Smart Design of Hull Forms Through Hybrid Evolutionary Algorithm and Morphing Approach

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ABSTRACT: Digitalisation of ship design, construction and operation are gaining increasing attention in the marine industry as ships become eco-friendlier and smarter. 'Smart designs' can be applied under this digital revolution as an intelligent design process that is highly automated and collaborative with 'smart manufacturing' and 'smart ships' through-life. Focusing on smart design, we introduce a hybrid evolutionary algorithm and morphing (HEAM) approach which combines an evolutionary algorithm with an efficient morphing-based shape variation approach to optimise and automate the hull form design process. By combining the process of design exploration, geometry modification and performance evaluation, it enables highly automated design process where new hull forms are created, compared and analysed so as to reduce the overall design cycle and produce more optimal designs. This paper a) introduces a framework on how smart design process can be connected with smart manufacturing and smart ships to form into through-life smart shipping network, b) describes the proposed HEAM approach to optimise and automate the hull form design process and c) provides result of the HEAM approach to demonstrate the design efficiency and performance improvement.

1 INTRODUCTION

In the face of stiff competition, cost reduction and globalisation, marine industry today requires a quantum leap in the entire process of ship design, construction and operations to keep abreast and differentiate itself in the marketplace that is fast moving towards digital technologies. With the arrival of Industry 4.0 and artificial intelligence 2.0, digitalisation of ship design, construction and operation are gaining increasing attention in the marine industry as ships become eco-friendlier and smarter. However, the emphasis of 'smart' design has been lacking in comparison to 'smart' manufacturing and a 'smart' ship. In particular, how can we further automate the ship design process and integrate with smart manufacturing and smart ship considering the entire ship lifecycle? With industry 4.0, manufacturing is now moving towards more intelligent system or machineries that are highly connected. In the context of shipping, vessels are also becoming smarter with more automated systems and begun to move towards unmanned or fully autonomous vessel, with the world's first autonomous container feeder vessel YARA birkeland to be launched in 2018. Smart design is hereby proposed as an intelligent design process that is highly automated and collaborates closely with smart manufacturing and smart ships throughout the entire product lifecycle. By connecting up smart design with smart manufacturing and smart ships, important information can be shared seamlessly across entire lifecycle of a ship and becomes a fully integrated through-life smart shipping network.

As marine industry moves towards eco-friendlier and energy-efficient ships, the design and optimisation of hull forms continue to play an important role to help reduce fuel consumption and carbon dioxide emission. Traditional method of ship design and hull form optimisation requires many manhours by ship design firm and shipyards using the 'trial-and-error' approach, which is inefficient and does not guarantee optimum designs. While latest simulation based design methods and tools help to automate some of these processes, they still require considerable human input and success at end result depends heavily on the designer's experience and knowledge. Considering smart design, we introduce an innovative concept which aim to address the above issues by automating the hull form design process with minimum user interference and yet not compromising the quality of the results. This is achieved by combining evolutionary algorithm with efficient shape variation approach known as morphing and hereby proposed as hybrid evolutionary algorithm and morphing (HEAM) approach.

The focus of this paper is to introduce the concept of smart design as well as HEAM approach which possesses the potential to improve design efficiency and produce more optimal hull forms. Section 2 describes the concept of smart design which can link up smart manufacturing and smart ship operation process considering entire lifecycle. Section 3 proposes the HEAM approach which combines evolutionary algorithm with morphing to automate the hull form design and optimisation process. Section 4 provides the results of HEAM concept, followed by discussion and conclusion in section 5.

2 SMART DESIGN OF SHIP AND HULL FORM

Hull form design and optimisation is an important topic in the marine industry due to more stringent environmental regulations and reduction of operation cost due to fuel consumption. An efficient hull form will help to reduce resistance acting on the vessel and thereby reducing fuel consumption and emission to the environment. As the marine industry moves toward digitalisation, it is essential to further automate the design process and connect up with other lifecycle processes to achieve fully automated smart design. An illustration of the various stages of hull form design developments are provided in Figure 1 as below.

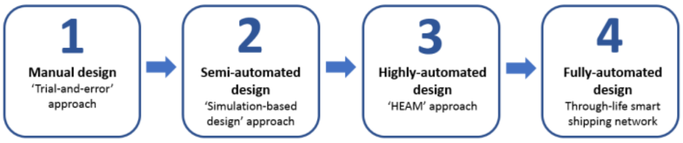

Figure 1. Development towards fully automated design process

From above figure, it started off with traditional method of hull form design which is based primary on 'trial-and-error' where ship designers create the initial hull form from scratch or modify from existing proven hull designs (stage 1). This manual method is extremely time consuming and only allows few design variation and testing. Since the introduction of computer into ship design, simulation-based design (SBD) approach became dominant as it accelerates the design process by semi-automating the shape variation and optimisation process and validating the performance using computational fluid dynamics (stage 2). While SBD method helps to automate some of the design process, they still require considerable human input and the result often depends heavily on the designer's experience and knowledge. This method is also isolated and does not usually consider external feedbacks such as manufacturing or ship operation. With the development of digitalisation and artificial intelligence, we can further automate the design process so as to reduce the iterative process and free up the designer's time for more critical task. This process is proposed under HEAM approach (stage 3) and will be covered in next section. Subsequently, the end goal is to fully automate the design process and connect up the entire product lifecycle process to also include ship construction and operation. This can be achieved via through-life smart shipping network (stage 4) which will be further elaborated below.

