm (IDEA) was recently proposed by Singh *et al.* [15]. Since the Pareto optimal solution for a constrained problem usually lies on a constraint boundary, IDEA tries to focus the search near the constraint boundaries by maintaining a set of infeasible solutions (in addition to feasible solutions). During the ranking process, a few marginally infeasible solutions (based on their constraint violations) are ranked above the feasible solutions. The presence of infeasible solutions effectively translates to approaching the constraint boundary from both feasible and infeasible search spaces, which helps in faster convergence, as demonstrated in the earlier study [15].

2.4 Hydrodynamics Module: Drag Estimation

A fundamental interest in the field of hydrodynamics is the reduction of submerged vehicle power requirements and drag minimization is one of the most effective means of achieving this. For drag estimation, the following formula has been used:

$$D = \frac{1}{2}\rho V^2 C_V S \quad (2)$$

where ρ is the density of the fluid in kg/m^3 , V is the velocity in m/s , S is the wetted surface area of the vehicle in m^2 , and C_V is the coefficient of viscous resistance for the smooth bare hull and D is the vehicle drag in N.

Three methods: Virginia Tech (VT) [13], MIT [9] and G&J method [8] are employed in this study to measure the coefficient of viscous resistance (C_V) in three different ways to ensure uniformity in drag estimation of the design vehicle.

3 Numerical Experiments

3.1 Problem Formulations

While satisfying the design requirements, optimization of two kinds of objectives are sought. First is the minimization of drag, which is important because minimum drag leads to least power consumption for propulsion, and corresponding savings in the operating costs. Second is to maximize one of the lever arms, as a longer lever arm assists in better diving and turning of the vehicle. The term ‘lever arm (LA)’ defined here as the longitudinal distance of the pump from the centre of buoyancy of the vehicle. To this effect, two formulations are studied in this paper as described below.

Single Objective Formulation. The single objective optimization problem is posed as the identification of an AUV hull form with minimum drag as well as clash-free optimal placement of the internal objects subject to the constraints on payload (P_l), CG-CB separation (s), length (l) and weight (w) of the vehicle. The objective function, constraints and design variables are listed in the Eq. (3) as Formulation 1.

Minimize:

$$f(1) = D$$

Constraints:

$$\begin{aligned} g(1) &= P_l \geq 15 \text{ kg}; \quad g(2) = P_l \leq 18 \text{ kg}; \\ g(3) &= a \geq 150 \text{ mm}; \quad g(4) = b \geq 200 \text{ mm}; \quad g(5) = s \leq 10 \text{ mm}; \\ g(6) &= l \leq 1300 \text{ mm}; \quad g(7) = w \leq 30 \text{ kg} \end{aligned}$$

Design variables:

$$\begin{aligned} 1 &\leq P_1 \leq 10; \quad 1 \leq P_2 \leq 10; \quad 1 \leq P_3 \leq 10 \\ 1 &\leq O_1 \leq 4; \quad 1 \leq O_2 \leq 4; \quad 1 \leq O_3 \leq 4 \\ 0 &\leq X_{V1} \leq 1 \text{ mm}; \quad 0 \leq X_{V2} \leq 1 \text{ mm} \\ 0 &\leq X_{L1} \leq 1 \text{ mm}; \quad 0 \leq X_{L2} \leq 1 \text{ mm} \\ 0 &\leq X_{F1} \leq 1 \text{ mm}; \quad 0 \leq X_{F2} \leq 1 \text{ mm}; \quad 0 \leq X_{F3} \leq 1 \text{ mm} \\ 0 &\leq Y_{V1} \leq 1 \text{ mm}; \quad 0 \leq Y_{V2} \leq 1 \text{ mm} \\ 0 &\leq Y_{L1} \leq 1 \text{ mm}; \quad 0 \leq Y_{L2} \leq 1 \text{ mm} \\ 0 &\leq Y_{F1} \leq 1 \text{ mm}; \quad 0 \leq Y_{F2} \leq 1 \text{ mm}; \quad 0 \leq Y_{F3} \leq 1 \text{ mm} \\ 0 &\leq Z_V \leq 600 \text{ mm}; \quad 0 \leq Z_L \leq 600 \text{ mm}; \quad 650 \leq Z_F \leq 1000 \text{ mm} \\ 75 &\leq r_t \leq 350 \text{ mm}; \quad 100 \leq l_t \leq 200 \text{ mm} \\ 2 &\leq n \leq 3; \quad 200 \leq l_n \leq 400 \text{ mm} \end{aligned} \tag{3}$$

The constraints and the design variables for the problem formulations are illustrated in Fig. 6 showing exactly which parts of the AUV geometry they define. The design variables are: the type of pump selections for vertical, lateral and forward movements from available catalogue pumps respectively (P_1 , P_2 , P_3), orientation of the selected pumps for respective movements (O_1 , O_2 , O_3), position of the selected pumps along X axis (X_V , X_L , X_F), along Y axis (Y_V , Y_L , Y_F) and along Z axis (Z_V , Z_L , Z_F) for respective movements, and the tail and nose parameters.

