Hybrid Evolutionary Shape Manipulation for Efficient Hull Form Design Optimisation

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Abstract

'Eco-friendly shipping' and fuel efficiency are gaining much attention in the maritime industry due to increasingly stringent environmental regulations and volatile fuel prices. The shape of hull affects the overall performance in efficiency and stability of ships. Despite the advantages of simulation-based design, the application of a formal optimisation process in actual ship design work is limited. A hybrid approach which integrates a morphing technique into a multi-objective genetic algorithm to automate and optimise the hull form design is developed. It is envisioned that the proposed hybrid approach will improve the hydrodynamic performance as well as overall efficiency of the design process.

1. Introduction

Faced with volatile fuel prices, low charter rates and new environmental regulations, ships nowadays are expected to be more innovative and energy efficient. In ship design, the shape of the hull is one of the most important design parameters that need to be determined as early as possible. This is due to its impact on the overall performance efficiency and any major changes of the hull form in later design or construction stages will have detrimental effects to the cost and delivery schedule of vessel.

Today, new hull designs are heavily reliant on the designer's experience and often used existing designs as a starting point. Although the use of simulation-based design (SBD) is becoming increasingly prevalent, where new hull designs are modelled and evaluated virtually before final verification through physical model testing, the adoption rate is slow. Possible reasons include the lack of automated shape manipulation and robust optimisation techniques to generate feasible designs, *ANG, J.H. et al (2015)*. In the face of an aging workforce and increased costs, more automated and integrated design processes for the ship hull are now a necessity. The next paradigm in smart design and manufacturing, known commonly as Industry 4.0, provides the capabilities and opportunities to bridge this gap where the design of the hull form will become a fully integrated and automated process, *ANG, J.H. et al (2016)*. It is crucial for shipyards and design firms to capitalise on these new technological advancements in order to overcome the difficult market conditions.

This paper puts forth and develops a hybrid evolutionary shape manipulation approach which enables automatic design optimisation in pursuit of efficient hull form designs. In Section 2, a review of related works in state-of-the-art in hull form design and optimisation is provided. Section 3 introduces and elaborates the hybrid evolutionary shape manipulation approach for hull form design and optimisation. In Section 4, the findings obtained are presented and discussed. Section 5 concludes the paper.

2. Related works

2.1. Hull form optimisation

Ship design optimisation is an iterative process where multiple design parameters which determine the cost and performance of the vessel are improved to give an optimal solution or a set of optimal solutions. These design parameters can include powering, lines plan (hull form), structure, weight estimate, stability, etc. Due to need to determine the hull form in early design stage and its effect to other design parameters, hull form optimisation is one of the most important topic of research and hence the focus of this paper.

Traditionally, hull form optimisation involves mainly the designer manually modifying the shape of the hull (or hull lines) and evaluating the performance of the new shape using different simulation software. This ‘trial and error’ approach is extremely time-consuming and optimum designs are not guaranteed. Formal hull form optimisation that integrates the process of geometry modification, optimiser and performance evaluation can helps to automate the entire design process. An example of simulation-based hull form optimisation concept is provided in Figure 1, which describe the process of automated hull form optimisation using evolutionary algorithm as main optimiser, geometry modification to transform the shape of hull, evaluate the performance using computational fluid dynamic (CFD) techniques and iterates until the conditions are met and provide a range of optimal solutions, *ANG, J.H. et al (2015).*

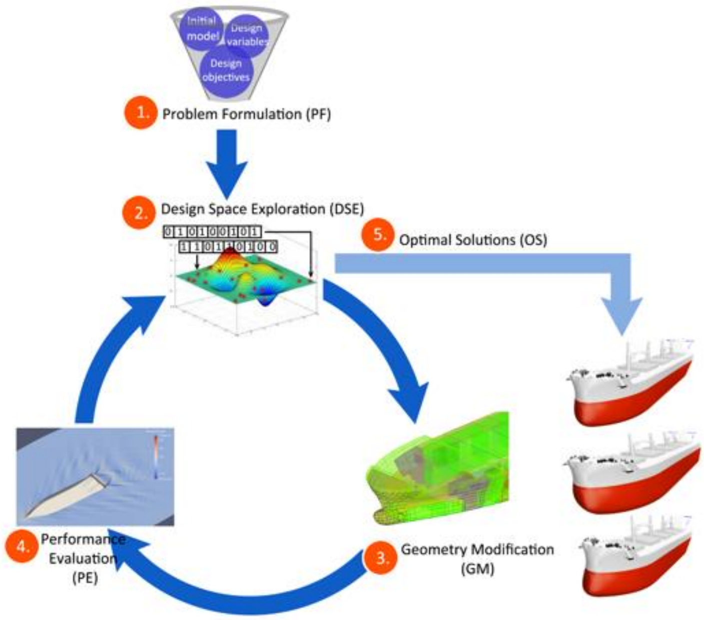

Fig.1: Simulation-based hull form optimisation concept

2.2. Optimiser

The optimiser plays a key role in the hull form design optimisation process. Here, it can be thought of as parametric optimisation where key design parameters relating the shape of the hull are modified in an iterative loop to produce a set of optimal values at the end of the optimisation process. Key optimisation techniques that were applied to hull form optimisation includes Simplex method of Nelder and Mead, *Jacquin, E., et al. (2004), Kostas, K.V., et al. (2014),* Sequential Quadratic Programming (SQP), *Park, D.W. and H.J. Choi (2013),* evolutionary algorithm such as Genetic Algorithm (GA), *Tahara, Y., et al. (2003), Baiwei, F., et al. (2011), Kim, H. (2012),* and Particle Swarm Optimisation (PSO), *Campana, E.F. et al (2009), Chun, H. H (2010), Tahara, Y. et al. (2011), Xi Chen et al (2014).*

Specifically, Simplex method is a derivative-free local search method which only uses the values of the objective and does not require any derivative information, *Koziel, S. and Yang, X.S. (2011).* SQP is a gradient based method which possesses a robust and stable scheme to solve local quadratic programming problem through approximation by Taylor expansion around a set of design variable, *Suzuki, K., et al. (2005).* As per *Peri, D. and F. Tinti (2012),* gradient-based algorithms such as SQP are very efficient methods for local optimisation however suffers from the drawback of finding sub-optimal solutions when the design problem is not convex.