2.1 *Related works in simulation-based hull form design*

Simulation-based designs (SBD) are used widely for performing numerical optimisation and evaluation of hydrodynamic performance of the hull form. Most simulation-based hull form design optimisation consists of three key processes- firstly, (1) the hull shape is linked to a design exploration function to search systematically for optimal design. Next, (2) the geometry modification function will change the shape of the hull to create new designs. Following which, (3) the new shape generated will be evaluated on its performance function. This process will continue to iterate until the stopping criteria or most optimal hull design is achieved. An illustration of simulation based hull form design optimisation process is provided in Figure 2.

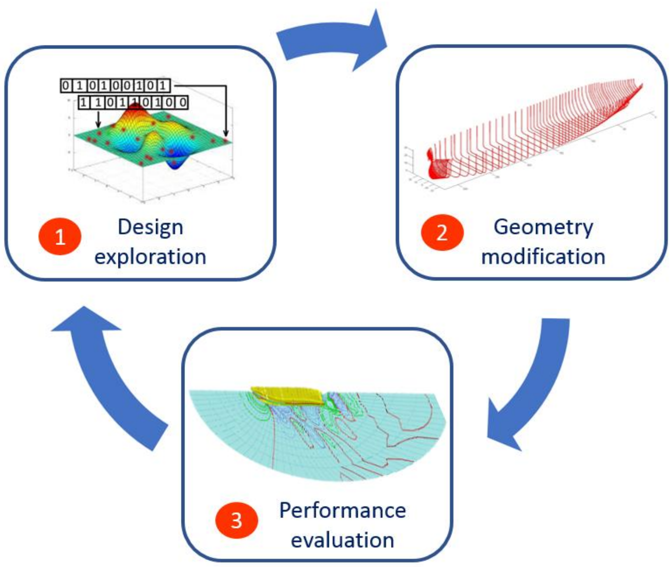

Figure 2. Simulation-based hull form design optimisation process

While the key steps or process are somewhat similar, there are many different methodologies that are applied in hull form optimisation. Design exploration, also known as optimiser, is a parametric optimisation process where key design parameters such as shapes of the hull are modified in an iterative loop to produce a set of optimal hull forms at the end of the optimisation process. Some recent examples of design exploration methods applied to hull form optimisation include Simplex of Nelder and Mead (Jacquin et al. 2004, Kostas et al. 2014), Sequential quadratic programming (Park et al. 2015, Berrini et al. 2017) and evolutionary algorithm such as genetic algorithm (Baiwei et al. 2011, Kim 2012) and particle swarm optimisation (Tahara et al. 2011, Xi Chen et al. 2014).

Geometry modification plays an important role in ensuring the hull shape can be easily manipulated to form new shapes in order for the optimiser to investigate and evaluate. The key challenge here is to ensure every new shape generated must be smooth and of feasible design. There are 2 main approaches used to modify hull geometry- direct modification and systematic variation. Direct modification changes the hull geometry by adjusting the hull coordinates manually using control points through curve or surface representations. While this method is highly flexible, it requires large number of control points to represent the shape and hence not very efficient for modifying the entire hull shape. Examples of direct modification includes Beizer curve, non-uniform rational basis spline (NURBS) and T-splines (Kostas et al. 2014). On the other hand, systematic variation modifies the hull shape using a function which considers global hull parameters (e.g. block coefficient, Cb) or series of local hull representation. This method is particularly useful for global modification which enables the entire hull form to be transformed more efficiently. However, shape changes are somehow more restricted and not very flexible as compared to direct modifications. Some recent examples of systematic variation methods applied in hull form optimisation include parametric modification (Saha & Sarker 2010, Brizzolara & Vernengo 2011) and free-form deformation (Campana et al. 2013).

Performance evaluation assess each candidate solution produced from the optimiser based on the objective function. The most important performance parameters that are influenced by shape of the hull include resistance and sea-keeping behavior and hence selected as key objective functions in most hull form design optimisation applications. For evaluation of resistance, Computational fluid dynamic (CFD) are used extensively in hull form optimisation which had been proven as an effective means to simulate the fluid flow around vessel. Examples of CFD methods used for resistance evaluation include potential flow (Nowacki 1996) and Reynolds Averaged Navier-Strokes Equation- RANSE (Tahara et al. 2006, Zha et al. 2014). For sea-keeping analysis, there are several numerical methods which include strip theory, unified theory, green function method, etc. (Bertram 2000).

2.2 *Related works in smart design, construction and operation*

With the development of digitisation and big data, it enables ships to become more connected and smarter. However, most ship lifecycle process now are rarely connected in reality. To illustrate this, we can look at the lifecycle and key milestone of a typical ship's lifetime as provided in Figure 3 below.

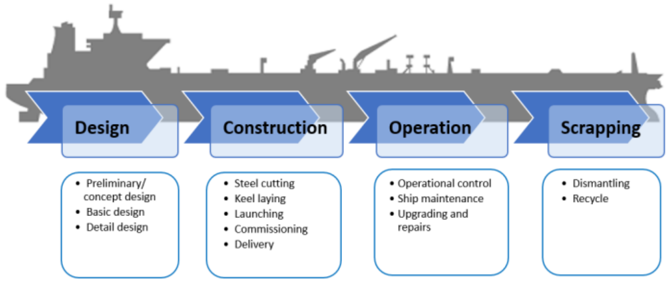

Figure 3. Typical ship life-cycle and key processes

From above figure, while the life-cycle processes are progressive and closely linked, information are not transferred interchangeably from one process to the other. As an example, once shipbuilder completes construction and ship owner takes over ownership of the vessel, they do not share operational information back to the shipbuilder which are useful for them to monitor the actual performance and use the information to improve on its subsequent designs. As such, it should be recognised that full digitalisation of ship life-cycle cannot be realised without elevating each process into more connected and automated process which considers the entire value chain.

