A Framework for Scenario-Based Hydrodynamic Design Optimization of Hard Chine Planing Craft

Ahmad F. Ayob, UMT, Terengganu/Malaysia, z3237562@student.adfa.edu.au
Tapabrata Ray UNSW@ADFA, Canberra/Australia, t.ray@adfa.edu.au
Warren F. Smith UNSW@ADFA, Canberra/Australia, w.smith@adfa.edu.au

Abstract

An optimization framework for the design of hard chine planing craft incorporating resistance, seakeeping and stability considerations is presented. The proposed framework consists of a surface information retrieval module, a geometry manipulation module and an optimization module backed by standard naval architectural performance estimation tools. Total resistance comprising calm water resistance and added resistance in waves is minimized subject to constraints on displacement, stability and seakeeping requirements. Three optimization algorithms are incorporated in the optimization module: Non-dominated Sorting Genetic Algorithm (NSGA-II), Evolutionary Algorithm with Spatially Distributed Surrogates (EASDS), and Infeasibility Driven Evolutionary Algorithm (IDEA). The individual performance of each algorithm is reported. The proposed framework is capable of generating the optimum hull form, which allows for a better estimate of performance compared to methods that generate only the optimum principal dimensions. The importance and effects of the vertical impact acceleration constraint on manned and unmanned missions are also discussed.

Nomenclature

B	Beam (m)	L	Length (m)
C_v	Speed coefficient	LCB	Longitudinal centre of buoyancy (m)
Disp.	Displacement (kg)	R_A	Added resistance (N)
Fn	Froude number	R_C	Calm water resistance (N)
GM	Metacentric height (m)	R_T	Total resistance (N)
$H_{1/3}$	Significant wave height (m)	T	Draft (m)
I_e	Half angle of entrance (degrees)	*Vol.*	Displaced volume (m^3)
I_a	Vertical impact acceleration (g)		

1. Introduction

Ship design involves the practice of satisfying requirements based on a vessel's intended tasks and rationalization, *Schneekluth and Bertram (1998)*. The design of a ship should meet statutory requirements, mission requirements, economic criteria, safety requirements and so on. The choices of main dimensions of the ship affect the hydrostatic and hydrodynamic performance of the ship such as its resistance and response in the seaway. Ship design optimization allows the tradeoff between various performance requirements and is an indispensable element of modern day design processes. Consideration of seakeeping performance during the phase of design has been reported in a number of recent studies. *Sarioz and Narli (2005)* presented an example of seakeeping assessment under various vertical acceleration regimes outlined in ISO 2631, *Mason and Thomas (2007)* illustrated the use Computational Fluid Dynamics (CFD) and Genetic Algorithm (GA) for the optimization of International America's Cup Class (IACC) yachts, *Peri and Campana (2003)* designed a naval surface combatant with total resistance and seakeeping considerations. Other examples involving multiple design aspects i.e. resistance, seakeeping, cost and safety optimization based on specific scenarios have been presented by *Smith (1992)*, *Ray (1995)*, *Ganesan (1999)*, *Neti (2005)* and *Berseneff et al. (2009)*.

Most of the above studies focused on displacement crafts and there are only a handful studies dealing with planing crafts. Minimization of calm water resistance for planing crafts appears in *Almeter (1995)* and *Mohamad Ayob et al. (2009)*. Presented in this paper is a scenario based hydrodynamic optimization of planing craft in seaway operations. An integrated approach is taken that simultaneously considers resistance and motions in a seaway. A number of efficient optimization algorithms are employed for solving the problems posed. The Non-dominated Sorting Genetic Algorithm-II (NSGA-II) by *Deb et al. (2002)* is incorporated in the planing craft optimization framework. In addition to NSGA-II, a surrogate assisted optimization scheme (referred here as EASDS) by *Isaacs et al. (2007)* and an Infeasibility Driven Evolutionary Algorithm (IDEA) *Ray et al. (2009)* is incorporated for increased efficiency.

In order to support design optimization of planing craft, the underlying framework should:

1. allow easy incorporation of different scenarios, design criteria etc. with alternate analysis modules providing different levels of fidelity;
2. allow shape representation and manipulation that is able to generate different variants of hull forms with the required fairness and chine definitions; and
3. include an optimization method that is capable of dealing with single and multi-objective optimization problems with constraints. Furthermore, since the performance evaluations are computationally expensive, the optimization algorithms employed should be efficient.

The proposed framework is built using a modular concept with the Microsoft® COM interface as the underlying communication platform between applications. A modular design in any optimization framework opens the possibility of conducting more complex analysis, *Ray (1995)*, where other optimization schemes and high fidelity multidisciplinary analysis tools can be added and executed for comparative purposes. A number of researchers have discussed helpful proposals for integration of different tools within a ship design framework. *Neu et al. (2000)* applied Microsoft® COM interface in containership design optimization. *Mohamad Ayob et al. (2009)* used Maxsurf Automation, *Maxsurf (2007)* (a form of Microsoft® COM interface) for planing craft design optimization. *Abt et al. (2009)* presented a broader aspect of integration between tools, including integration of in-house and commercial codes using XML files, generic templates and Microsoft COM interface.

