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EFFICIENT HULL FORM DESIGN OPTIMISATION USING HYBRID EVOLUTIONARY ALGORITHM AND MORPHING APPROACH

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SUMMARY

An efficient hull form design can improve the overall efficiency of a marine vessel by reducing drag and therefore lowering carbon dioxide emission and fuel consumption. Traditional methods of hull form design and optimisation process, using trial-and-error approach require many designers' man-hours to produce more efficient hull form designs, which may be only sub-optimal and inefficient. This paper introduces an intelligent hull form design optimisation concept which aims to address the above issues. Combine with Industry 4.0 concept, the objective is to upgrade hull form design into a smart design process. This is accomplished by coupling an intelligent global search method-evolutionary algorithm with an efficient shape manipulation approach known as morphing. By doing so, process of hull form design optimisation can be achieved with minimum user intervention to produce optimal hull form more efficiently. A case study comparing existing proven designs to new hull forms created from the proposed hybrid evolutionary algorithm and morphing approach are presented.

1. INTRODUCTION

Hull form design and optimisation is an important topic in the shipbuilding industry. This is especially so in the face of more stringent environmental regulations and reduction of ship operational cost due to fuel consumption. An efficient hull form will help to reduce overall resistance acting on the vessel and thereby saving fuel and reduce harmful emission. Traditionally, hull form design and optimisation is carried out manually by ship designers using 'trial and error' approach where they will first select the most suitable hull form design from a pool of existing proven designs, improve the shape of hull manually and test the new hull form design using numerical tools or model test. This cycle will continue until the most optimal hull design is obtained. This manual process is very time consuming and only allows a few hull design variation and testing. While latest simulation based design (SBD) methods may help to automate some of these processes, they still require considerable human input and the result often depends heavily on the designer's experience and knowledge.

Hull form design optimisation (HFDO) is one of the SBD methods applied to perform detail investigations of hydrodynamic performance and numerical optimisation of the hull form. Typically, HFDO consists of the following steps; it starts with formulating the problem under (1), followed by design space exploration (2) which carries out the optimisation process. The next process is geometry modification (3) where the shape of hull is modified to produce new designs. Lastly, the hydrodynamic performances are evaluated in (4) using numerical methods or Computational Fluid Dynamics (CFD) analysis. The final output of this process is optimal solutions (5) which consist of hull forms that provide the best performance. The HFDO process is illustrated in Figure 1 as below.

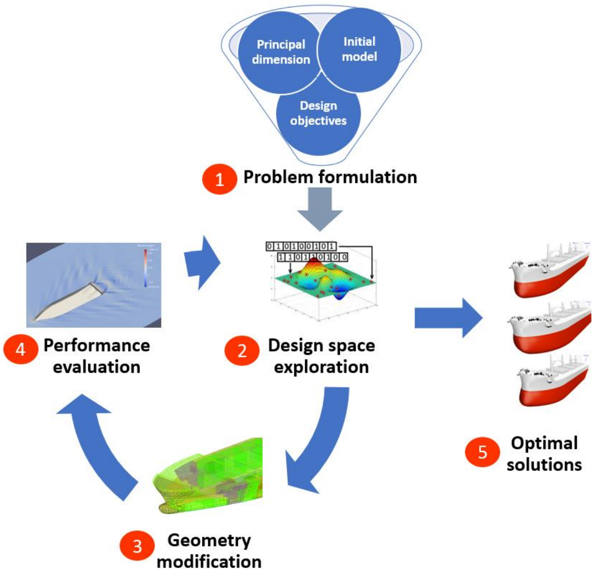


Figure 1: Hull form design and optimisation (HFDO) process [1]

While HFDO has proven to be a very efficient tool for hull form optimisation, it has not been widely adopted- largely due to the lack systematic shape variation and robust optimisation techniques [1]. Research in this area had evolved by using more advance optimisation and evaluation methods. Some recent works related to hull form design and optimisation process include [2] where they used Sequential Quadratic Programming for design space exploration, section area curve for geometry modification and evaluated the performance using potential and the viscous-flow solver. [3] applied Radial Basis Function for geometry modification, optimised using artificial bee colony algorithm and evaluated using CFD. [4] combined Sequential Quadratic Programming and shape modification using geometrical parameterisation and evaluated the performance using vortex line method for sailing yacht foil design.