Evolutionary algorithms (EAs) are a group of generic population-based meta-heuristic optimisation techniques. EAs are widely applied as they can solve complex problems to come up with a set of globally optimal solutions. However, due to their randomness, they are difficult to formulate and their results cannot be predicted in advance, *Zelinka, I., et al. (2013).* GA which was first developed by *Holland, J.H. (1975),* is a nature-inspired search heuristic method based on Darwinian Theory of natural selection and the 'survival-of-the-fittest' principle. Particle swarm optimisation (PSO) is another evolutionary strategy that is applied to solve global optimisation problem. It simulates the social behaviour of swarm of birds or bees which are capable to share information while looking for food.

2.3. Geometry modification

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 manipulation - direct modification and systematic variation. Direct modification involves the process of changing the hull geometry from model source (Beizer curve, B-splines, etc.). Using control points, hull coordinates or vertices can be adjusted manually through curve (2D) or surface (3D) representations. This method provides flexibility to the designer for local transformation involving specific section of the hull form- bulbous bow, propeller area, etc. However, due to its large number of control points required to represent the shape and largely human dependent, this method is not suited for modifying entire hull form or automated shape transformation. Example of direct modification applied in hull form optimisation includes T-spline, *K.V. Kostas (2014),* cubic B-spline surface, F-spline, etc.

Systematic variation, on the other hand, modifies the hull shape using a function which considers global hull parameters (Cb, Cp, etc.) or a series of local hull representation (NURBS, patches, etc.). Systematic variations are particularly useful for global modification involving entire hull or particular section of the hull (forebody/ afterbody) as well as automatic hull form optimisation with minimum user intervention. Example of systematic variation applied in hull form optimisation includes Karhuen-Loeve expansion (KLE), *Diez, M., et al. (2014)*, *Xi Chen (2014)*, Free-Form Deformation (FFD), *Campana, E.F., et al. (2013),* and parametric modification*, Saha, G.K. and Sarker, A.K. (2010), Brizzolara, S. and G. Vernengo (2011).*

Specifically, FFD provides mapping to change the coordinates of complex a geometry shape by enclosing it within simpler ones, *D. Peri, et. al. (2009)*. It is based on scheme of trivariate Bernstein polynomials. While FFD is simple to use and quick to apply in hull form modification, successful application depends greatly on the experience and skill of the designer to control the directions, *Ang, J.H, et al. (2015)*. Parametric modelling and transformation is another useful method which captures the essence of intended shapes and possible variations. The advantages of this method is that it offers better control on the overall hull shape to be optimised and is faster to apply, *Pérez, F., et al. (2007).*

2.4. Performance evaluation

Performance evaluation will evaluate each candidate solution produced from the optimiser depending on the objective function. Multi-objective optimisation becomes predominate as compared to single objective. This is especially true for ship design problem. The most important factors that influence the shape of hull include resistance and propulsion, sea-keeping behaviour in seaway, manoeuvring, cargo capacity, etc., *Papanikolaou A. (2014)*. Consequently, these performance parameters became the key objective functions applied and evaluated in hull form optimisation. For resistance evaluation, Computational fluid dynamic (CFD) had been used extensively in hull form optimisation to simulate the fluid flow around vessel. Prevalent CFD methods used for resistance evaluation include potential flow, *Nowacki, H. (1996),* and Reynolds Averaged Navier-Strokes Equation (RANSE), *Zha, R.S., et al (2014), Tahara Y., et al (2006), Perival, S. (2001).*

Specifically, potential flow is governed by Laplace equation and discretised using body surface and free surface panels, *Nowacki, H. (1996)*. Potential flow model are particularly useful for free surface flows, due to the effects of viscosity are often limited to small boundary layer, *Betram, V. (2008)*. However, in many hydrodynamic cases, it can only be used as preliminary evaluation due to limitation such as no computation of viscous drag, linear free surface, etc. RANSE are used to solve viscous fluid flows and able to represent complex free surfaces, which enables it to accurately evaluate total resistance, propulsion, appendages and added resistance. Key advantage of RANSE methods are it can capture global and local wave patterns as well as viscous effects at full scale. However, it requires high computational time and quality of result may differ significantly depending on user settings or commercial software used, *Betram, V. (2008)*. More recently, more complicated evaluation process was implemented for resistance evaluation which includes Neumann-Michell (NM) theory, *Huang, F.X. et al (2014)*, *Jeong S.Y. and Kim H.Y. (2013)*, Unsteady Reynolds averaged Navier stokes, *Chen, X., et al (2014)*, *Blanchard, L., et al (2013)*, etc. Various numerical methods used for sea-keeping analysis includes strip theory, unified theory, green function method, etc., *Bertram, V. (2000)*. Of which, strip theory is one of the main technique used for calculation of wave induced motion of ship.

3. Hybrid evolutionary shape manipulation approach

Considering main issues in existing hull form optimisation with respect to the lack of automated shape manipulation and robust optimisation techniques to generate feasible designs, we proposed a hybrid evolutionary shape manipulation approach, which 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(s)- and that of morphing- generate smooth intermittent shapes by combining two or more designs, we can potentially improve the overall efficiency and probability in deriving at the 'optimum design'. An overview of the proposed concept is provided in Figure 2.