2. Optimization framework components

The optimization framework proposed in this paper consists of three applications namely Matlab, Microsoft® Excel and Maxsurf. Maxsurf Automation Library built upon Microsoft® COM interface is used as a medium of communication (inter-process) between applications. Presented in Fig. 1 is a generic sequence diagram to illustrate the workflow of the current optimization framework. The inter-process communication is initialized with the selection of principal dimensions (L, B, T) by the optimizer module in Matlab. Parametric transformation is invoked to generate a candidate hull followed by evaluation of the hydrostatics and calm water resistance of the candidate hull in Maxsurf using the methods of *Savitsky (1964)*. Finally the seakeeping performance is evaluated using the *Savitsky and Koelbel (1993)* method. This completes one workflow loop. The detail flowchart on the optimization framework is presented in Fig. 2 with further discussion of this provided in subsequent sections.

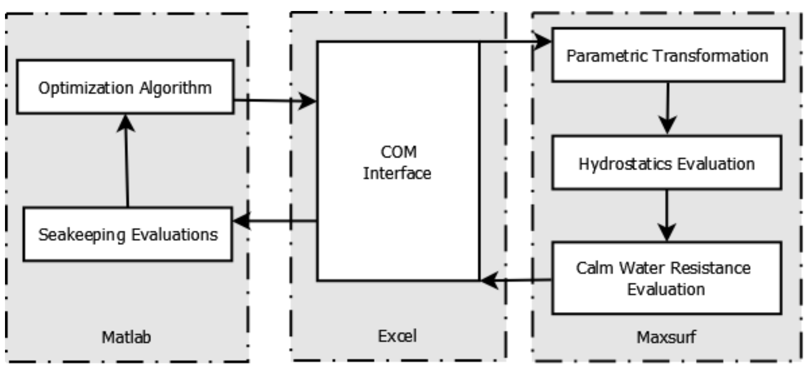


Fig. 1: Inter-process communication flow between applications

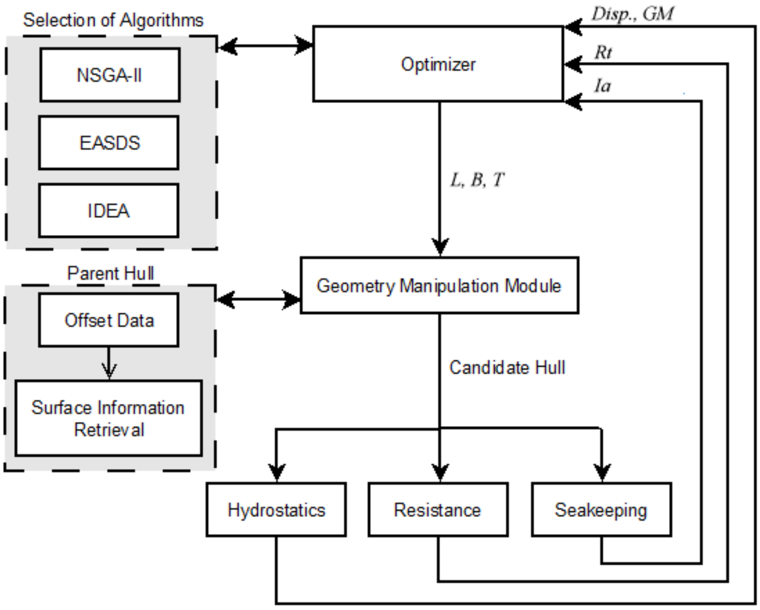


Fig. 2: Detail flowchart on the optimization framework

2.1. Geometry tools

The geometry tools consist of a *surface information retrieval module* and a *geometry manipulation module*. Shown in Fig.2, the surface information retrieval module is employed to generate B-spline representation of the hull while the geometry manipulation module changes the shape of the hull based on principal dimensions given by the optimizer.

The formulation of surface information module is based on the inverse B-spline method, *Rogers and Adams (1990)*. A set of known surface (offset) data is used to determine the defining polygon net for a B-spline surface that best interpolates the data. This method is further expanded to yield a representation of a hard chine form that normally represents a planing craft, *Mohamad Ayob et al. (2009)*. Three B-spline surfaces defined by their own respective polygon nets station-wise with the exclusion of the bow are connected to produce hard chines of the planing craft as shown in Fig. 3.

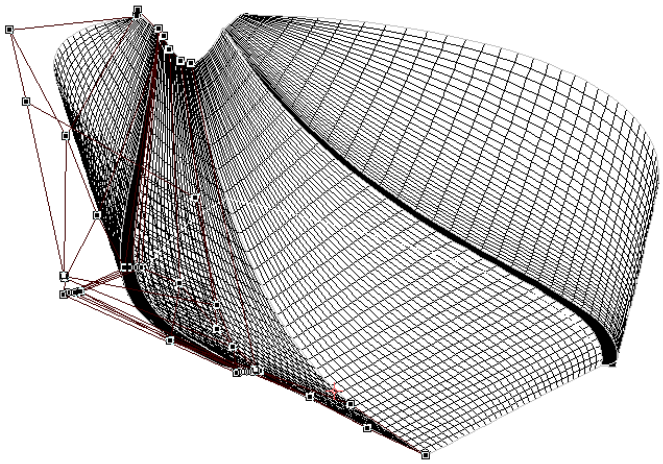


Fig. 3: Three-dimensional view of the planing craft with governing control points

Since the work of *Lackenby (1950)*, the parametric transformation method has been used widely by naval architects to modify the form parameters of an existing parent hull form. While *LCB* and C_p values of the resulting hull can be maintained when the hull sections are moved forward and aft, the displacement value of the hull is changed in the process. In this study the parametric transformation module of Maxsurf is considered as it offers the capability to produce new candidate hull forms while maintaining the displacement and coefficient values of the parent hull, *Maxsurf (2007)*. Control points defining the non-uniform rational B-splines surface (NURBS) of the ship are moved in a smooth fashion producing an acceptable fair surface of the resulting hull. An elaborate discussion on the development of Maxsurf parametric transformation can be found in *Mason and Thomas (2007)*.