An emerging trend in design and manufacturing- widely known as industry 4.0 (i4) - integrates cyber and physical systems for smart design and manufacturing and has the potential to transform the future of ship design and manufacturing. With more powerful computers and incorporation of i4 into design and manufacturing, computational intelligence methods such as evolutionary algorithm will play an even more important role in producing more efficient, cost-effective and innovative ships. The objective of this paper is to introduce a hybrid evolutionary algorithm and morphing approach which enables intelligent and automated design optimisation in pursuit of efficient hull form designs. In Section 2, an overview of industry 4.0 and smart design concept is proposed to link up HFDO process and product lifecycle. Section 3 introduces and elaborates the hybrid evolutionary shape manipulation approach for hull form design and optimisation. In Section 4, the preliminary findings obtained are presented and discussed. Section 5 concludes the paper.

2. INDUSTRY 4.0 AND SMART DESIGN

2.1 INDUSTRY 4.0

Industry 4.0 (i4) - often referred to as the fourth industrial revolution- aims to merge the real and virtual space through cyber-physical systems. I4 promises a paradigm shift from traditional segregated manufacturing process to fully connected manufacturing system, which is fast gaining worldwide attention. There are several studies [5, 6] that describe the basic components and enabling technologies of i4, which includes internet of things (IoT), collaborative robots, cyber-security, cloud computing, additive manufacturing, augmented reality and big data analytics. Increasingly, computational intelligence will play more important role in realising the full potential of i4.

2.2 CLOSED-LOOP SHIP PRODUCT LIFECYCLE AND SMART DESIGN

Traditionally, ship design process is carried out manually with ship designers relying on their experience and conventional computer aided design (CAD) or design simulation tools. As computational methods and high-performance computing advances, the use of more high-end optimisation (i.e. evolutionary algorithm) and hydrodynamic performance evaluation procedure such as CFD are becoming more prevalent in the ship design process. However, the adoption of these advance techniques in the marine industry is somewhat limited due to lack of a 'close-loop' approach where the design process can become fully automated with little or no user dependencies. To achieve this goal, a framework that considers the entire product lifecycle of ship into a 2-way closed-loop process is proposed in [7] and presented in Figure 2 below.

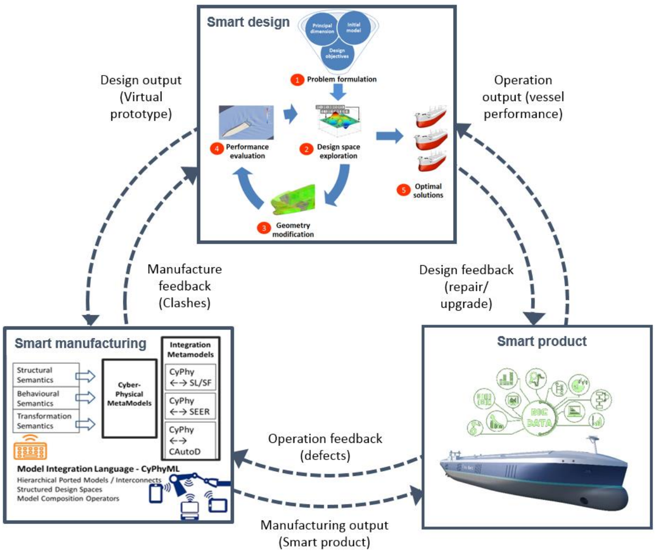


Figure 2: Two way closed-loop framework for smart design, manufacturing and operation [7]

Under this product lifecycle framework, smart design such as HFDO plays an important role to help realise the goal of i4 when integrated with smart manufacturing and smart products. Recently, the digital twin concept has gained popularity as it becomes more cost effective to implement, possibly due to the rise of i4 related technologies such as IoT, cloud and data analytics. Building on these concepts, smart design is hereby proposed as an intelligent and automated design process that collaborates closely with digital manufacturing and digital product throughout the entire product lifecycle. By means of smart design, this design automation tool can i) automatically search from a large database of proven hull designs, modify the hull geometry to create more design variations and evaluate the potential designs using CFD analysis, ii) capture and incorporate designer's knowledge into the design process so as to reduce dependency of experienced designers, iii) interconnect with smart manufacturing and smart product for through-life design, with a final goal of producing more efficient and innovative hull form designs.

3. HYBRID EVOLUTIONARY SHAPE MANIPULATION APPROACH

Considering the various issues and trends highlighted earlier, smart design can be developed by combining design automation process and computation intelligence considering through-life design in i4. This can be achieved by incorporating techniques in evolutionary strategies (genetic algorithm), geometry manipulation technique (surface morphing), advance simulation (CFD) and combine them into an intelligent hull automation design tool. This tool can then be used to automate the hull form design and optimisation process and interface with smart manufacturing and smart product across product lifecycle to produce more innovative hull form designs.