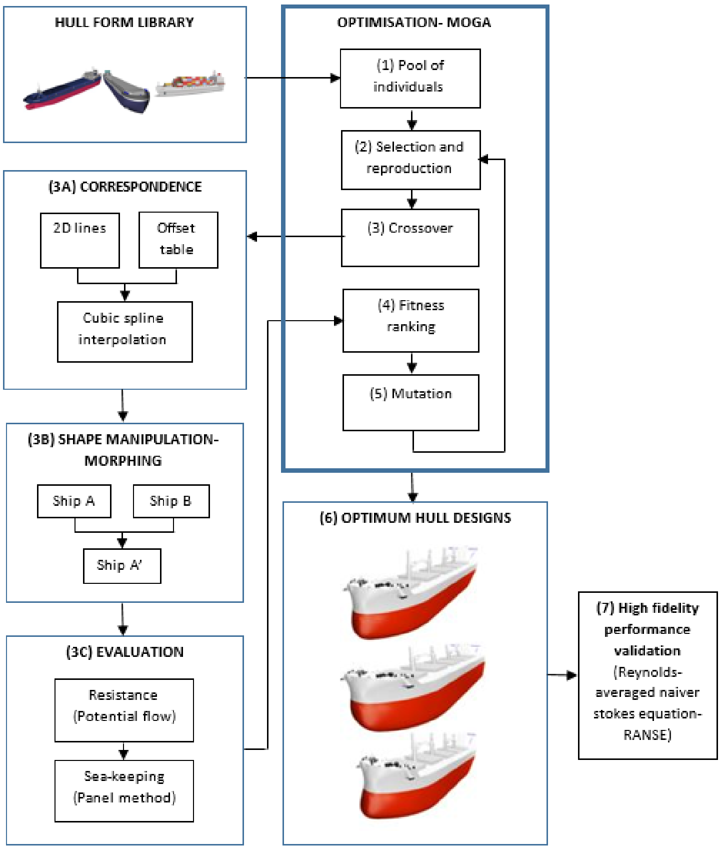

Fig.2: Hybrid Evolutionary Shape Manipulation Approach

3.1. Hybrid Genetic Algorithm

A GA is a stochastic global search method that mimics the process of natural biological evolution, based on the abstraction of Darwin's evolution of biological systems. It operates on a population of potential solutions by applying the survival-of-the-fittest principle to produce better approximation to a solution, *Chipperfield, A. et al. (1994).*

Like any real world problems, ship design often requires dealing with multiple conflicting objectives including lower resistance, higher cargo capacity, shorter construction duration and cost to be solved. Hence, it may not be entirely practical to expect any optimisation method to provide one single 'optimum' solution to such multi-objective problems. Instead, it may be more useful if an optimiser can help identify a set of potential (Pareto-optimal) solutions where the user can select the most appropriate and suitable solution according to his needs.

The hybrid multi-objective GA developed in this paper consists of four main components namely: (1) initialisation, (2) selection and reproduction, (3) crossover and (4) mutation. For brevity, the following sections details key mechanisms of the hybrid GA for hull form design optimisation and the reader is referred to *Konak, A., et al (2006)*, for basic working principles of a GA.

3.1.1. Initialisation

Initialisation is the first step in the GA where the pool of 'initial solutions' is populated. 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 a shipyard is used. 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.

In the GA terminology, these existing designs (also termed 'phenotypes') are first encoded as chromosomes ('genotypes'). This is a unique way of representing existing designs in the decision variable domain, *Chipperfield, A. (1994).* For the approach developed in this paper, real-value chromosomes using morphing parameter which captures the ship's geometry in 3D (x,y,z planes) is used. 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.

3.1.2. Selection and reproduction

In GA, selection is the process of i) determining the number of times (trials) each individual in the population can be chosen for reproduction and ii) conversion of expected number of trials into discrete number of offspring. The most popular selection scheme is the 'roulette wheel' mechanism which can probabilistically select individuals based on their performance, *Chipperfield, A. (1994).*

For proposed hull form application, we can translate fitness value into real value by determining the number of times or frequency a particular hull form will be selected. This is followed by determining the selection probability each hull form will be selected based on its fitness or good attributes as compared to other hull forms in the hull form library, which is also known as sampling. In order to determine the fitness level of each individual, the individual (hull form) pools are first evaluated based on the objective functions such as reduced resistance, improved sea-keeping performance, etc. After which, each individual is assigned with a 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.

3.1.3. Crossover

Crossover is the most important operator in GA and it combines two chromosomes (parents) to form new chromosome (offsprings). By applying the crossover operator, genes of good chromosome tends to appear more frequently in the population, leading to convergence to overall good solution, *Konak, A., et al (2006).* By manipulating the genes of the chromosome, it is assumed certain individual genes code will produce 'fitter' individual after recombination. A recombination operator is hereby used to exchange genetic information between a pairs or large group of individuals, *Chipperfield A (1994).* Two point crossover is most commonly used for reproduction where two points are randomly chosen and design variables are exchanged between the parent variable vectors*, Poloni, C. (2003).*

In our proposed hybrid evolutionary shape manipulation approach, we apply morphing as the main driver within crossover process to i) provide encoding scheme using morphing parameters to our hybrid GA to manipulate the shape of hull and ii) combine 2 or more existing hull forms (parents) to generate new hull designs (offsprings). The detail morphing process will be further elaborated in the next section.

3.1.3.1 Morphing

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 by *Tahara, Y. (2006), Peri, D. (2009), Kang, J.Y. and Lee, B.S. (2010)* and *Baiwei, F. et al. (2011).*

In this paper, we performed 2D curve morphing based on hull lines data. Since the beginning of shipbuilding and subsequent introduction of computer-aided design, 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: (i) it is a simple means to represent the entire shape of the hull and (ii) it is relatively easy to modify the hull form by adjusting the lines, *Papanilolaou, A. (2014).* It also serves as a primary source of hull form data which are used for subsequent plan approval and construction. Figure 3 shows an example of a typical lines plan of a cargo ship.

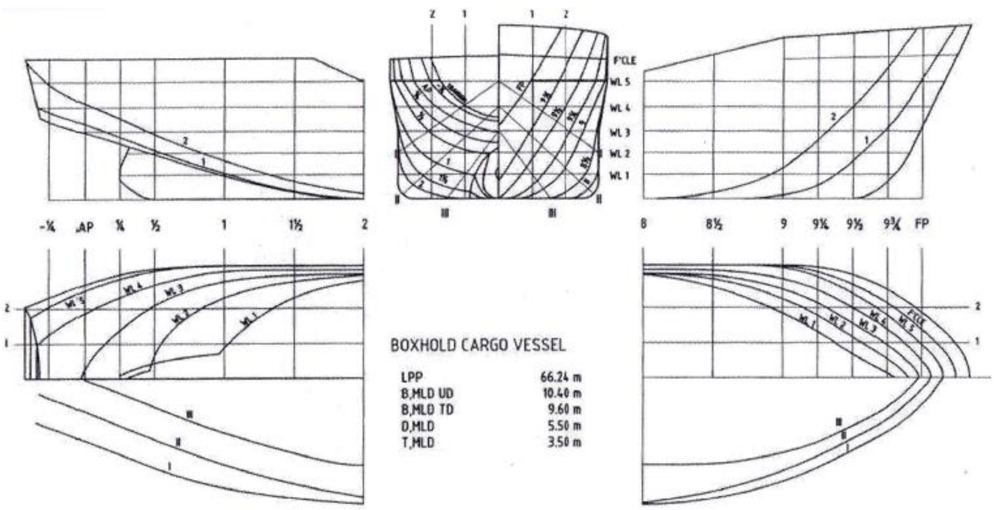

Fig.3: Ship lines plan of cargo ship (Friis et al. 2002)