2.2. Resistance estimation module

Calm water resistance estimation of planing craft is bounded by certain validation criteria. The details of the range of validation is discussed in the work of *Savitsky (1964)* and *Savitsky and Ward Brown (1976)* and in this study will be employed as constraints to the optimization problem. The details of the planing craft studied in this paper are presented in Table I. As discussed in *Savitsky and Ward Brown (1976)*, a craft is in full planing mode for speed coefficient C_v > 1.5. In this regime, the resulting dynamic forces cause a significant rise of the center of gravity, positive trim, emergence of the bow and the separation of the flow from the hard chines.

Table I: Characteristics of the planing craft

Displacement	7204.94 kg
Length	10.04 m
Beam	2.86 m
Draft	0.7 m
Metacentric height (*GM*)	2.0 m
Speed	20.81 kts
$C_V = V/(g \times B)^{1/2}$	2.02

2.3. Seakeeping estimation technique

The method described in Section 2.2 is suitable for calm water resistance. However, an additional formulation is required in order to calculate the total resistance, R_T of the planing craft operating in a seaway. *Fridsma's (1971)* experimental tank test data on planing craft operating in rough water has been reworked by *Savitsky and Ward Brown (1976)* in a form of equations suitable for computer programming. The estimation modules discussed serve as mathematical model in order to search for the optimum design inside the framework. Total resistance and average vertical impact acceleration over irregular waves having energy spectrum of Pierson-Moskovitz is used in this study.

2.4. Maxsurf Automation

Maxsurf Automation is an interface that provides extensive possibilities of integration between different naval architectural tools, whether developed in-house or commercially, *Maxsurf (2007)*. The automation library is built upon the Microsoft® COM framework, thus allowing automation of calls between compatible applications.

2.5. Optimization algorithms

In this framework, three state of the art optimization algorithms have been used namely NSGA-II, EASDS and IDEA. The algorithms are written in Matlab and integrated via the Microsoft® COM interface discussed earlier.

An elitist, population-based, zero-order, stochastic algorithm known as the Non-dominated Sorting Genetic Algorithm II (NSGA-II) is used as the underlying optimization algorithm. NSGA-II is known to be able to solve a wide range of engineering problems. The algorithm starts with a population of solutions that undergo crossover and mutation to generate offsprings. The current population and current offspring population are sorted based on non-domination and only the best *N* individuals are selected, where *N* is the population size. For complete details the readers are referred to the work of *Deb et al. (2002).*

Most forms of evolutionary algorithm including NSGA-II require the evaluation of numerous candidate solutions prior to its convergence, thus their applicability is restricted for computationally expensive optimization problems. In order to overcome the problem of lengthy computational time, surrogates or approximations can be employed. In this study an evolutionary algorithm with spatially distributed surrogates (EASDS) is employed. The evolutionary algorithm is embedded with multiple surrogates such as the ordinary response surface method (ORSM), the normalized response surface method (RSM), the ordinary radial basis function (ORBF), the normalized radial basis function (RBF) and the kriging method (DACE). The algorithm performs actual analysis for the initial population followed by periodical evaluations in every few generations. A new candidate solution is predicted by the surrogate model with the least prediction error in the neighbourhood of that point. The complete details of the algorithm are explained in *Isaacs et al. (2007).*

Solutions to real-life constrained optimization problems lie often on constraint boundaries. In reality, a designer is often interested in looking at the solutions that might be marginally infeasible. Most optimization algorithms including NSGA-II intrinsically prefer a feasible solution over an infeasible solution during the search. However, some recent works suggest that effectively utilizing the marginally infeasible solutions during the search can expedite the rate of convergence. To this effect, Infeasibility Driven Evolutionary Algorithm (IDEA) by *Ray et al. (2009)* is also used in this study.

3. Numerical experiments

In this section, the definition of the seaway operability condition, optimization problem formulation and results for various scenarios are presented. The significance of various design criteria are further discussed in the following subsections.

3.1. Definition of the seaway and operability condition

The case study refers to a design around coastal waters of Visakhapatnam in India. The wind speed data for the above location is obtained from *Shreeram and Rao (2005).* An approximate value of the significant wave height, $H_{1/3}$ data is estimated along the range of 12 nautical miles (22 km) and is presented in Table II. The location of interest is shown in Fig. 4.