Considering life-cycle for ships, we look at how these key processes can be elevated into smart design, construction and operation. Smart designs are relatively new concept and not explored widely in particular ships or hull form design. It can be defined as an intelligent design process which is highly automated and ability to collaborates closely with smart manufacturing and smart ship or operation throughout the entire lifecycle. Some early works on smart design by authors include (Ang et al. 2017a). Other smart design application related to ship includes smart ship system design for electric ships (Chalfant et al. 2017).

Smart construction or manufacturing is currently a high interest topic that is being driven under the advent of industry 4.0 (i4). I4, also known as forth industrial revolution, aims to merge the real and physical space through cyber-physical system. It provides a platform to transform traditional segregated manufacturing process into fully connected manufacturing system. Basic components and enabling technologies of i4 includes internet of things, collaborative robots, cybersecurity, cloud computing, additive manufacturing and big data analytics. I4 or smart factory concept are increasingly adopted and implemented in high tech manufacturing and aviation industry. There are currently very few applications of i4 in shipbuilding. One recent work done is a study of smart pipe system for shipyard (Paula et al. 2016).

Smart operation or commonly known as smart ships is increasingly in demand as ship builders aims to build more efficient and smarter vessels. Smart ships can be defined as vessels that are highly connected through the use of big data for real time monitoring and controls so as to enhance operation performance. Smart ships are driven with promises to reduce operation cost and improve safety and believed to revolutionise ship design and operation. There are several works done recently on smart ship which includes one that considers the design of control of power and propulsion system for smart ship (Geertsma et al. 2017) and another that consider smart ships in general (Jan 2017). Smart scrapping or decommissioning of ships are not considered here due to its short duration comparing entire lifecycle but might be worth to look into in future works.

2.3 *Through-life smart shipping network*

As mentioned in the beginning, the emphasis of smart design has been lacking in comparison to smart manufacturing and smart products. In particular, how is smart design going to integrate with smart manufacturing and smart product when considering entire product lifecycle? One promising solution is a framework that connects and creates a feedback loop to link up smart manufacturing and smart product to smart design. By connecting up smart design with digital manufacturing and smart operations into a unified digital model, important information can be shared seamlessly across entire product lifecycle of a ship and becomes a fully integrated through-life smart shipping network, as introduced in (Ang et al. 2017a) and illustrated in Figure 4.

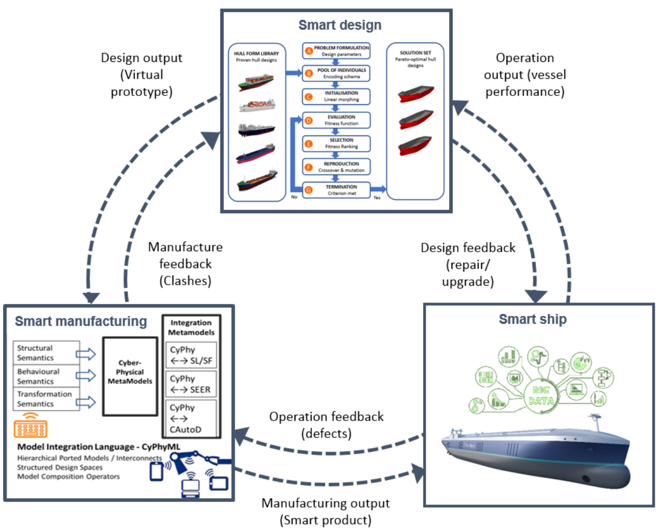

Figure 4. Through-life smart shipping network

By closing the loop between ship operation and design through smart product, useful through-life data such as ship operating environment and actual performances can be collected, analysed and feedback into smart design process for producing more optimum future designs. In addition, smart design can be further enhanced by combining design automation process and digital product model under i4. By linking digital product model into the automated design process, we can provide an automated feedback loop from smart product back to design to improve the design performance of future vessels.

3 HYBRID EVOLUTIONARY ALGORITHM AND MORPHING APPROACH

Considering the issue in current simulation based hull form optimisation with respect to the lack of efficient shape manipulation and robust optimisation techniques to automate the hull form design process and goal to elevate to smart design, a hybrid evolutionary algorithm and morphing (HEAM) approach was proposed by authors in (Ang et al. 2017b). The proposed methodology integrates evolutionary algorithm and curve morphing to automate the hull form design optimisation and elevate into smart design.

3.1 *Evolutionary algorithm*

Evolutionary algorithms (EA) are a group of generic population-based meta-heuristic optimisation techniques that are widely used in many different applications due to its ability to solve complex problems and produce a set of globally optimal solutions. Among various EA methodologies, one of key methods used in hull form optimisation is genetic algorithm (GA). GA was first developed by (Holland 1975), which is a nature-inspired search heuristic method based on Darwinian Theory of natural selection and the 'survival-of-the-fittest' principle. GA works on the principle of 'genes' and 'chromosomes' as illustrated in Figure 5.