A) Correspondence

Firstly, before morphing can be performed, we need to first ensure the hull form curve corresponds with each other. This correspondence process is done by creating the same number of points within a section curve for 2 existing (parent) vessels which are to be morphed. In the case where the number of vertices are different for two vessels, one can perform cubic spline interpolation to create same number of points at different interval of the section curve. To give an example, based on data from offset table, section curve at $X=0$ for vessel A consist of 7 points (Y and Z). On the other hand, section curve at $X=0$ for vessel B contain 10 points. In order to morph the section curve at $X=0$ for both vessel A and B, we can create 10 equal points on each curve by cubic spline interpolation (see figure 4).

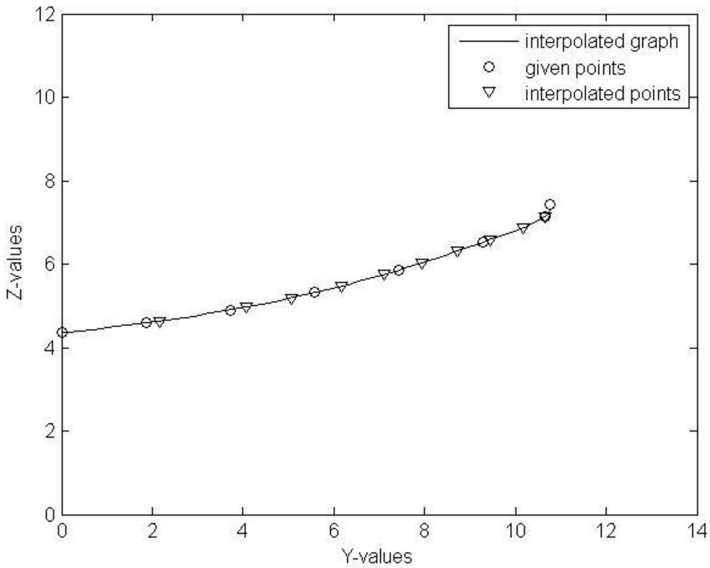

Fig.4: Correspondence using cubic spline interpolation

Cubic spline interpolation is a piecewise continuous curve which passes through each of the values in a table of points. It can be represented in the following equation:

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

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

B) 2D curve morphing

In this hybrid GA-morphing concept, we apply 2D curve morphing as the systematic shape variation method and apply to crossover function within GA to create new combinations.

I) Linear morphing
Firstly, we apply linear morphing to transform one hull shape to another, which will generate the 'intermediate' shapes in between the 2 'parents'. Using linear morphing equation:

$$M(t) = (1 - t) \times R_0 + t \times R_1 \qquad (2)$$

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.

Using hull lines provided from the body plan of source and target vessel, we can morph and generate n no of intermediate shapes just by changing the morphing parameter(t). 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 the morphing equation with steps of 0.2 ($t = 0,0.2, \ldots,1$), we are able to generate 4 intermediate curves as illustrated in figure 5.

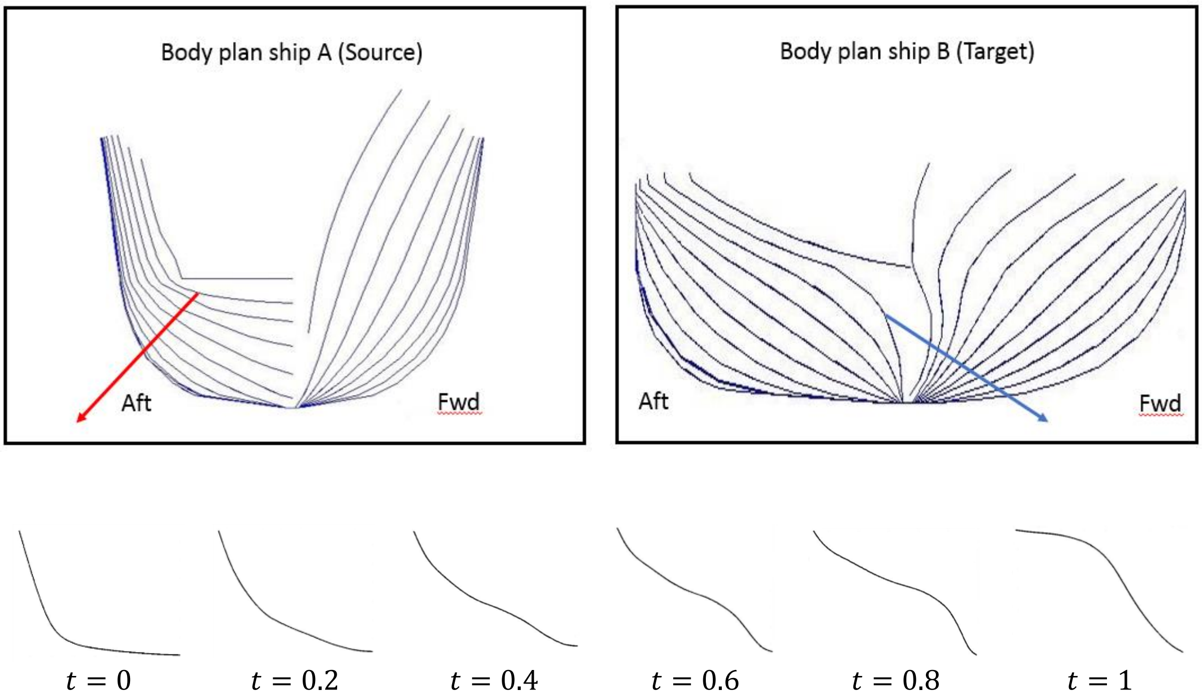

Fig.5: Linear morphing at station 0.5 from ship A (source) to ship B (target)

By applying constant morphing parameter *(t)* across all transverse frame or stations, we can effectively morph or create many intermittent forms between the source and target model, which will be further demonstrated in section 4 using actual ship model.