3.1 GENETIC ALGORITHM

Evolutionary computing such as Genetic algorithms (GA) proved to be very useful and become standard techniques in many HFDO process. GA is a nature-inspired search heuristic method based on Darwinian Theory of natural selection and the ‘survival of the fittest’ principle [8]. Unlike conventional optimisation method, GA has many desirable traits and offer significant advantages to efficiently navigate large and challenging design search space to produce globally optimal non-dominated solutions. Key to the workings of GA is the principle of ‘genes’ and ‘chromosomes’. Through the use of genetic operators namely selection, crossover and mutation, information exchange takes place between these chromosomes over a number of iterations, typically with the fittest solutions replacing weaker ones, eventually leading to a set of optimal solutions. Examples of HFDO process using GA include [9], where the authors developed a hull form design system using GA, successive quadratic programming (SQP) and Rankine-source panel method for minimum wave-making resistance of a container ship. Several other works that applied GA for ship design optimisation includes [10-12].

3.2 GEOMETRY MODIFICATION- MORPHING

In any hull form optimisation, geometry modification plays an important role in ensuring the hull geometry can be easily manipulated to form new shapes in order for the optimiser to investigate and evaluate. This is no trivial task as every new shape generated must be smooth and a feasible design. There are 2 main approaches in hull form modification - direct modification and systematic variation. Direct modification involves manual adjustment of points and curves such as B-splines, which are usually quite localised and time-consuming to modify. Systematic variation includes parametric modelling, free-form modification which allows global modification and allows the hull geometry to be modified more efficiently. More recently, morphing method are being applied for systematic variation of hull forms. Morphing, also known as metamorphosis is a technique that is used widely in the animation industry to generate a sequence of images that smoothly transform a source into a target image. In computer graphic and industrial design, it is also used to compute a continuous transformation from one source shape to another target shape. In ship application, morphing was applied in [13, 14].

3.3 HYBRID EVOLUTIONARY ALGORITHM AND MORPHING APPROACH

Considering the main issues in existing hull form optimisation with respect to the lack of automated shape manipulation and robust optimisation techniques to generate feasible designs, a hybrid evolutionary algorithm and morphing (HEAM) approach based on HFDO concept was first proposed by the authors in [15]. The proposed methodology integrates a Genetic Algorithm (GA) and morphing techniques into a single optimisation platform. By combining the advantages of GA - ability to search for the best global solution - and that of morphing- ability to generate smooth intermittent shapes from the combination of two or more hull form designs, we can potentially create an optimum hull form design with improved efficiency. An overview of the proposed HEAM concept is provided in Figure 3.

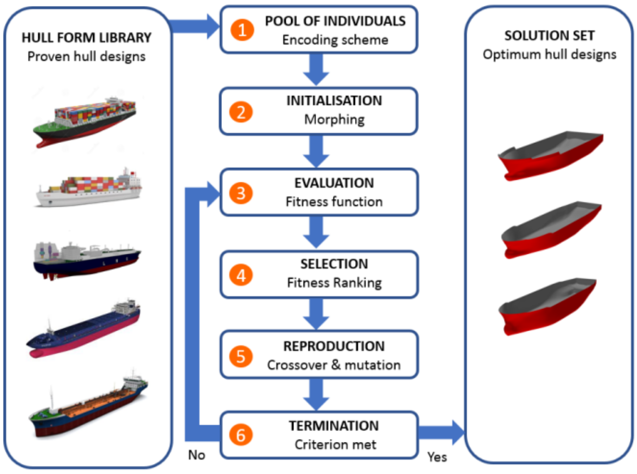
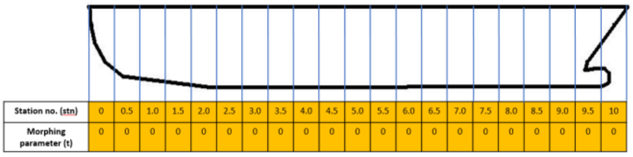


Figure 3: Hybrid evolutionary algorithm and morphing (HEAM) approach

The HEAM proposed in this paper consists of 6 main components namely: (1) pool of individuals- encoding scheme, (2) initialisation- morphing, (3) evaluation-fitness function, (4) selection- fitness ranking, (5) reproduction- crossover and mutation and (6) termination. The following sections details key mechanisms of the HEAM for ship hull form design and optimisation.