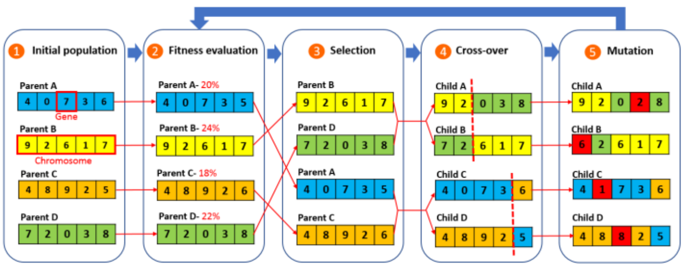

Figure 5. Genetic algorithm working principle

Through the use of genetic operators namely selection, crossover and mutation, information represented by genes are exchange between these chromosomes over a number of iteration, typically with the fittest solutions replacing the weaker ones and eventually leading to a set of optimal solutions. The key feature of using GA for hull form optimisation is the ability to generate many new hull design combinations, search very huge solution space and subsequently narrow down to a few optimal designs.

3.2 *Curve morphing*

Metamorphosis, also known as morphing, is a technique used widely in the animation industry to generate a sequence of images that smoothly transform a source to another target image. It is also applied in computer graphic and industrial design to compute a continuous transformation from a source to another target shape. Morphing can be a very useful tool for the designer to modify, manipulate, transform the shape or geometry of the design in pursuit to improve the design attributes such as performance, quality, aesthetic, etc. Morphing can be catergorised into 2 main types- two-dimensional (2D) or three dimensional (3D). 2D morphing consist of image morphing and curve morphing and 3D morphing include surface morphing and volume morphing. In ship application, (Tahara et al., 2006) applied morphing using 3D patch model from NAPA to transform a ship hull model into another target model. (Kang & Lee 2010) applied 3D mesh-based surface morphing to generate intermediate hull models between two parent vessels.

Since the beginning of shipbuilding and subsequent introduction of computer-aided design (CAD), 2D offset table remains the most fundamental representation of ship's hull form. Hence until today, it is still used as the basis for designer to model and modify the hull design. The advantage of using 2D hull lines from offset table are it is simple to represent the entire shape of the hull and easy to modify the hull form by adjusting the lines. In this paper, we apply curve morphing based on 2D hull lines to transform the shape of hull through interpolation and extrapolation between the hull lines of two or more hull forms.

Using morphing equation:

$$M(t) = (1 - t) \times R_0 + t \times R_1 \quad (1)$$

where *M(t)* is the morphed shape, *t* is the morphing parameter, R_0 denotes the source shape and R_1 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 R_0. Likewise, when $t = 1$, $M(t) = R_1$ which is the target shape. To illustrate the concept, by using hull lines provided from the body plan of source and target vessels, we can morph and generate large number of intermediate shapes just by changing the morphing parameter *(t)*. Other than interpolating between the source and target vessel, we can also extrapolate beyond the 2 hull lines to create new 'extended' lines. As an example, we take one hull line each from ship A (source) and ship B (target) at station 0.5 for both vessels. By applying curve morphing equation, we can generate interpolated and extrapolated curves as illustration in Figure 6.

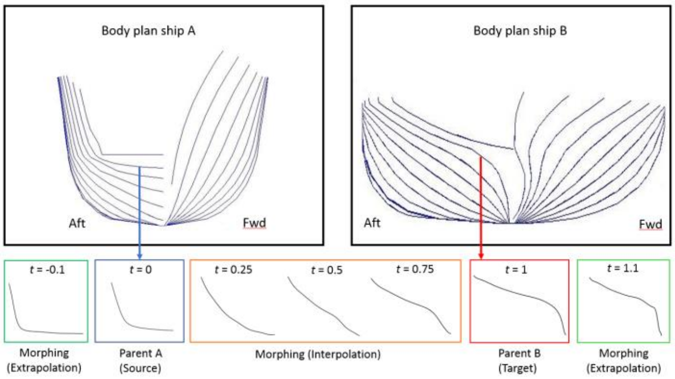

Figure 6. Curve morphing through interpolation and extrapolation at station 0.5

It can observe by applying only one morphing parameter *(t)* constantly across all transverse stations, we can effectively morph or create the entire hull form between the source and target vessels. Key feature of this curve morphing approach is the ability to capture complex shapes such as hull form using minimal design variables, which in this case is represented by morphing parameters *(t)*.

3.3 *Hybrid evolutionary algorithm and morphing approach (HEAM)*

By combining the advantages of GA- ability to search for 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 now potentially create a wide range of hull form designs with improved efficiency and thereby finding the most optimal hull form. An overview of the proposed HEAM concept is provided in Figure 7.

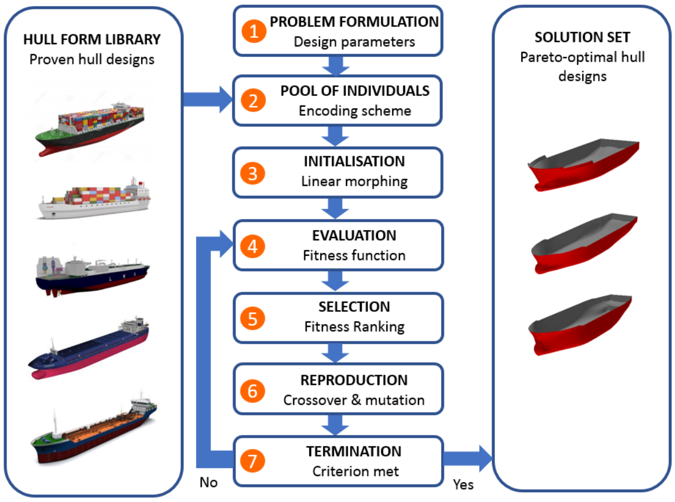

Figure 7. Hybrid evolutionary algorithm and morphing approach

The HEAM concept comprises 7 main components, namely (a) problem formulation, (b) pool of individuals, (c) initialisation, (d) evaluation, (e) selection, (f) reproduction and (g) termination.