II) Time-varying morphing

In order to create as many variation and possible combination of hull form designs so as to increase the solution space, another method proposed is time-varying morphing where two different sections of hull form can be combined seamlessly using morphing method. This is achieved by setting varying morphing parameter *(t)* at different transverse curve along the stations or frame lines (x-planes). Using sample ship A and B again as example, we 'cut' the body of both vessels at mid-ship (middle body) and combine both of them as illustrated in figure 6.

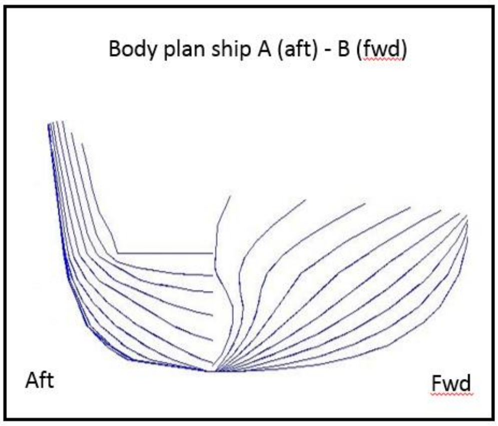

Fig.6: Combination of ship A aft body and ship B forward body

From the figure above, we can clearly see it will not be a feasible model solely by joining 2 unrelated hull form together as there are a sudden change in way of mid body which results in unsymmetrical forward and aft body. However, by applying a gradual morphing parameter *(t)* on multiple curves along different stations (X-axis), we can effectively create a smooth transition from aft section of ship A to forward section of ship B. In figure 7, we applied morphing to mid body of the vessel by setting morphing parameters *(t)* of 0.1-0.9 to station 3-7 (highlighted) of the vessel. Note there are no changes to the lines of ship A (source) when $t=0$ and vice versa for ship B (target) when $t=1$.

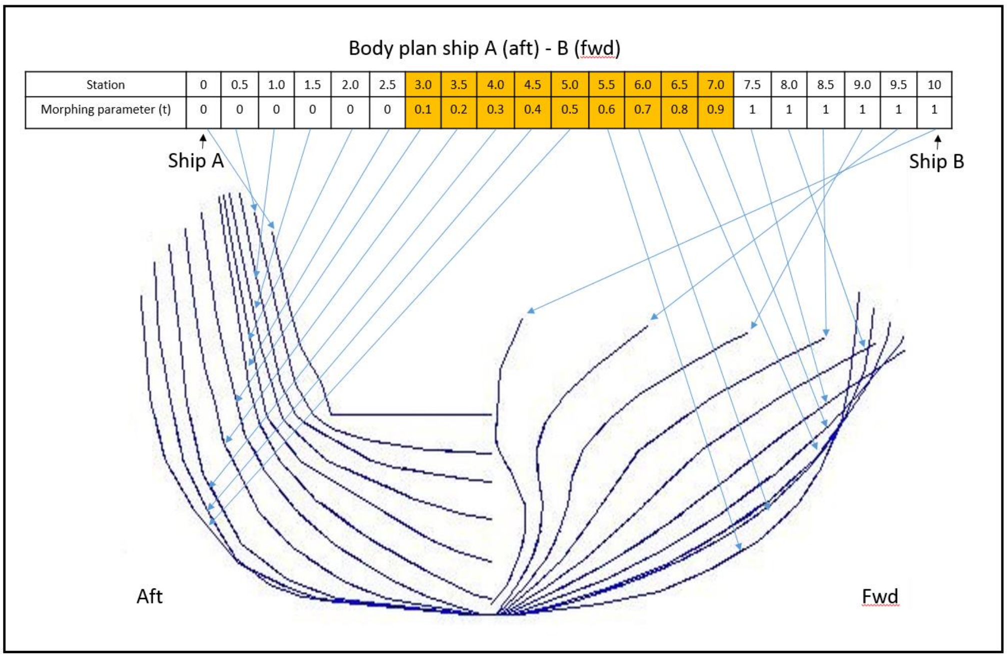

Fig.7: Morphing applied to mid body of combined ship A (aft) and ship B (forward)

Using similar concept, we can effectively change the hull shape towards more of ship A or ship B just by varying the morphing parameters at different part of the vessel, as illustrated in figure 8a and 8b. Note that there is no changes to the lines (or shape) of aft body of ship A when morphing is applied to forward body of ship B (figure 8a) and likewise no changes to forward body of ship B when morphing is applied to aft body of ship A (figure 8b).

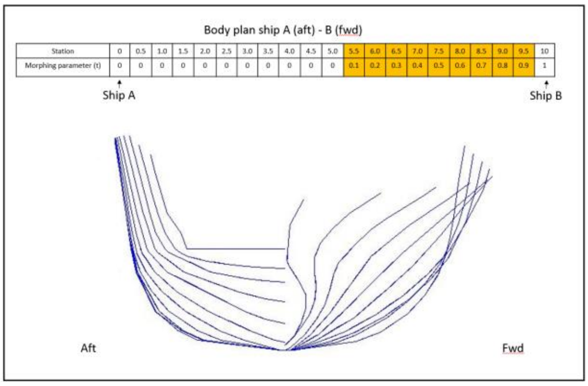

Fig.8a: Morphing applied to forward body of combined ship A (aft) and ship B (forward)

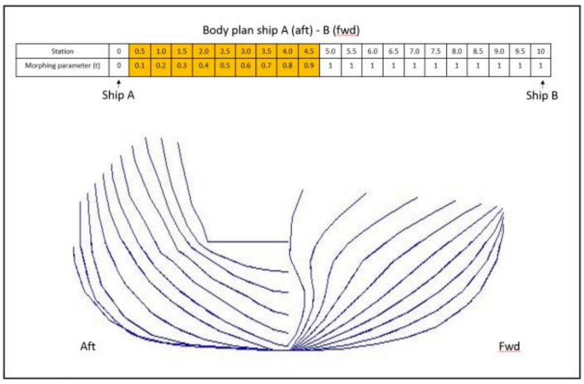

Fig.8b: Morphing applied to aft body of combined ship A (aft) and ship B (forward)

From above examples, we demonstrated how two different hull bodies can by 'joined' smoothly together using time-varying morphing technique. By varying the morphing parameter *(t)* at different transverse frame, we can choose which attributes the curve should be transformed, whether it should be more of ship A (toward $t=0$) or ship B (towards $t=1$). This provide great flexibility to change the hull shape effectively at any location of the ship and yet maintain a smooth transition.