3.3 (a) Pool of Individuals- Encoding Scheme

Under this HEAM approach, the first step is to create a pool of ‘initial solutions’ and ‘mapped’ into unique encoding scheme. In the context of ship design, this can be drawn from existing hull forms from a design library or created from scratch. The approach developed in this paper is based on the former where existing hull forms from ship design firm or shipyard is used. Similar to existing ship design process, these hull forms are used as reference or parent designs which will be further improved to meet the new design objectives. The advantage of using existing designs is the assurance of their performances, whilst may not be optimal, are validated to meet basic design objectives and could thus potentially shorten the design cycle. For the approach developed in this paper, real-value chromosomes using morphing parameter (t) which captures the ship’s geometry in 3D (x,y,z planes) according to their respective location or stations, as illustrated in Figure 4. This provides a simple yet direct representation of the ship geometry and helps to reduce the occurrence of infeasible designs (odd shape, unsmooth surface, etc.) generated during later parts of the optimisation process.



Station no. (stn)	0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10
Morphing parameter (t)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 4: Encoding scheme using real value chromosome (*t*=0)

Depending on the number of hull form available in the library, each vessel will be assigned different morphing parameters- e.g. 1st vessel (parent A) will be assigned morphing parameter *t*=0 and 2nd vessel (parent B) will be assigned *t*=1, 3rd vessel (parent C) will be assigned *t*=2 and so on. The advantage of this hybrid approach is we can include as many hull forms in order to increase the variety of shapes and hence increasing the search space to include more novel or optimal designs.

3.3 (b) Initialisation-Morphing

Since the beginning of shipbuilding and subsequent introduction of CAD, two-dimensional (2D) hull lines remains the most fundamental graphical representation of the ship's hull form. This is the starting point where experienced designers model and modify the hull design prior to hydrodynamic calculations. The advantages of using 2D hull lines are it is a simple means to represent the entire shape of the hull and it is relatively easy to modify the hull form by adjusting the lines. It also serves as a primary source of hull form data which are used for subsequent plan approval and construction. In this proposed HEAM approach, we apply morphing to i) provide encoding scheme using morphing parameters (t) to modify the shape of hull, ii) generate intermediate solutions from initial pool (parents) to form initial population and iii) combine 2 or more existing hull forms (parents) to generate new hull designs (child).

At this stage, morphing is applied to transform one hull shape to another, which will generate the 'intermediate' shapes in between the 2 'parents'. Using morphing equation:

$$M(t) = (1-t) \times R0 + t \times R1 \qquad (1)$$

Where $M(t)$ is the morphed shape, t is the morphing parameter, $R0$ denotes the source shape and $R1$ the target shape. From above equation, we can see when $t = 0$, $M(t)$ is also equal to 0 and hence the morphed shape is equivalent to source shape $R0$. Likewise, when $t = 1$, $M(t) = R1$ which is the target shape.

Using hull lines provided from the body plan of source and target vessels (parents), we can morph and generate large number of intermediate shapes (child) just by changing the morphing parameter (t). Other than using morphing for interpolation, morphing can also be used to 'extrapolate' between 2 hull lines. As an example, we take one hull lines each from sample ship A (source) and sample ship B (target) at station 0.5 in way of stern of both vessels. By applying morphing through interpolation and extrapolation using different morphing parameter (t), we are able to generate both interpolated and extrapolated curves as illustrated in Figure 5.

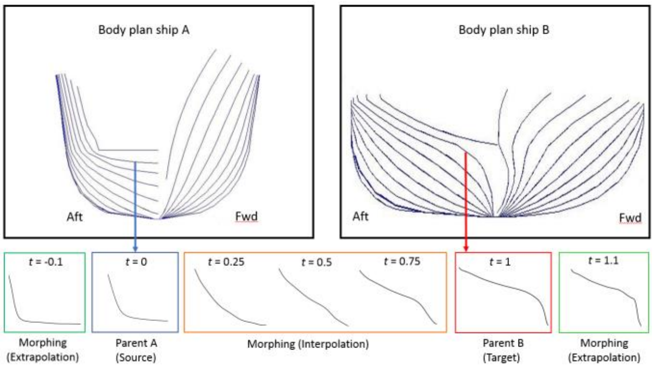


Figure 5: Morphing through interpolation and extrapolation at station 0.5

Using the same principle, we can effectively morph and create many intermittent forms between parent A and parent B by applying constant morphing parameter (t) across all transverse frame or stations. At this stage, we use morphing to create new individuals (child) which will form the initial population. This helps to increase the initial population size in the case of limited hull form in the library and allows the creation of more initial solutions prior the optimisation procedure.

3.3 (c) Evaluation- Fitness Function

The next step is to assign fitness function to each individual by evaluating the performance of each hull form designs based on objective function. In hull form optimisation, this can be reducing of hull resistance or ship's motions. For both objectives, the goal is to minimise the cost functions as follow:

$$\text{Min } f(\chi), \qquad \chi \in X \qquad (2)$$

Where f is the vector of design objectives, χ is vector of design variables and X is the feasible design variable space.