3.3.1 *Problem formulation*

Before any optimisation process, it is important to first specify the design parameters which include ship type, principle dimensions as well as objective functions. Depending on the number of existing hull designs in hull form library, they can be catergorised by different ship types and selected to form the initial hull designs based on the design requirement. Principle dimensions such as length between perpendiculars (Lpp), beam (B), draft (T) would need to be specified as per design requirement. In this HEAM approach, we can scale up or down the existing vessels from hull form library to meet the design requirement by applying linear transformation to modify the hull form according to desired length, beam and draft. Depending on vessel type, objective functions relating to hull form optimisation may include reducing resistance and seakeeping motion for vessels.

3.3.2 *Pool of individuals*

The next step of HEAM is to create the first pool of individuals and map them into unique encoding scheme. In ship design process, this can be obtained from existing hull forms from the hull form library or create from scratch. The advantage of using existing designs is the assurance of their performance which are validated to meet design objective and helps to shorten the design cycle, although the improvements are often incremental. Another alternative is to model a new hull form from scratch which will allow more freedom of design thereby allowing the creation for more innovative hull form designs. For the proposed HEAM approach, real-value chromosomes using morphing parameters *(t)* which captures the ship's geometry in X and Y planes according to their respective frame or stations across Z planes, as illustrated in Figure 8. This provides a simple yet direct representation of the ship geometry which allows the hull shape to be transformed easily by changing the morphing parameters *(t)* at various station locations along the entire vessel.

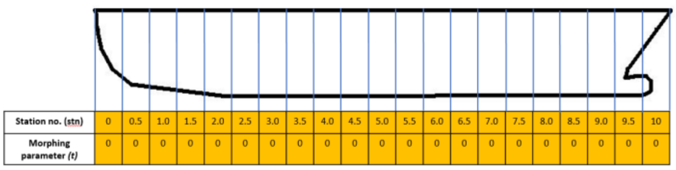

Figure 8. Encoding scheme using real value chromosome *(t=0)*

For initial population, first vessel model (parent A) will be assigned morphing parameter *t=0* and second vessel model (parent B) will be assign *t=1*. More vessel models can be included using same arrangement to increase the variety of shapes and hence increasing the search space to achieve more optimal designs.

Under this HEAM approach, we introduce three applications of curve morphing by incorporating into above encoding scheme- i) constant morphing, ii) linear morphing and iii) varying morphing. Constant morphing is applied to morph the entire hull form using same morphing parameters within the encoding scheme. For example, by applying the same morphing parameters *(t)* across the entire length of vessel, we can generate large number of intermittent designs as demonstrated in Figure 9.

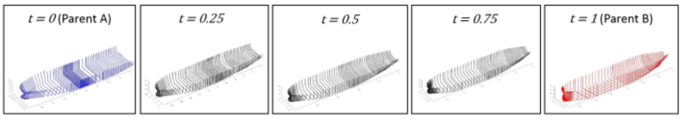

Figure 9. Two parent vessels and intermediate vessels created by parallel morphing

Other than interpolating between 2 parent vessels, we can also extrapolate beyond the parent vessels using morphing method to create more 'new' designs. Linear morphing is used during crossover and mutation function to smoothen the curve by applying gradual morphing parameters *(t)* between two parent models. Varying morphing is used when we combine both constant and linear morphing or when multiple vessel types are combined together.

3.3.3 *Initialisation*

Prior to morphing operation, we need to prepare the hull coordinates for all the parent vessels so as to ensure the hull form corresponds to each other. Considering no two offset tables are identical in terms of number of coordinate points, we perform correspondence so as to create same number of points across all section curve for the parent vessels which are to be morphed. This can be done using cubic spline interpolation to create additional points at different interval of the section curve. Cubic spline interpolation is a piecewise continuous curve which passes through each of the values in a table of points, which is represented in the following equation:

$$S_i(x) = a_i(x - x_i)^3 + b_i(x - x_i)^2 + c_i(x - x_i) + d_i \quad ; \quad \text{for } x \in [x_i, x_{i+1}] \qquad (2)$$

where *S(x)* denotes the spline and $[x_i, y_i]$ represents a table of points for $i=0,1,\ldots,n$ for function *y=f(x)*

As an example, section curve X=0 for vessel A contain 7 points and same curve for vessel B contain ten points in their respective offset tables. In order to morph the section curve at X=0 for both vessel A and B, we need to create ten equal points on section curve X=0 for both vessel using cubic spline interpolation, as per illustrated in Figure 10 below.

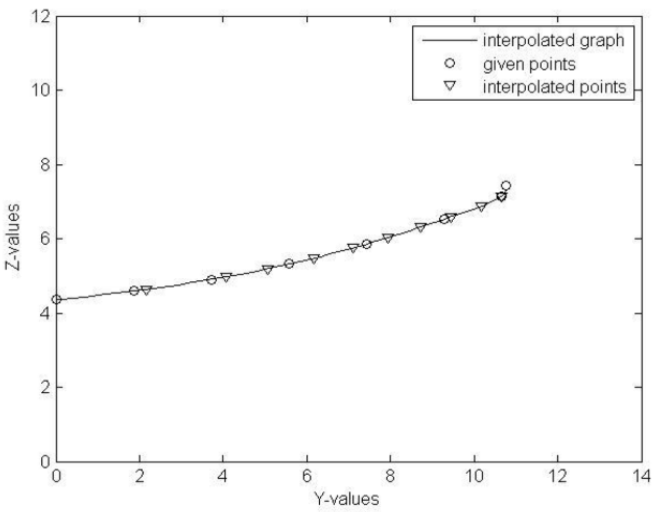

Figure 10. Curve correspondence using cubic spline interpolation

3.3.4 *Fitness evaluation*

In order to measure the 'fitness' of the parent vessels, we need to evaluate the performance of each hull form design based on the objective function. In most hull form optimisation, the objective function will be to reduce hull resistance and ship's motion. For both objectives, the aim is to minimise the cost function as follow:

$$Min\ f\,(\chi),\ \chi \in X \tag{3}$$

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 need to translate the 2D hull geometry into 3D surfaces by mapping the offset table into hull surfaces using surface generation method such as NURBS. The 3D surfaces will then be panelised and the resistance can be evaluated using numerical methods such as potential flow or Reynolds Averaged Navier-Strokes Equation (RANSE). For motion analysis, strip theory can be used which are available in most hydrodynamic analysis tools. Under this HEAM approach, we proposed the candidate design solutions should be assessed using low-fidelity CFD method potential flow for resistance analysis. This is in view of the large number of candidate solution to be evaluated and potential flow are preferred due to its efficiency and fairly good estimation during early ship design. High fidelity CFD method such as RANSE can be applied at later stage to validate the optimal design.

3.3.5 *Selection*

In GA, selection is a process of selecting which solution will be used in reproduction for generating new solutions. The principle is to always select the good solutions in order to increase the chance to obtain better individuals. For proposed HEAM approach, we apply roulette wheel selection which probalisatically selects individuals based on their performance for next round of reproduction.

3.3.6 *Reproduction- crossover and mutation*

Crossover is an important operator in GA where chromosomes of two parents are combined to form new chromosome of the child. Principle of this operator is to create new individuals by mixing the good genes of their parents and subsequently lead to fitter individuals. In this HEAM approach, we apply linear morphing to combine two or more existing hull form (parents) to generate new hull form designs (child) through interpolation to create smooth intermediate curves between the two parents, as illustrated in Figure 11 below.

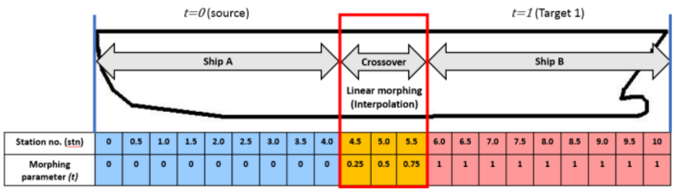

Figure 11. Crossover between ship A aft and ship B forward body through linear morphing (interpolation)

On top of morphing two different hull form together in one hull concept, we can also join multiple hull forms (three or more) using varying morphing by simply applying linear morphing at intermittent stations between different vessels. For combining vessels which are vastly different in term of sizes, rescaling through linear transformation can be applied to reduce or enlarge the hull form to match the other vessel.

Mutation is the next reproduction process within 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 HEAM approach, we apply linear morphing at random station through extrapolation to create the chromosome of new solutions as illustrated in Figure 12 below.

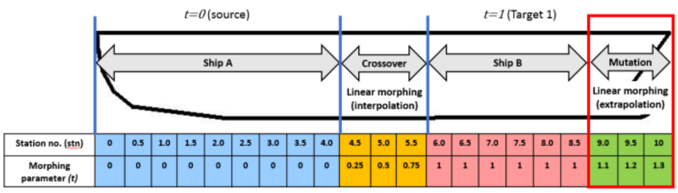

Figure 12. Mutation at random stations through linear morphing (extrapolation)

While mutation is entirely random in nature, linear morphing can help to reduce the possibility of infeasible designs such as unsmooth surface or odd shape generated during the optimisation process.

3.3.7 *Termination criterion and solution set*

Once all solution designs are ranked and termination condition are met, the iteration will stop and provide the results identifying the pareto optimum design. In this HEAM approach, the termination condition can be based on total number of iterations or terminate if there no further improvement after 10 iterations. Ultimately, the designer should decide the termination criterion based on number of initial designs available in hull form library and lead time for this initial design process.

4 RESULTS AND DISCUSSIONS

To demonstrate the flexibility and benefits of curve morphing and proposed HEAM approach, we performed two case studies to- i) optimise the hull form of container vessel using two parent models through constant and linear morphing and ii) 'split' and combine three different vessel types using varying morphing.

4.1 *Hull form optimisation of container vessel using HEAM approach*

In this first case study, we applied multi-objectives optimisation using HEAM approach to produce the hull form of a new container vessel using two existing vessels as initial designs. The design objective is to reduce total resistance and seakeeping motion of a container ship with principle dimension of 185m length between perpendicular (Lpp), 32m beam, 9m draft and design speed of 20 knots. The principle dimensions for two parent container vessels are provided as follow.

Table 1. Principle dimensions for two existing parent vessels.

Principle Dimensions	Container A	Container B
Lpp	185m	202.1m
Beam (B)	32m	32.2m
Draft (T)	9m	10.5m

From the two parent vessels selected, we applied correspondence to match the number of coordinate points and performed linear morphing (interpolation and extrapolation) to form the initial population. After creating the initial designs, the designs are evaluated based on their total pressure resistance and maximum heave response function. In this study, the performance of each candidate design is evaluated using potential flow method and strip theory in NAPA program and it took less than five minutes to evaluate one hull form design using standard quad core workstation. Prior to reproduction, we performed rescaling using linear transformation of parent vessel B to meet the design criteria set in this case study. The crossover and mutation points were then selected randomly through the HEAM program written in Matlab. This randomness helps to generate more novel candidate designs which may not been considered by the designer if carried out manually. The preliminary results of the hull form generated from HEAM program are provided as below.