III) Multi-target morphing

Using same principle above, we propose another method that can possibly 'cut' and join 2 or more vessels at different section such as ship A aft body to ship B mid body to ship C forward body. By changing the source and target model, we can effectively morph the vessel into a combination of more than two vessels- see illustration in figure 9.

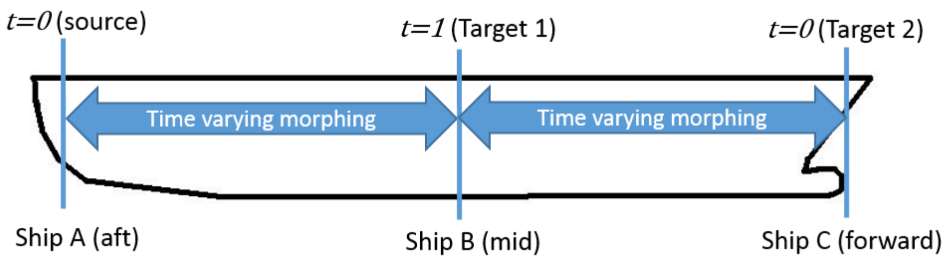

Fig.9: Combination of ship A aft body and ship B mid body and ship C forward body

Using earlier example, we include one more sample ship model C (figure 10) and perform multi-morphing and result shown in figure 11.

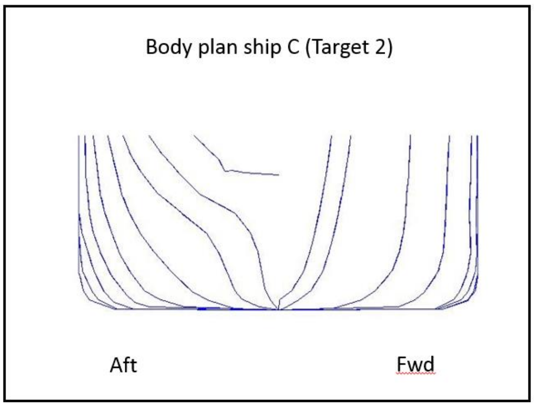

Fig.10: Sample ship C body plan

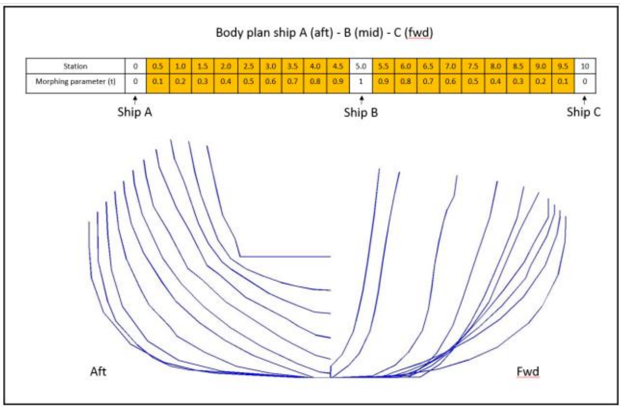

Fig.11: Combination of ship A aft body, ship B mid body and ship C forward body

On top of morphing 2 or more hull forms together into one hull concept, multi-target morphing can also be applied by mixing different combinations- example instead of joining ship A-B and B-C, we can also join ship A-C and C-B, etc. While time-varying and multi-target morphing may be simple to apply directly for geometrically similar ships, it can also be applied to ships sizes that are vastly different which will be further demonstrated in section 4.

3.1.3.2 Evaluation

After the new hull forms are generated through direct morphing and new hull combinations produced from cross morphing, these designs will form the ‘offspring’ which will be evaluated in the evaluation process to determine the fitness level of individuals before next round of reproduction. As highlighted in earlier section, performance functions that are closely related to shape of hull includes resistance, sea-keeping, manoeuvring, etc. Depending on the objective function set, appropriate evaluation method can be used to analyse the performance of the selected hull forms. In our example, we proposed potential flow for resistance evaluation and panel method for sea-keeping analysis due to its fast calculation although it is not as accurate as compared to advance RANSE method. This process is not conducted in this study but would be included later as part of author’s ongoing work.

3.1.4. 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 hull form optimisation, this can be carried out in terms of additional geometry modification where designer can perform local shape transformation (bulbous bow, etc.) using free-form deformation techniques, etc.

3.1.5. Termination

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. We also propose to include a high fidelity validation process after termination and attainment of a range of Parato 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.

4. Results and discussions

In order to demonstrate the feasibility of our proposed hybrid evolutionary shape manipulation approach, we will morph two existing vessels; a volume carrier (Very Large Crude Carrier-VLCC) and an offshore (pipe-laying) vessel using the 2D curve morphing. The principle dimensions for both vessels are provided as follows:

Table I: Principle dimensions

	VLCC	**Pipe-lay**
Length overall (Loa)	327m	182m
Length between perpendiculars (Lpp)	314m	168m
Breath (B)	58m	46m
Height (H)	31m	23m
Design draft (T)	20m	11m

Firstly, based on offset table and lines plan, the offset data (*x*,*y*,*z* plane) for both vessels were inputted into table format. Correspondence check was then carried out to ensure that both ‘parents’ have equal number of points. To handle missing data, cubic spline interpolation was used to create additional vertices so as to ensure equal number of vertices before morphing. Figure 12 shows the isometric view of the two 'parent' vessels and the 'child' obtained at morphing parameter *(t)* = 0.25, 0.5 and 0.75. It takes less than 2 seconds to compute the morph data for one hull generation.