Multi-objective Formulation. The multi-objective optimization problem is posed as the identification of an AUV hull form with minimum drag and maximum length of one of the lever arms as well as clash-free optimal placement of the internal objects. The objective functions are listed in the Eq. (4) as Formulation 2, while the constraints and variables are the same as in the single objective case.

Minimize:

$$f(1) = D; \quad f(2) = -LA \tag{4}$$

where $LA = \min(LA_1, LA_2)$.

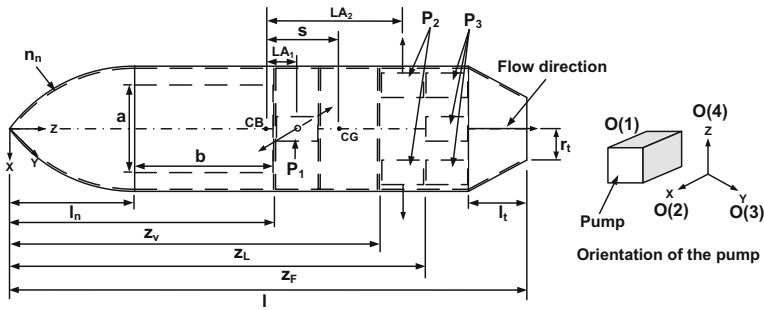


Fig. 6. The constraints and design variables for problem formulations

It can be noted that the optimization algorithms employed in this study are formulated to minimize the objective functions of a problem. Therefore, to maximize the length of lever arm in the Formulation 2, a negative sign has been placed; thereby formulating both the objectives as a minimization problem.

3.2 Computational Setup and Results

For each formulation, thirty independent runs of NSGA-II and IDEA are performed. A crossover probability of 0.9, mutation probability of 0.1, crossover distribution index of 10, mutation distribution index of 20 and an infeasibility ratio (for IDEA) of 0.2 has been used for the algorithms. The number of function evaluations used by each algorithm is kept equal at 40000 for a fair comparison. A population size of 200 has been used for both algorithms. The computing time per evaluation is about 0.05 s on a Intel Xeon processor machine of 3.33 GHz with 6.00 GB memory.

Single Objective Optimization Results. Shown in Fig. 7a is the result of the best run for the single objective drag minimization problem using NSGA-II and IDEA. It is observed that both optimization algorithms are able to minimize the drag in around 30000 function evaluations. The statistics of results computed across 30 runs for each algorithm is reported in Table 1. It is seen that the best, median and the average objective values obtained by IDEA are better than NSGA-II. In addition, the standard deviation across the multiple runs is much less than NSGA-II, indicating that it is able to achieve better objective values more consistently. This is also reflected in the median runs as shown in Fig. 7b, where IDEA is seen to converge faster than NSGA-II.

Results of Optimum AUV Design. Based on the results obtained by carrying out optimization of drag, Fig. 8 shows the optimal shape and internal configuration of the optimized AUV. The resulting performance criteria of the optimized AUV as listed in Table 2, clearly indicate that the design constraints are satisfied while achieving minimum drag.

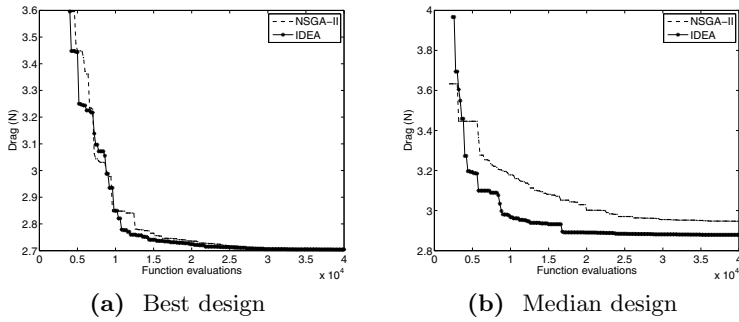


Fig. 7. Progress plots of the best and median designs using NSGA-II and IDEA

Table 1. Single objective drag minimization results

Design	NSGA-II	IDEA
Best (N)	2.70443	2.70424
Mean (N)	3.05906	2.87254
Median (N)	2.94658	2.87850
Worst (N)	5.65062	2.99905
SD (N)	0.50019	0.05839