Table 2. Principle dimensions and results of candidate solutions generated using HEAM program

Vessel	Lpp(m)	B(m)	T(m)	TP*(kN)	PR+(deg/m)
Parent A	185	32	9	75.72	1.0933
Parent B rescale	185	32	9	61.34	1.0788
Crossover	185	32	9	60.26	1.0744
Mutation	185	32	9	60.17	1.0672

* Total pressure resistance
\+ Maximum pitch response function

From the above results generated from first run of the HEAM program, we can already see some improvement for the new vessel (child) created from crossover and mutation process as compared to two existing parent vessels. In case of crossover process, linear morphing was applied by combining parent A (aft) and parent B rescaled (forward). The next step of HEAM approach is the mutation process where extreme forward of the vessel are mutated through extrapolation from parent A to parent B rescale using morphing parameter *(t)*=1.1 to generated the child vessel. As compared to parent vessel A and B (rescaled), child vessel achieves an improvement of 20.5% and 1.9% respectively in total resistance pressure. In terms of pitch motion, the child vessel obtained an improvement of 2.38% and 1.07% as compared to parent vessel A and B (rescaled) respectively. While the improvement is considered minor comparing stronger parent B (rescaled) and child vessel, it should be noted this result is generated based on only one run of the program. The potential of this method would be realised with more iterations of the HEAM program, which will be presented in our next study. The overall wave generated are compared between parent B (rescaled) and child vessel and illustrated in Figure 13 below.

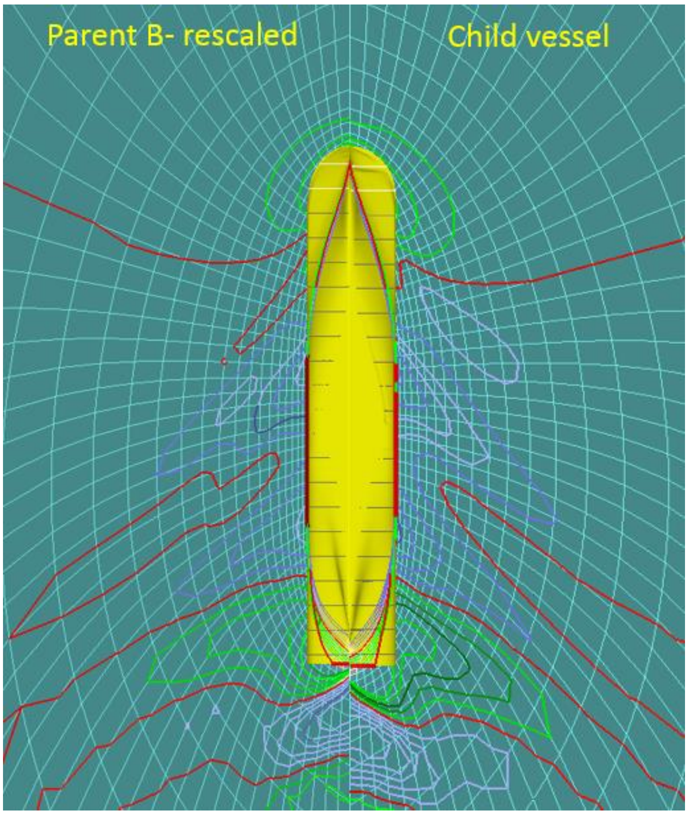

Figure 13. Wave profile comparing vessel parent B- rescaled and child vessel

4.2 *Combination of three different vessel types using two-point crossover and varying morphing*

In the next case study, we demonstrate here the possibility of combining three different vessel types into one hull form through two-points crossover and varying morphing. This unique feature allows the segregation of hull form into three main sections- stern section, mid-section and bow section, thereby enable the creation of more innovative hull form combination through mix-and-match process within the HEAM approach. Firstly, we select three different vessel types- a container vessel, one bulk carrier and an oil tanker. The principle dimensions for three vessels are provided as below

Table 3. Principle dimensions for three different types of sea-going vessels.

	Aft body	Mid-body	Forward body
Dimensions	Container	Bulk carrier	Oil Tanker
Lpp	202.1m	215m	314m
Beam (B)	32.2m	36m	58m
Draft (T)	10.5m	15m	20.92m

Next, we performed rescaling using linear transformation to resize the vessels to the same principle dimension, which is the same as oil tanker in this example. Following which, the three vessels are 'split' into three separate sections and 'join' together using multi-target morphing. The combined vessels are illustrated as below in Figure 14.

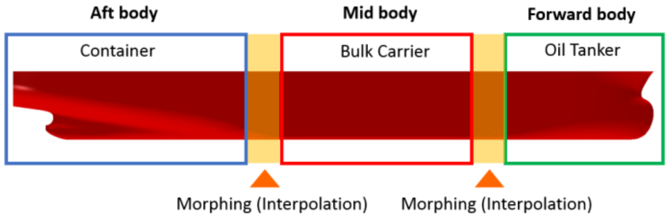

Figure 14a. Combination of three different vessel types using multi-target morphing