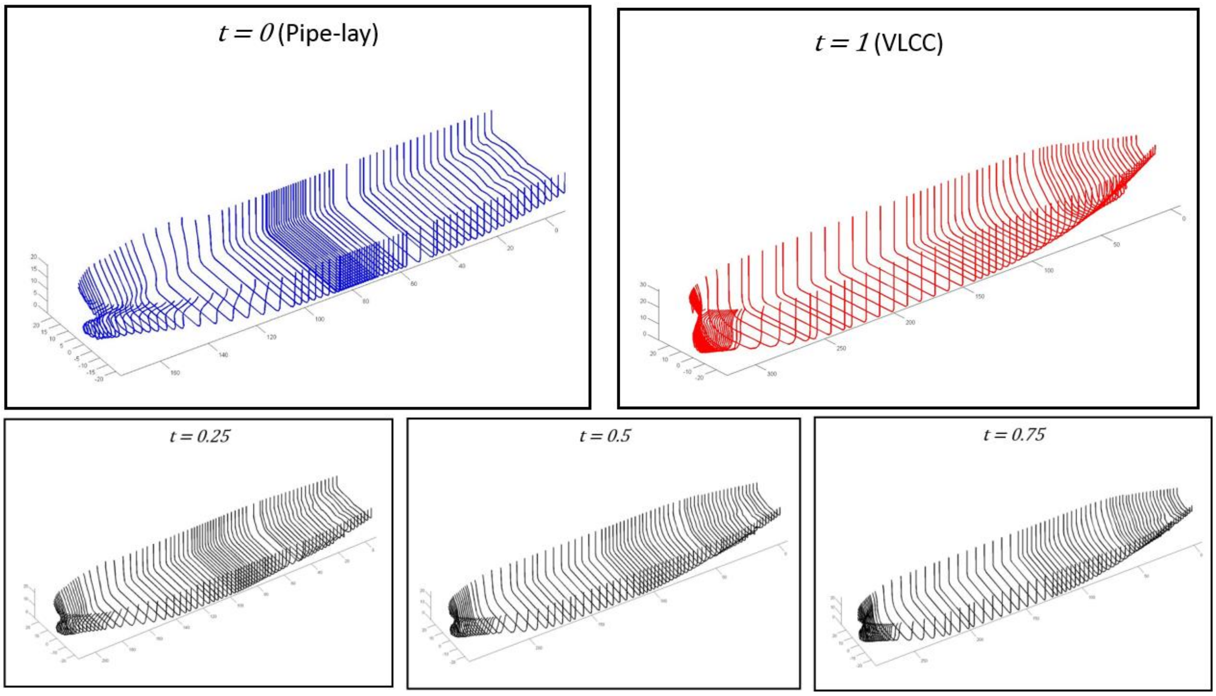

Fig.12: Isometric view of two parent vessels (Pipe-lay and VLCC) before linear morphing and the child produced at (*t*) = 0.25, 0.5 and 0.75.

Once this is completed, the 2D data can then be converted to surfaces using CAD modelling tool such as NAPA as shown in figure 13. This will provide better visualisation as well as subsequent preparation for meshing and CFD evaluation.

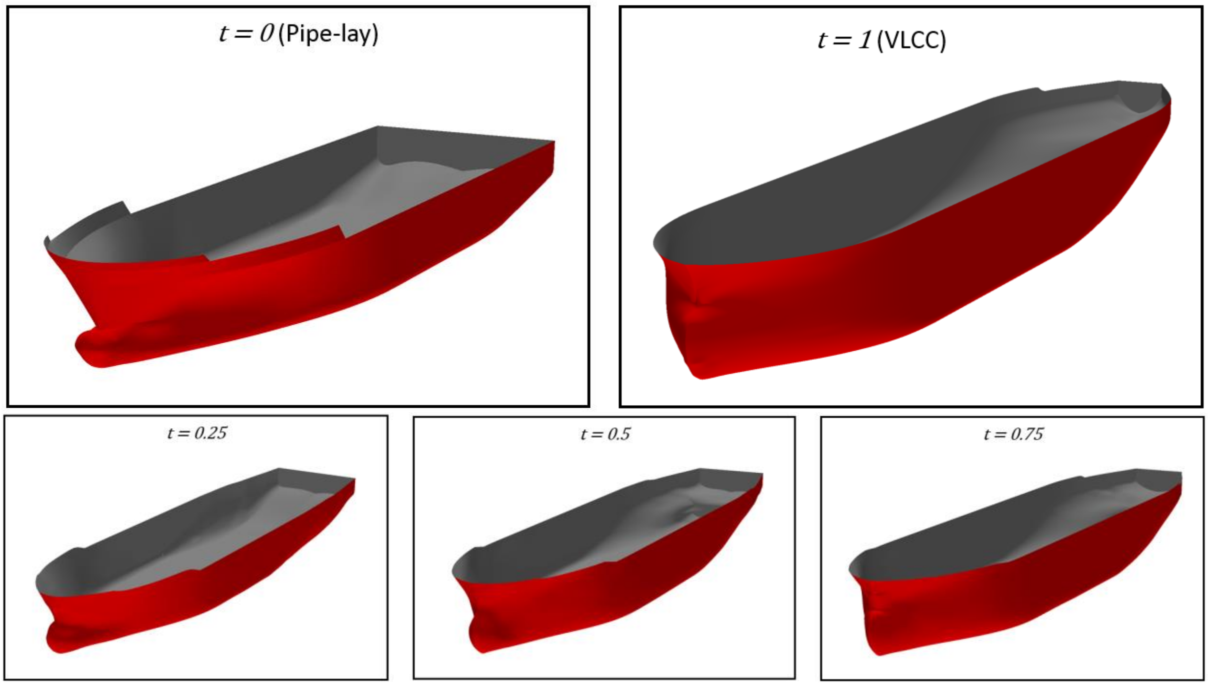

Fig.13: 3D hull surface generated from 2D curve using NAPA

In order to generate more hull combinations and apply to crossover function within GA, we 'cut' both vessels in the mid-ship section and combined them as illustrated in in figure 14.