Table II: Chosen significant wave height data for numerical experiment

Wind Speed	Sea State Code	Significant Wave Height
4 m/s	1	0.4 m
5 m/s	2	0.6 m
6 m/s	2	0.8 m
7 m/s	3	1.1 m

Habitability of a craft can be assessed by means of *ISO (1985)* where vertical acceleration, exposure time and frequency are linked together to yield the seakeeping criteria. An example of its applicability was illustrated by *Sarioz and Narli (2005).*

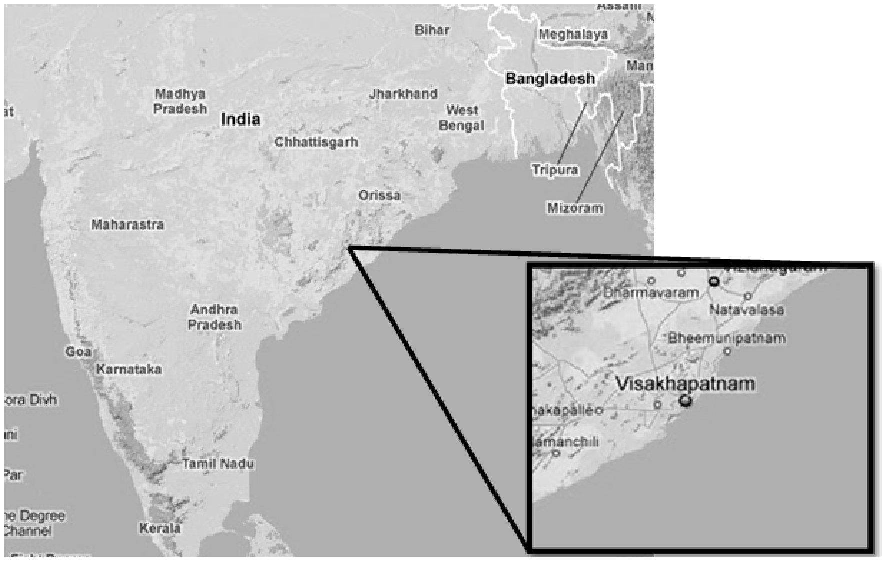


Fig.4: Territorial waters of India near Visakhapatnam, 12 nautical miles from the coastal line

3.2. Optimization problem formulation

The optimization problem is posed as the identification of a planing craft with minimum total resistance subject to the constraints on displacement, stability (transverse metacentric height) and impact acceleration corresponding to the operational sea-states. The planing craft used in this study represents a craft similar to U.S. Coast Guard (USCG) Surf Rescue Boat (30-foot SRB) (*Halberstadt (1987)*). The ship is designed to operate in sea up to 3 m waves, with a maximum speed of 30 knots. The seaway scenarios are expressed in Table II by significant wave heights $H_{1/3}$ assuming Pierson-Moskovitz spectra. The objective functions and constraints are listed below, where subscripts B, I, T, C and A resemble basis hull, candidate hull, total resistance, calm water resistance and added resistance due to waves, respectively.

Minimize: $f = R_T$, where $R_T = R_C + R_A$

Design variables: 9m<L<11m (L_B=10.04m) ; 1.8m<B<3.8m (B_B=2.862m) ; 0.6m<T<0.8m (T_B=0.7m)

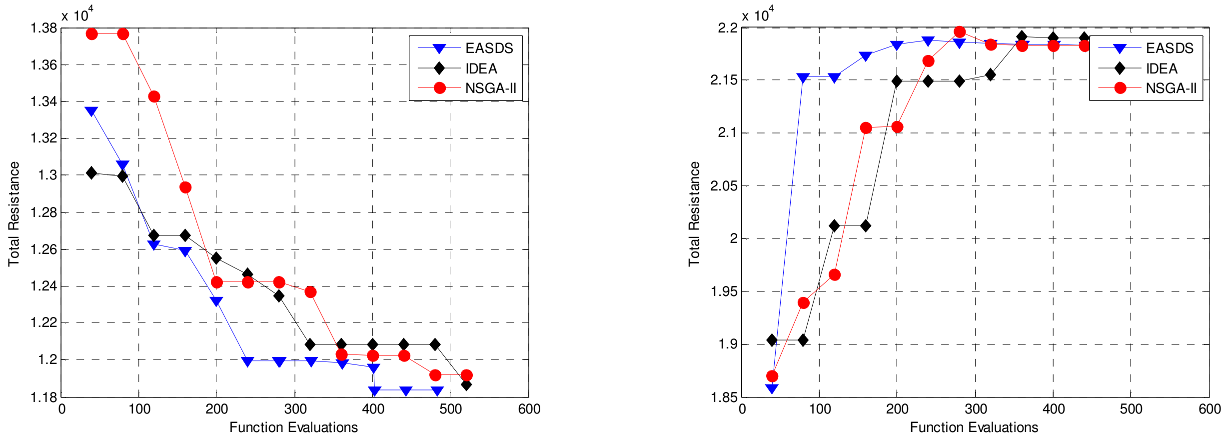
Constraints: $g(1) : Disp_I > Disp_B$; $g(2) : GM_I \geq GM_B$; $g(3) : 3.07 < L_I/Vol_I^{1/3} < 12.4$
$g(4) : 3.7^o < I_{eI} < 28.6^o$; $g(5) : 2.52 < L_I/B_I < 18.28$; $g(6) : 1.7 < B_I/T_I < 9.8$

A vertical impact acceleration limit is part of the seakeeping assessment criteria. Based on *Savitsky and Koelbel (1993)* the maximum vertical impact acceleration chosen at any location of the planing craft for one or two hours of operation is 1.5g. Thus, an additional constraint $g(7) : I_a < 1.5g$ is imposed. This additional criterion is a crew performance criterion, and not a hull design criterion.