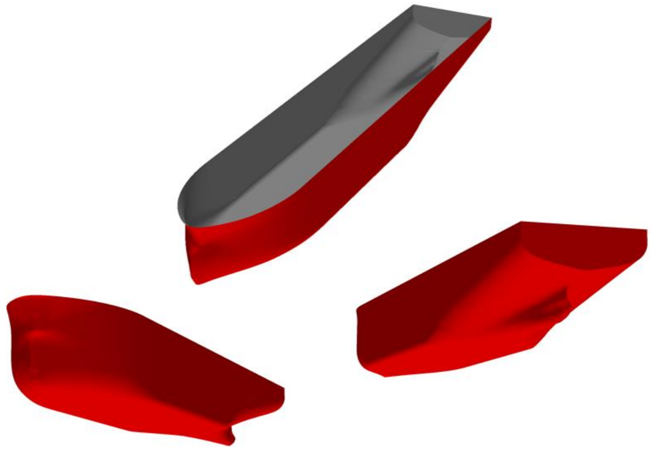

Figure 14b. Isometric view of 3 combined vessels

We can see from above example the versatility of two-points crossover and varying morphing methodology which can combine three very different vessels in terms of function and size. This is very useful when applied in HEAM program which can potential create many more different types of hull form combinations and more innovative designs. It is recognised one key limitation of using existing vessel design within this HEAM approach is the new designs are closely linked to the parent and lack of freedom to create more innovative designs. To overcome this limitation, designer can also select from existing vessels or create from scratch their own designs for HEAM to morph and generate new designs. For example, designer can choose between different design types of hull form in way of three main sections of the vessel- stern, mid and bow section as illustrated in Figure 15.

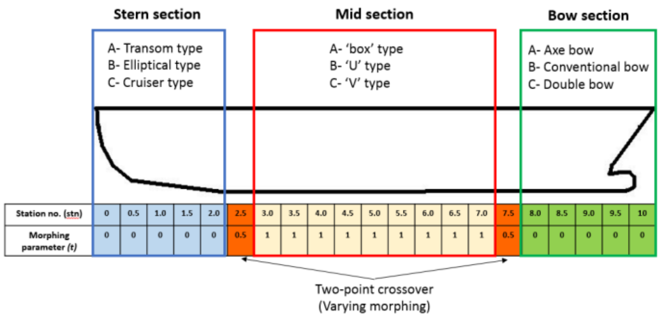

Figure 15. Possibility of mix-and-match of different designs using two-points crossover and varying morphing

Subjected to the availability of the different hull form designs in the hull form library, this varying moprhing function will help to increase the solution space and thereby provides another function within HEAM or additional ‘tool’ for designers to create more innovative hull form.

4.3 *Discussions*

As compared to existing hull form design process, there are several benefits of this HEAM approach. Firstly, it starts from a pool of existing proven hull forms designs as compared to improvement from only one ‘sister-ship’ hull designs, which enables the exploration of wider solution spaces and generating more optimal hull forms. Second, by performing morphing via interpolation and extrapolation between these proven designs, it enables automated geometry modification without any designer input. It should be noted the concept of HEAM approach is not to replace the role of designer but instead to supplement and provide as an additional tool for designer to examine a wide variety of existing hull form and narrow down to few optimal designs very quickly before working on the design further. Thirdly, by incorporating morphing parameter into encoding scheme within HEAM, we can effectively transform the entire hull shape with as little as one design variable- morphing parameter, *t*, thereby increasing the overall efficiency of geometry modification and optimisation process. Finally, HEAM allows ‘mix-and-match’ of hull forms through unique crossover and mutation functions which enables the creation of more innovative hull form. As demonstrated in the results section, this approach has the flexibility to combine 3 very different vessels whereby increasing the solution space for more optimal hull. It should be noted HEAM approach is not limited to only ship hull form. It can also be extended to other related design applications such as aerospace and automobile main body design.

In order to realise the full benefits of HEAM and to be applied to ship design process, there are still several issues that needs to be addressed and overcome. Firstly, it is widely known within the industry automating the hull form design process is already very challenging in its own sense. In fact, there are no known procedure or tools that are able to automatically translate hull coordinates to surface and meshing for evaluation. In this study, we are only able perform the translation from morphed points to surfaces manually using NAPA modeling software and feed the results back to HEAM program. Secondly, one can observe from second case study that the principle dimensions of the three vessels were adjusted drastically as the result of re-scaling in order for all the vessels to join together. Hence, this may not represent the actual hull form characteristic as compared to the original vessel. Thirdly, the full benefits of GA are best exploited in applications with huge data set or solution space. In our example, we are limited to only few hull forms due to manual surface modeling and CFD evaluation. Finally, while crossover function within GA helps to create new designs by combining the genes of two parent vessels, it is recognised the combination of two good genes might leads to creation of a bad gene with poorer performance. Nevertheless, more studies will be carried out on the above issues and we hope to address them in our subsequent publication.

5 CONCLUSION

In this paper, we presented two concepts- through-life smart shipping network and smart design through HEAM approach. These two concepts provide the direction towards digitalised and smart shipping where design, construction and operation of ships can become more integrated and efficient. Through-life smart shipping network combine the key lifecycle processes into an integrated network where useful information can be exchanged at different phases in an collaborative manner. HEAM approach combines morphing and GA to generate series of new hull designs in a more automated manner and perform ‘intelligent’ search to narrow down to more optimal designs. By incorporating curve morphing concept into unique encoding scheme, we utilise GA operators such as crossover and mutation function to transform the hull shape through constant morphing, linear morphing and varying morphing. Two case studies are applied to optimise the hull form of container vessel through HEAM approach consisting constant and linear morphing and also combined three different parts of vessel into one single hull using varying morphing. Through computational intelligence and connected lifecycle network, it is envisioned this smart HEAM approach will help to improve the overall efficiency and ability to produce more efficient and smarter ships in the near future.

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