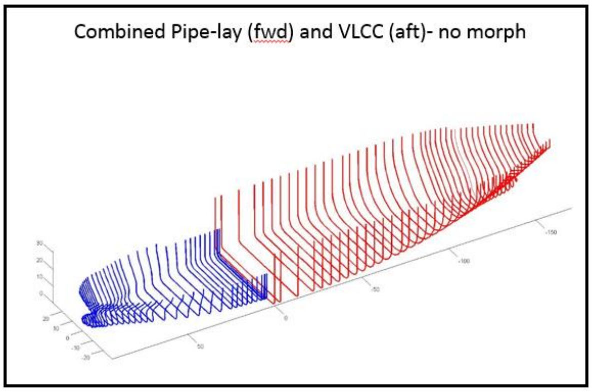

Fig.14: Combination of pipe-lay forward body and VLCC aft body

As seen in figure 14, it seems impossible to join both vessels properly due to the large differences in size - the VLCC shown in red is almost twice the size of the pipe-lay vessels shown in blue. However, it is possible to overcome this disparity by performing time-varying morphing at the mid body using very small morphing parameter *(t)* value.

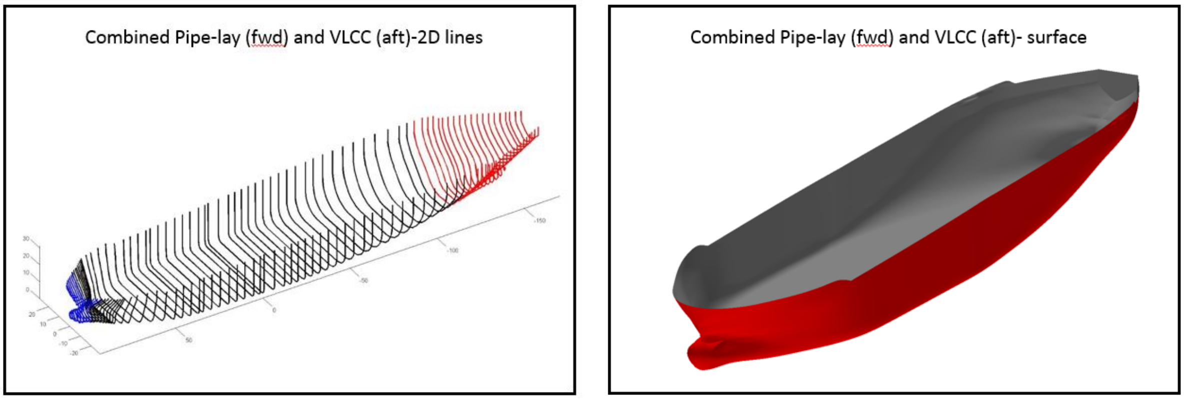

Fig.15: Isometric view of combined vessel with time-varying morphing

As shown in Figure 15, when (*t*) is set at 0.02, the combined vessel at mid body has a smooth 'blending' at the cutting site, producing a feasible hull form that is ready for evaluation. It should be noted that for hull forms with vastly different geometries, *t* needs to be set at smaller intervals while a larger (*t*) should be used for geometrically similar ones.

4.1. Discussions and future works

In this paper, we presents a novel method using 2D curve morphing and applied to hull form manipulation which can effectively transform the shape of hull in 3 ways -i) linear morphing, ii) time-varying morphing, iii) multi-morphing. Linear morphing allows the transformation of entire hull form from one ship to another. Time-varying morphing allows gradual transformation of different sections of the ship which depict the 'joining' of 2 vessels, whereby allowing partial feature of both ships to be retained. Multi-morphing allows the transformation of 2 or more ships using concept of time-varying morphing which enable changing of the shape hull while retaining particular sections of multiple vessels.

It can be seen that the concept put forth in this paper provides a simple, yet promising solution to hull form design optimisation. Through 2D curve morphing, it effectively transforms the shape of a hull and is able to generate a variety of different hull forms. Despite its advantages, several factors need to be considered:

1) For completeness, design criteria such as principle dimensions (length, breath, and height), displacement, and deadweight, etc., constitute part of the design constraints and should also be considered during the optimisation process.
2) It should be noted that some design firms or shipyards may not readily possess a large database of existing hull forms. This means that they may not be able to provide a diverse initial population which is an important factor for effective design space exploration. The method should therefore be able to automatically create new hull forms models from manual sketches or first principles in CAD software to populate the initial population.

In summary, advantages of proposed 2D curve morphing technique are as follow:

1) Fast generation of intermediate hull forms as well as combination of different vessels.
2) Hull shapes generated are based on existing proven designs, thereby ensuring its smoothness and feasibility.
3) Hull lines are simple to represent in phenotype space within GA and it provides more flexibility for shape modification as compared to surfaces.
4) Allows hull bodies to be ‘cut’ along the length of the hull body and ‘combined’ with another hull body seamlessly.

As demonstrated in this study, morphing technique presents many opportunities and possibilities when applied to hull form optimisation. Some proposed future works include the following:

1) To further investigate different morphing methods so as to create more shape variation. In field of metamorphosis, there are many interesting works which looks into the transformation of shapes in pursue of better design performance. Some good example of non-linear morphing includes weighted-average morphing, feature based morphing, etc.
2) Automatic conversion from 2D curve to 3D surface and meshing before CFD evaluation
3) Couple the proposed hybrid evolutionary shape manipulation approach with performance evaluation to achieve fully automated hull form design tool.

5. Conclusion

Eco-friendly shipping and energy efficiency are two of the most important topics in the shipping industry. This is particularly so in the face of more stringent environmental regulations and volatile fuel prices. The shape of hull affects the overall performance of a vessel and is therefore the area where the biggest improvements could be reaped. Simulation-based design is proven to be a very efficient tool for hull form optimisation as compared to manual modelling and other simulation based design techniques. Nonetheless, it has not been widely adopted largely due to the lack systematic shape variation and robust optimisation techniques.

In this paper, we developed a hybrid evolutionary shape manipulation approach by combining GA and morphing. The key advantage of this hybrid approach is that it capitalises on both smart optimiser as well as systematic shape variation to develop into a fully automated and efficient hull form optimisation tool. We also presented a novel application of 2D curve morphing method, which can be applied easily to transform the shape of hull by generating many intermediate hull form between 2 or more existing vessels. By combining different sections of the hull body through time-varying and multi-target morphing, we are able to generate many ‘new’ and potential designs when combined with GA. This ensures an effective search for optimal designs. It is envisioned this hybrid evolutionary shape manipulation approach can help to improve the overall design efficiency and hydrodynamic performance of smart vessels in near future.

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