3.3. Optimization results

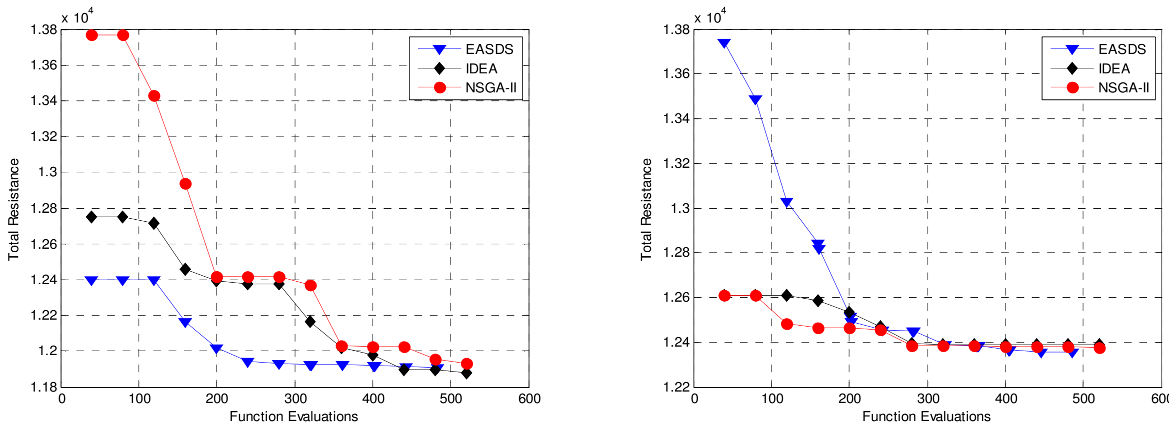
For each algorithm (NSGA-II, IDEA and EASDS), 10 independent runs are performed. A population size of 40, crossover probability of 1, mutation probability of 0.1, crossover distribution index of 10, and mutation distribution index of 20 were used for each algorithm. The number of function evaluations used by each algorithm is kept approximately equal for a fair comparison. The surrogate models used are restricted to RSM, ORSM, RBF, ORBF and DACE. A training period of 3 and prediction error of 0.05 has been used for EASDS.

The R_T value corresponding to the best run of each algorithm (EASDS, IDEA and NSGA-II) is plotted against function evaluations for sea state 1 in Fig. 5(a). All the algorithms are in general able to derive savings in R_T as compared to the basis hull while satisfying the constraint on vertical impact acceleration. Similar results were obtained for studies conducted at sea state 2. In the case of designs under sea state 3 conditions as shown in Fig. 5(b) and Table V to VII, the basis hull has vertical impact acceleration larger than 2g violating the constraint. Runs of all the algorithms are able to achieve feasible designs while satisfying the constraint on impact acceleration, though at a cost of an increased R_T.

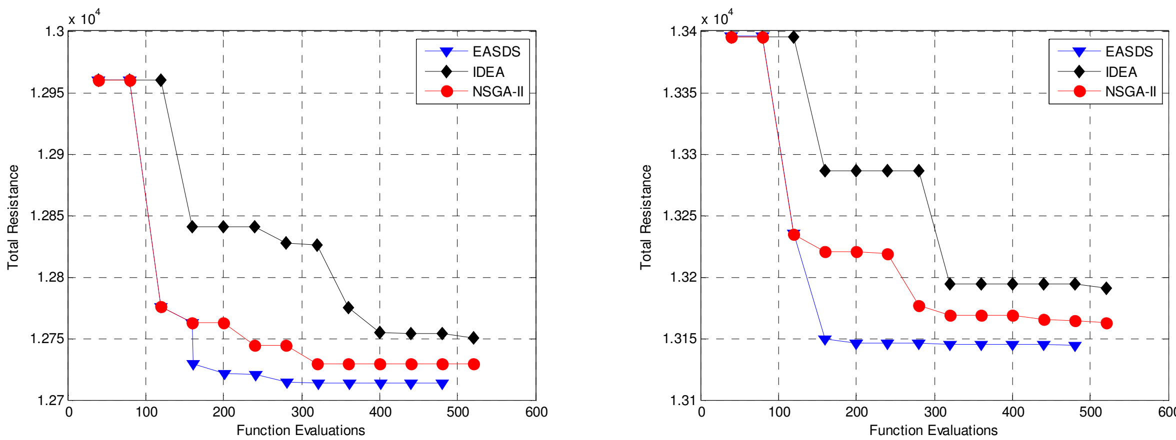


(a) Sea-state 1 ($H_{1/3}$ = 0.4m) (b) Sea-state 3 ($H_{1/3}$ = 1.1m)

Fig. 5: Optimization progress plot of ship with vertical impact acceleration constraint



(a) Sea-state 1 ($H_{1/3}$ = 0.4m) (b) Sea-state 2 ($H_{1/3}$ = 0.6m)



(c) Sea-state 2 ($H_{1/3}$ = 0.8m) (d) Sea-state 3 ($H_{1/3}$ = 1.1m)

Fig. 6: Optimization progress plot of ship without vertical impact acceleration constraint

The value of impact acceleration and R_T of the basis hull at sea state 3 is 2.11g and 13545.90 N respectively, while all optimized designs have impact acceleration 1.5g and R_T of 21830.67 N, 21829.52 N and 21833.40 N for NSGA-II, EASDS and IDEA, respectively. The optimized hull forms found by the optimizers have similar characteristics where larger values of L, B and T result in a larger displacement in order to satisfy the vertical impact acceleration constraint. The details on the dimensions are highlighted in Tables V to VII.