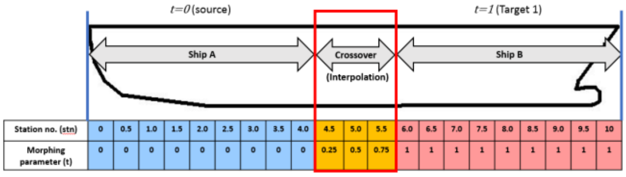
At this stage, we will translate the hull geometry from 2D coordinates to three-dimensional (3-D) surfaces by mapping the offset table into hull lines and surfaces using surface design tool such as NAPA. The 3-D surfaces can then be panelised or meshed and evaluated using CFD analysis. For this HEAM approach, we proposed that the hydrodynamic performance of all candidate design solutions should be assessed using low-fidelity CFD simulation such as potential flow for resistance analysis. This is in consideration of the large number of candidate design solution to be evaluated and potential flow method is usually preferred due to its efficiency and fairly good estimation for early ship design. High-fidelity CFD simulation such as Reynolds Averaged Navier-Strokes Equation (RANSE) can then be applied at final design stage to validate the design.

3.3 (d) Selection- Fitness Ranking

In GA, selection is a process of selecting which solutions will be used in crossover for generating new solutions. The principle is to always select the good solutions in order to increase the chance to obtain better individuals. Generally, there are 3 types of selection strategies- i) rank selection, ii) roulette wheel selection and iii) elitist selection. Rank selection assigns numerical ranking of each individual in the population based on their fitness, roulette wheel mechanism probabilistically selects individuals based on their performance and elitist selection pre-select the best candidates and retain them for next population. For proposed HEAM approach, we use rank selection based on the fitness level of each individual evaluated. This is done by ranking each candidate based on their fitness value and individual that are assessed to be highly ‘fit’ with relate to entire population from the evaluation process are selected for next round of reproduction.

3.3 (e) Reproduction- Crossover

Crossover is a very useful operator in GA where it combines two chromosomes (parents) to form new chromosome (child). Principle of this operator is to create new individuals by mixing the good genes of their parents and subsequently leads to fitter individuals. At this stage, we apply morphing as the main driver within crossover process to combine 2 or more existing hull forms (parents) to generate new hull designs (child). This can be achieved by setting varying morphing parameter (t) at different transverse curve along the stations or frame lines (x-planes), illustrated in Figure 6 below.



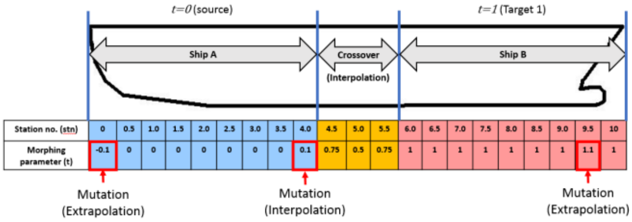
Station no. (stn)	0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10
Morphing parameter (t)	0	0	0	0	0	0	0	0	0	0.25	0.5	0.75	1	1	1	1	1	1	1	1	1

Figure 6: Cross-over through combination of ship A aft body and ship B forward body

The aim here is to create as many variation and possible combination of hull form designs so as to increase the solution space. On top of morphing 2 hull forms together into one hull concept, morphing can also be applied by joining multiple hull forms at different locations by changing the morphing parameters (t) at desired stations.

3.3 (f) Reproduction- Mutation

Mutation is a process in GA where new genes are created in random to produce a new genetic structure, which helps to introduce new elements into the population. In this proposed HEAM approach, we alter the morphing parameter at random stations through interpolation or extrapolation to create a new solutions (chromosome) illustrated in Figure 7 below.



Station no. (stn)	0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10
Morphing parameter (t)	-0.1	0	0	0	0	0	0	0	0.1	0.75	0.5	0.75	1	1	1	1	1	1	1	1.1	1

Figure 7: Mutation at random locations through morphing (interpolation or extrapolation)

As demonstrated above, there are many possibilities to ‘inject’ new elements into the chromosome just by changing the morphing parameters (*t*) randomly through interpolation or extrapolation. Other than introducing new elements, another key advantage using this method is the morphed shape are mostly feasible and hence helps to increase the overall shape modification and search efficiency of GA.

3.3 (g) Termination Criterion and Solution Set

Once all solutions are ranked and termination conditions are met, the iteration will stop and provide the results identifying the non-dominated solutions or Pareto optimum designs. It is now up to the designer to choose the final design, which will best meet the customer’s requirement. In this proposed HEAM approach, the termination condition can be set based on total number of iterations or terminate if there are no further improvement after 10 iterations. Ultimately, it depends on the designer requirement as to how much time are available or number of initial hull form in the library.