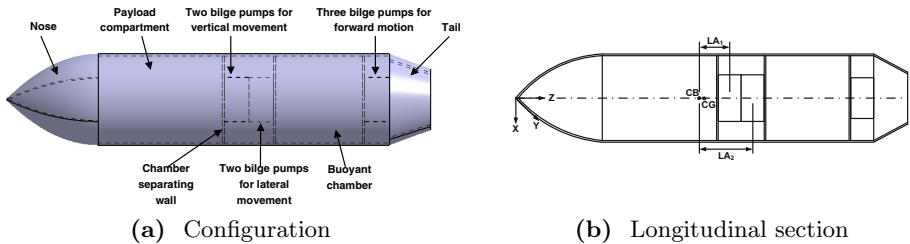


Fig. 8. Hull shape and configuration of the resulting optimized AUV

Table 2. Performance criteria of the resulting optimized AUV

Vehicle particulars	Value	Vehicle particulars	Value
Nose length	294 mm	Length of the second lever arm	155.77 mm
Parallel mid-body length	716 mm	Length of the payload compartment	282 mm
Tail length	100 mm	Length of the buoyant chamber	247 mm
Overall length of the AUV	1110 mm	X-coordinate of CG	0.01254 mm
Outer diameter of the AUV	223 mm	Y-coordinate of CG	0.03201 mm
Length to diameter ratio	4.98	Z-coordinate of CG	524.775 mm
Max. size of the inner square	150 mm	X-coordinate of CB	0
Wetted surface area	0.9897 m ²	Y-coordinate of CB	0
Displacement volume	0.0256 m ³	Z-coordinate of CB	517.162 mm
Mass of the displaced water	25 kg	CG-CB separation	7.613 mm
Mass of the AUV	9 kg	Nominal speed	1 m/s
Payload capacity including batteries	16 kg	Drag (VT method)	2.50177 N
Total mass of the AUV	25 kg	Drag (G&J method)	2.55203 N
Length of the first lever arm	95.44 mm	Drag (MIT method)	2.70424 N

Multi-objective Optimization Results. Multi-objective optimization i.e. minimization of drag and maximization of one of the lever arms is performed using NSGA-II and IDEA. The parameters used are kept the same as that for single objective formulation. Since multi-objective optimization yields a set of non-dominated solutions, the results can not be compared based on objective values obtained (as in single objective optimization). Therefore, a number of performance metrics have been developed in literature to evaluate the quality of the non-dominated set obtained, and to compare the performance of two or more sets. These performance metrics attempt to quantify the convergence and diversity of the obtained non-dominated set. In the present study, two commonly used performance metrics have been used to compare the results obtained using NSGA-II and IDEA: *displacement* [4] and *hypervolume* [17] metrics. A lower value of displacement metric indicates a better non-dominated set. On the other hand, the larger the value of hypervolume, the better is the non-dominated set.

The performance metrics averaged over multiple runs of final solutions obtained using NSGA-II and IDEA are listed in Table 3. It is seen that on average, IDEA is able to achieve lower values of displacement and higher values of hypervolume as compared to NSGA-II. This indicates that IDEA is able to achieve comparatively better non-dominated sets. The best values obtained using IDEA are also better than NSGA-II. The best front (based on displacement metric) obtained using the two algorithms is shown in Fig. 9.

Table 3. Performance metrics for two objectives formulation

	NSGA-II results			
	Best	Mean	Median	Worst
<i>Displacement</i>	0.623945	3.11685	2.39152	7.91698
<i>Hypervolume</i>	772.847	499.548	592.241	58.3212
	IDEA results			
	Best	Mean	Median	Worst
<i>Displacement</i>	0.358976	1.90145	1.57697	5.60445
<i>Hypervolume</i>	715.755	604.82	642.521	265.639

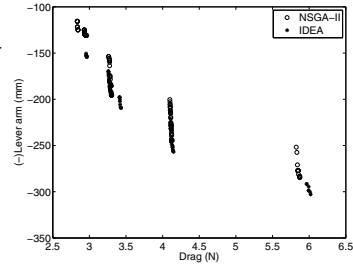


Fig. 9. Best results of the two objectives optimization problem using NSGA-II and IDEA

Once the optimization process is done, then the non-dominated set of solutions can be presented to the decision maker (end user), who can choose a design most suited to his/her needs. For example, in this case the decision maker can choose from a set of optimal designs with minimum drag, or maximum lever arm length, or an intermediate value of both the objectives. Thus the multi-objective formulation can cater to a number of end users, while ensuring that all the basic design criteria are met.

4 Conclusions

In this paper an evolutionary approach for the concept and preliminary design of AUVs is presented. The modular design optimization framework is embedded with a geometry/configuration representation/manipulation module, standard marine performance analysis methods and efficient optimization methods. The seamless integration of the modules allows the designer to identify optimum AUV designs based on a set of user requirements. Both single and multi-objective constrained optimization formulation of the AUV design problems are considered in this paper and solved using two state-of-the-art evolutionary algorithms, NSGA-II and IDEA. The studies highlight the benefits of preserving marginally infeasible solutions in IDEA that accounts for its superior performance over NSGA-II for constrained optimization problems. The modularity and the catalogue driven structure adopted in the framework allows for the design of AUVs for various design requirements and/or with different propulsion and power system options.

The preliminary design obtained from the framework can be further analyzed using a computational fluid dynamics (CFD) tool for more accurate estimates of drag, dynamic performance and controllability. It is also worth highlighting that such performance estimation modules can be easily integrated into the framework and used during the course of optimization.

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