The results for the optimization without the impact acceleration constraint are shown in Fig. 6. Total resistance values of the best run of each algorithm (EASDS, IDEA and NSGA-II) are plotted against function evaluations for typical sea states of 1, 2 and 3. In all sea-states, EASDS was able to converge faster than IDEA and NSGA-II. One can observe by comparing Fig. 5(b) and Fig. 6(d) that an increase of R_T as high as 61% is necessary to satisfy the impact acceleration constraint, as compared to a reduction by 2.97% when the impact acceleration constraint is ignored.

Shown in Fig. 7 is the progress for the median designs obtained using NSGA-II, EASDS and IDEA for sea-state 1. Given the approximately same number of function evaluations, IDEA converges faster than the other two algorithms while EASDS converges better than NSGA-II. A more comprehensive comparison between algorithms can be observed in Tables III and IV where the best values of median designs at all sea-states are depicted in bold type. EASDS consistently performs better than NSGA-II and IDEA in solving the minimization problem with the impact acceleration constraint, while IDEA outperforms the other two algorithms for the problem without the impact acceleration constraint.

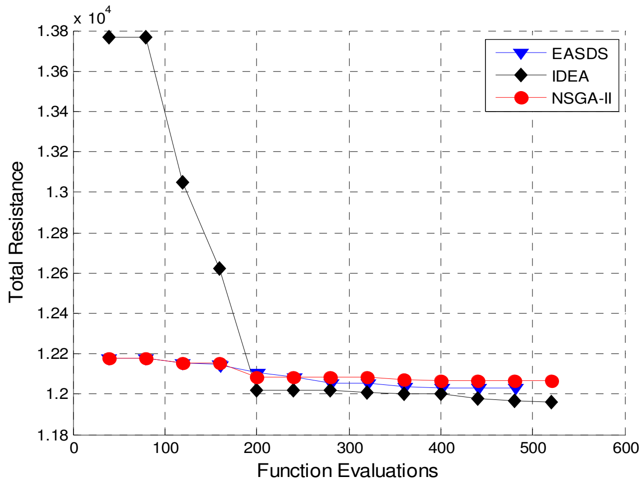


Fig 7: Median design obtained using EASDS, IDEA and NSGA-II

Table III: Comparison between R_T (N) of median designs with I_a constraint

	Sea-state 1 (0.4m)	Sea-state 2 (0.6m)	Sea-state 2 (0.8m)	Sea-state 3 (1.1m)
NSGA-II	12060.96	12460.96	13858.59	21844.52
EASDS	11955.90	**12415.75**	**13314.61**	**21842.02**
IDEA	**11933.19**	12549.24	13709.51	21871.29

Table IV: Comparison between R_T (N) of median designs without I_a constraint

	Sea-state 1 (0.4m)	Sea-state 2 (0.6m)	Sea-state 2 (0.8m)	Sea-state 3 (1.1m)
NSGA-II	12065.10	12460.96	12968.60	13506.20
EASDS	11999.19	**12415.75**	12916.91	13468.44
IDEA	**11962.04**	12445.15	**12880.76**	**13315.37**

3.4. Scenario results

Two different scenarios are considered in this section. The first refers to the minimization of R_T with the impact acceleration constraint, while the second refers to the minimization of R_T without the impact acceleration constraint. The former is common for rescue missions where ship crews engage in life saving procedures while the latter scenario is suitable for unmanned surveillance missions where the craft need to be operated at high speeds and seasickness and personal injury caused by vertical impact acceleration is not a consideration. The percentage of resistance minimized is determined using the expression below:

$$\text{\% of Minimized } R_T = \frac{\text{Basis Hull } R_T \text{ - Optimized Hull } R_T}{\text{Basis Hull } R_T} \text{ x } 100\%$$

3.4.1. Minimization of R_T with vertical impact acceleration constraint

Results for minimization of R_T with vertical impact acceleration constraint obtained using NSGA-II, EASDS and IDEA are tabulated in Table V to VII, respectively. In the case of designing under sea state 1 conditions, all the three algorithms were able to reduce the R_T when compared with the basis hull. However at sea-state 2 ($H_{1/3}$ = 0.8m) and sea-state 3 ($H_{1/3}$ = 1.1m) the basis hull violated the study imposed vertical impact acceleration limit.