As highlighted earlier, we also propose to include a high-fidelity validation process such as RANSE method after termination and attainment of a range of Pareto optimum hull designs. This is to ensure the optimum hull form obtained from the optimisation process is truly ‘optimal’ and it also provides an additional reference for the designer when deciding on the final hull form design. It is useful to note while RANSE is a highly accurate CFD method used for ship evaluation within the marine industry, it is highly computation expensive and mostly suited at latter part of design stage where only a few narrowed down designs are required to be evaluated.

4. RESULTS AND FUTURE WORKS

To demonstrate the feasibility of our proposed HEAM approach, we performed a case study to develop an optimised hull form for a container vessel with objective to minimise forward resistance.

4.1 INITIALISATION USING MORPHING TECHNIQUE

Firstly, we selected 2 container vessels and 1 oil tanker vessel to form the 1st pool of individuals. The principle dimensions for 3 vessels are provided as follows:

	Container vessel A	**Container vessel B**	**Tanker vessel C**
Length between perpendiculars (LBP)	202.1m	185m	314m
Breath (B)	32.2m	32m	58m
Draft (T)	10.5m	9m	9m
Design speed	20 knots	20 knots	16 knots

Table 1: Principle dimensions

Using the three parent vessels selected, we performed morphing (interpolation) to generate several new intermediate solutions in order to form the initial population. The generated designs are provided in Figure 8.

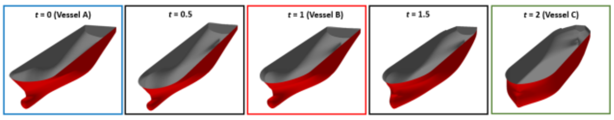
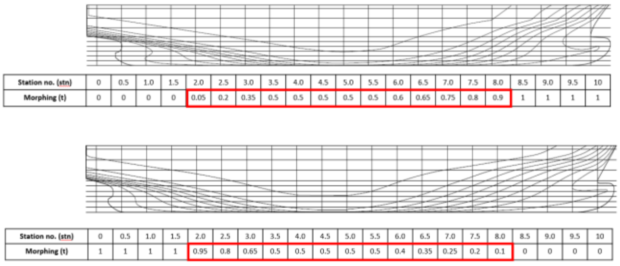


Figure 8: Isometric view of parent A, B and C hull surfaces and intermediate hull designs created using morphing (interpolation) method

With the initial population formed, the designs are evaluated and those solutions which are deemed to be fit are selected for next stage of reproduction. In this study, we evaluate the performance of each candidate design using potential flow method in NAPA program and it takes less than 5 minutes to evaluate one hull form design using standard quad core workstation.

4.2 CROSSOVER AND MUTATION

In this example, we performed crossover and mutation for vessel A and vessel B which provide the best performance before any modification. Firstly, we combined the stern area of vessel A to forward area of vessel B and then vice versa for the 2nd combination. The profile view of the combined vessel and shorten version of crossover encoding scheme are provided in Figure 9 as below.

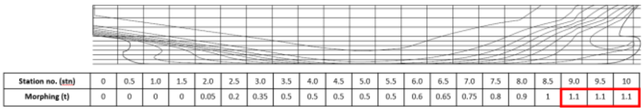


Station no. (stn)	0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10
Morphing (t)	0	0	0	0	0.05	0.2	0.35	0.5	0.5	0.5	0.5	0.5	0.6	0.65	0.75	0.8	0.9	1	1	1	1

Station no. (stn)	0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10
Morphing (t)	1	1	1	1	0.95	0.8	0.65	0.5	0.5	0.5	0.5	0.5	0.4	0.35	0.25	0.2	0.1	0	0	0	0

Figure 9: Crossover procedure at midship between (top) vessel A aft- vessel B forward and (bottom) vessel B aft and vessel A forward

For mutation, we selected one of the station lines (at station 10) and performed morphing (extrapolation) to inject new element into the design, illustrated in Figure 10 below.



Station no. (stn)	0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10
Morphing (t)	0	0	0	0	0.05	0.2	0.35	0.5	0.5	0.5	0.5	0.5	0.6	0.65	0.75	0.8	0.9	1	1.1	1.1	1.1

Figure 10: Mutation via morphing (extrapolation) at station 9-10

In actual mutation process, one should note that this modification can be carried randomly within GA to allow more unique combination and increase overall solution space.

4.3 PRELIMINARY RESULTS

From the hull forms generated, we evaluated the fitness level of each solution and obtained the following results.