Table V: Minimization of R_T with I_a constraint (NSGA-II best design)

	Sea-state 1 (0.4m)		Sea-state 2 (0.6m)		Sea-state 2 (0.8m)		Sea-state 3 (1.1m)	
	Basis	Optimized	Basis	Optimized	Basis	Optimized	Basis	Optimized
Disp. (kg)	7204.94	7206.36	7204.94	7206.90	7204.94	7333.90	7204.94	11579.56
L (m)	10.04	10.87	10.04	10.99	10.04	9.10	10.04	10.99
B (m)	2.86	3.07	2.86	2.79	2.86	3.59	2.86	3.71
T (m)	0.70	0.60	0.70	0.66	0.70	0.63	0.70	0.79
GM (m)	2.00	2.56	2.00	2.04	2.00	3.22	2.00	2.73
R_C (N)	11547.02	9838.28	11547.02	10175.79	11547.02	11065.94	11547.02	17466.37
R_A (N)	1343.84	2081.25	1570.54	2198.95	1761.35	2348.19	1998.88	4364.30
I_a (g)	1.01	1.03	1.32	1.27	1.64	1.50	2.11	1.50
R_T (N)	12890.86	11919.53	13117.56	12374.74	13308.37	13414.13	13545.90	21830.67
Minimized R_T (%)	7.54		5.66		(-) 0.79		(-) 61.16	

Table VI: Minimization of R_T with I_a constraint (EASDS best design)

	Sea-state 1 (0.4m)		Sea-state 2 (0.6m)		Sea-state 2 (0.8m)		Sea-state 3 (1.1m)	
	Basis	Optimized	Basis	Optimized	Basis	Optimized	Basis	Optimized
Disp. (kg)	7204.94	7206.05	7204.94	7205.06	7204.94	7229.68	7204.94	11581.66
L (m)	10.04	10.99	10.04	10.98	10.04	9.21	10.04	10.99
B (m)	2.86	3.04	2.86	3.04	2.86	3.65	2.86	3.72
T (m)	0.70	0.60	0.70	0.60	0.70	0.60	0.70	0.79
GM (m)	2.00	2.52	2.00	2.52	2.00	3.43	2.00	2.75
R_C (N)	11547.02	9752.45	11547.02	9768.31	11547.02	10546.33	11547.02	17438.15
R_A (N)	1343.84	2088.51	1570.54	2590.41	1761.35	2561.58	1998.88	4391.37
I_a (g)	1.01	1.02	1.32	1.33	1.64	1.50	2.11	1.50
R_T (N)	12890.86	11840.96	13117.56	12358.72	13308.37	13107.91	13545.90	21829.52
Minimized R_T (%)	**8.14**		**5.78**		**1.51**		(-) 61.15	

Shown in Table V is an increase of 0.79% over the total resistance of the basis hull at sea-state 2 ($H_{1/3}$ = 0.8m) for NSGA-II. However, Tables VI to VII show that EASDS and IDEA are able to identify a design with a lower R_T as compared to the basis hull, while satisfying the impact acceleration constraint. This highlights the efficiency of EASDS and IDEA in solving the constrained optimization problems considered here. The highest percentages in savings are presented in bold type inside the table.

For sea-state 3 ($H_{1/3}$ = 1.1m), all the algorithms are able to identify designs satisfying the vertical impact acceleration constraint but with an increase in R_T as compared to the basis hull. The increase of R_T percentage is symbolized using minus sign (-) inside of the table.

Table VII: Minimization of R_T with I_a constraint (IDEA best design)

	Sea-state 1 (0.4m)		Sea-state 2 (0.6m)		Sea-state 2 (0.8m)		Sea-state 3 (1.1m)	
	Basis	Optimized	Basis	Optimized	Basis	Optimized	Basis	Optimized
Disp. (kg)	7204.94	7213.11	7204.94	7213.99	7204.94	7260.53	7204.94	11572.02
L (m)	10.04	10.98	10.04	10.98	10.04	9.21	10.04	10.97
B (m)	2.86	3.03	2.86	2.82	2.86	3.65	2.86	3.72
T (m)	0.70	0.61	0.70	0.65	0.70	0.60	0.70	0.79
GM (m)	2.00	2.49	2.00	2.09	2.00	3.41	2.00	2.75
R_C (N)	11547.02	9798.61	11547.02	10151.34	11547.02	10619.00	11547.02	17462.53
R_A (N)	1343.84	2071.26	1570.54	2247.15	1761.35	2557.62	1998.88	4370.87
I_a (g)	1.01	1.02	1.32	1.28	1.64	1.50	2.11	1.50
R_T (N)	12890.86	11869.87	13117.56	12398.49	13308.37	13176.62	13545.90	21833.40
Minimized R_T (%)	7.92		5.48		0.99		(-) 61.18	

3.4.2. Minimization of R_T without vertical impact acceleration constraint

The results for minimization of R_T without vertical impact acceleration constraint using NSGA-II, EASDS and IDEA are tabulated in Table VIII to X, respectively. All three optimization algorithms are able to find candidate designs with low value of R_T while meeting the requirements for displacement and GM.

Table VIII: Minimization of R_T without I_a constraint (NSGA-II best design)

	Sea-state 1 (0.4m)		Sea-state 2 (0.6m)		Sea-state 2 (0.8m)		Sea-state 3 (1.1m)	
	Basis	Optimized	Basis	Optimized	Basis	Optimized	Basis	Optimized
Disp. (kg)	7204.94	7210.96	7204.94	7206.90	7204.94	7207.41	7204.94	7206.30
L (m)	10.04	10.88	10.04	10.99	10.04	10.98	10.04	10.97
B (m)	2.86	3.07	2.86	2.79	2.86	2.80	2.86	2.81
T (m)	0.70	0.60	0.70	0.66	0.70	0.65	0.70	0.65
GM (m)	2.00	2.56	2.00	2.04	2.00	2.06	2.00	2.07
R_C (N)	11547.02	9850.25	11547.02	10175.79	11547.02	10172.77	11547.02	10166.02
R_A (N)	1343.84	2081.75	1570.54	2198.95	1761.35	2556.53	1998.88	2996.65
I_a (g)	1.01	1.03	1.32	1.27	1.64	1.58	2.11	2.05
R_T (N)	12890.86	11932.00	13117.56	12374.74	13308.37	12729.30	13545.90	13162.67
Minimized R_T (%)	7.44		5.66		4.35		2.83	