ID	**Type**	**Length**	**Breath**	**Draft**	**Total pressure resistance (kN)**	**Forward pressure resistance coefficient (E-3)**
1	Vessel A (*t*=0)	202.1	32.2	10.5	251.635	0.027
2	Morphed (*t*=0.25)	197.82	32.15	10.125	179	0.034
3	Morphed (*t*=0.5)	193.55	32.1	9.75	149.1285	0.021
4	Morphed (*t*=0.75)	189.27	32.05	9.375	119.257	0.008
5	Vessel B (*t*=1)	185	32	9	80	0.007
6	Morphed (*t*=1.5)	249.5	32	9	2222.952	0.281
7	Vessel C (*t*=2)	314	58	9	3047.202	0.42
8	Crossover (A aft and B fwd)	185	32	9	136.455	0.017
9	Crossover (B aft and A forward)	213	32	9	163.761	0.017
10	Mutation (A aft and B forward)	183.29	32.2	9	76.828	0.003

Table 2: Principal dimensions and results of candidate solutions obtained from NAPA

From above preliminary results, we observed some improvements in performance as compared to the three initial vessels or parents. Taking solution ID 10, where we performed crossover of vessel A (aft) and vessel B (forward) and mutate through extrapolation, there was an overall improvement of 69% for vessel A and 3% for vessel B in terms of total resistance pressure. To further verify the results, we plot out the wave profile for both vessel A and vessel B against solution ID 10 in Figure 11 as below. It is noted the overall wave generated had reduced especially around the forward area of the vessel.

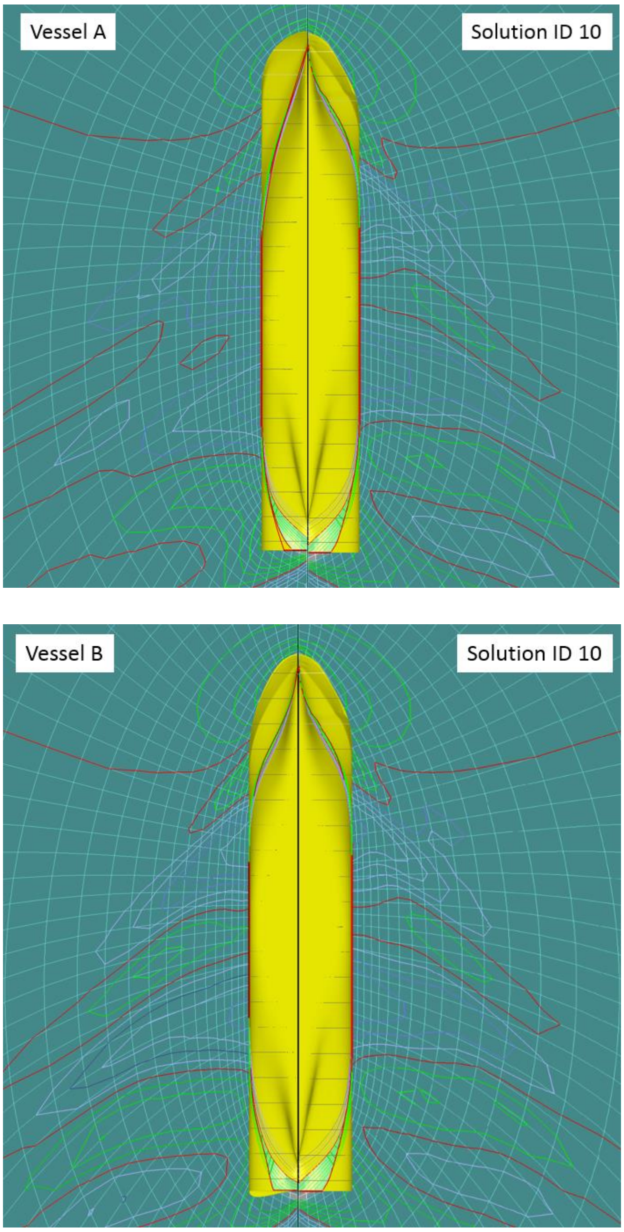


Figure 11: Wave profile comparing (top) vessel A-solution ID 10 and (bottom) vessel B- ID 10

4.4 DISCUSSION AND FUTURE WORKS

By comparing the preliminary results obtained using just a few solutions created using the proposed HEAM approach, we can see the potential of this method- the ability to create large number of feasible solutions in a highly efficient manner. We demonstrated through this case study by coupling up GA and morphing, this creates many possibilities to generate innovative hull forms especially when more parent hull forms are available. As the results shown here are only parts of our ongoing work, the full functionality of proposed HEAM approach and more case studies will be featured in subsequent publications.