At sea-state 2 ($H_{1/3}$ = 0.8m) and sea-state 3 ($H_{1/3}$ = 1.1m), the basis hull has a vertical impact acceleration value larger than 1.5g. If the operating condition permits high values of vertical impact acceleration such as unmanned surveillance and ruggedized shock mounted equipment, a reduction of R_T could be realized. In sea-state 1 ($H_{1/3}$ = 0.4m), NSGA-II, EASDS and IDEA result in reductions of R_T by 7.44%, 7.62% and 7.8 % respectively. For sea-state 2 ($H_{1/3}$ = 0.6m), NSGA-II, EASDS and IDEA result in reductions of R_T by 5.66%, 5.78% and 5.57% respectively. For sea-state 2 ($H_{1/3}$ = 0.8m), NSGA-II, EASDS and IDEA result in reductions of R_T by 4.35%, 4.47% and 4.19% respectively. Finally for sea-state 3 ($H_{1/3}$ = 1.1m), NSGA-II, EASDS and IDEA result in reductions of R_T by 2.83%, 2.97% and 2.62% respectively. EASDS consistently performs better than NSGA-II and IDEA in this particular example.

Table IX: Minimization of R_T without I_a constraint (EASDS best design)

	Sea-state 1 (0.4m)		Sea-state 2 (0.6m)		Sea-state 2 (0.8m)		Sea-state 3 (1.1m)	
	Basis	Optimized	Basis	Optimized	Basis	Optimized	Basis	Optimized
Disp. (kg)	7204.94	7205.29	7204.94	7205.06	7204.94	7206.40	7204.94	7205.98
L (m)	10.04	10.88	10.04	10.98	10.04	11.00	10.04	10.98
B (m)	2.86	3.08	2.86	3.04	2.86	2.80	2.86	2.79
T (m)	0.70	0.60	0.70	0.60	0.70	0.65	0.70	0.66
GM (m)	2.00	2.59	2.00	2.52	2.00	2.06	2.00	2.04
R_C (N)	11547.02	9814.42	11547.02	9768.31	11547.02	10143.50	11547.02	10189.59
R_A (N)	1343.84	2094.60	1570.54	2590.41	1761.35	2569.75	1998.88	2954.54
I_a (g)	1.01	1.03	1.32	1.33	1.64	1.58	2.11	2.04
R_T (N)	12890.86	11909.02	13117.56	12358.72	13308.37	12713.24	13545.90	13144.12
Minimized R_T (%)	7.62		**5.78**		**4.47**		**2.97**	

Table X: Minimization of R_T without I_a constraint (IDEA best design)

	Sea-state 1 (0.4m)		Sea-state 2 (0.6m)		Sea-state 2 (0.8m)		Sea-state 3 (1.1m)	
	Basis	Optimized	Basis	Optimized	Basis	Optimized	Basis	Optimized
Disp. (kg)	7204.94	7222.10	7204.94	7209.79	7204.94	7210.17	7204.94	7207.62
L (m)	10.04	10.99	10.04	10.98	10.04	10.97	10.04	10.99
B (m)	2.86	3.04	2.86	2.80	2.86	2.83	2.86	2.84
T (m)	0.70	0.60	0.70	0.66	0.70	0.65	0.70	0.64
GM (m)	2.00	2.52	2.00	2.05	2.00	2.10	2.00	2.13
R_C (N)	11547.02	9787.54	11547.02	10190.18	11547.02	10146.15	11547.02	10081.61
R_A (N)	1343.84	2089.12	1570.54	2197.11	1761.35	2604.18	1998.88	3109.66
I_a (g)	1.01	1.02	1.32	1.28	1.64	1.59	2.11	2.06
R_T (N)	12890.86	11876.67	13117.56	12387.29	13308.37	12750.33	13545.90	13191.27
Minimized R_T (%)	**7.87**		5.57		4.19		2.62	

4. Summary and conclusions

A hydrodynamic optimization framework for a hard chine planing craft in seaway operations is presented in this paper. The proposed framework incorporates three evolutionary algorithms, namely NSGA-II, EASDS and IDEA. The hull form optimization problem is formulated through minimization of R_T in four sea-states, with $H_{1/3}$ of 0.4m, 0.6m, 0.8m and 1.1m with and without vertical impact acceleration constraints to illustrate scenarios for manned and unmanned missions.

The framework allows an easy integration of various analysis modules of varying fidelity. The ability to generate an optimum hull form rather than the optimum principal dimensions allows for a better estimate of performance, while at the same time providing offsets directly to support other detailed analysis and even direct construction.

The inclusion of surrogate models through EASDS allows the possibility to identify better designs for the same computational cost as highlighted in the case studies. The proposal to accelerate the rate of convergence through the use of IDEA for constrained optimization problems is also illustrated. The importance and effects of the impact acceleration constraint on manned and unmanned missions are discussed. The proposed framework being modular in nature, allows for the possibility of including other underlying optimization schemes or high fidelity multidisciplinary analysis tools to support design of hard chine planing crafts.

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