The HEAM concept put forth in this paper provides a simple, yet promising solution to hull form design optimisation. Through morphing, it effectively transforms the shape of a hull and can generate a variety of different hull forms. It is also demonstrated through this paper that morphing can be used for both interpolation and extrapolation of the curve just by changing the morphing parameters (*t*). By coupling morphing parameter (*t*) into encoding scheme of GA, we utilise GA operators- crossover and mutation function to ‘combine’ and ‘create’ new solutions which helps increase the search space and producing more optimal hull forms.

By connecting this approach to smart design under i4, we can potentially link up this intelligent automated design process with smart manufacturing and smart product as part of product life cycle management. Through digital twin and computational intelligence, actual ship performance data or designer’s experience can be effectively captured to automatically validate and improve the hull designs.

5. CONCLUSION

Hull form design and optimisation is an important topic in shipbuilding industry due to its ability to reduce emission and fuel consumption of vessels. Traditional method using trial-and-error to improve hull form design is not effective and efficient. While SBD can be used improve the efficiency of the design process, they are not widely adopted due to the lack of systematic shape modification and robust optimisation techniques. It is also highly dependent on designers’ experience. With the introduction of industry 4.0 and digital twin concept, we can now link up entire ship design, manufacture and operation process into one connected product lifecycle. The solution put forward in this paper details a hybrid evolutionary algorithm and morphing approach that address the above issues and trends to make design process smarter. This is achieved by combining GA and morphing to modify the shape of the hull and allow more efficient search within the solution space. Morphing through interpolation and extrapolation are applied into crossover and mutation process to create new and more efficient hull form designs. A case study is applied to optimise the hull form of container vessel and the effectiveness of this approach is demonstrated with some preliminary results. We envisioned this proposed HEAM approach can transform the hull form design and optimisation process to create more innovative and efficient hull form designs.

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7. REFERENCES

1. ANG, J.H., GOH, C. AND LI, Y., 'Hull form design optimisation for improved efficiency and hydrodynamic performance of ship-shaped offshore vessels', *International Conference on Computer Applications in Shipbuilding*, 2015.

2. PARK, J.H., CHOI J.E. AND CHUN, H.H., 'Hull-form optimization of KSUEZMAX to enhance resistance performance', *Int. J. Nav. Archit. Ocean Eng*, 2015.

3. YANG, C. AND HUANG, F.X., 'An overview of simulation-based hydrodynamic design of ship hull forms', *Journal of Hydrodynamics*, 2016.

4. BERRINI, E., ET AL., 'Geometric model for automated multi-objective optimization of foils', *International Conference on Computational Methods in Marine Engineering*, 2017.

5 KAGERMANN, H., WAHLSTER, W. AND HELBIG, J., 'Recommendations for Implementing the Strategic Initiative INDUSTRIE 4.0', *Acatech National Academy of Science and Engineering*, 2013.

6. MARIO, H., TOBIAS, P. AND BORIS, O., 'Design Principles for Industrie 4.0 Scenarios: A Literature Review', *Technical University of Dortmund*, 2015.

7. ANG, J.H., GOH, C., SALDIVAR, A.A. AND LI, Y., 'Energy-Efficient Through-Life Smart Design, Manufacturing and Operation of Ships in an Industry 4.0 Environment', *Energies*, 2017.

8. BAGHERI, H. AND H. GHASSEMI, 'Optimization of Wigley Hull Form in order to Ensure the Objective Functions of the Seakeeping Performance', *J. Marine Sci. Appl.*, 2014.

9. TAHARA, Y., ET AL., 'Development of CAD_CFD optimizer integrated hull form design system', *J. Kansai Soc*, 2003.

10. JACQUIN, E., ET AL, 'Hull form optimisation using free surface RANSE solver', *Symposium on naval hydrodynamics*, 2004.

11. BAIWEI, F., ET AL., 'Ship resistance performance optimization design based on CAD_CFD', *International Conference on Advanced Computer Control*, 2011.

12. KIM, H., 'Multi-Objective Optimization for Ship Hull Form Design', *George Mason University, Computational and Data Sciences Department*, 2012.

13. KANG, J.Y.; LEE, B.S., 'Mesh-based morphing method for raid hull form generation', *Computer-Aided Design*, 2010.

14. BAIWEI, F. ET AL (2011), 'Ship resistance performance optimization design based on CAD_CFD', *International Conference on Advanced Computer Control*, 2011.

15. ANG, J.H., GOH, C. AND LI, Y., 'Hybrid Evolutionary Shape Manipulation for Efficient Hull Form Design Optimisation', *Conference on Computer Applications and Information Technology in the Maritime Industries*, 2016.

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