Intelligent Ship Arrangements: A New Approach to General Arrangement

Michael G. Parsons, Hyun Chung, Eleanor Nick, Anthony Daniels, Su Liu, and Jignesh Patel

Abstract

A new surface ship general arrangement optimization system developed at the University of Michigan is described. The Intelligent Ship Arrangements system is a native C++, Leading Edge Architecture for Prototyping Systems–compatible software system that will assist the designer in developing rationally based arrangements that satisfy design specific needs as well as general Navy requirements and standard practices to the maximum extent practicable. This software system is intended to be used following or as a latter part of ASSET synthesis. The arrangement process is approached as two essentially two-dimensional tasks. First, the spaces are allocated to Zone-decks, one deck in one vertical zone, on the ship's inboard profile. Then the assigned spaces are arranged in detail on the deck plan of each Zone-deck in succession. Consideration is given to overall location, adjacency, separation, access, area requirements, area utilization, and compartment shape. The system architecture is quite general to facilitate its evolution to address additional design issues, such as distributive system design, in the future.

Introduction

The creation of effective general arrangements is a difficult design task requiring considerable time and the consideration of many potentially conflicting design goals, requirements, and constraints.

The overall objective of the Intelligent Ship Arrangements (ISA) system development has been to provide an optimization technology and design tool to assist the arrangements designer to create effective, rationally based surface ship arrangements with the maximum amount of intelligent decision making support. The system needed to be highly flexible to support the many design variations to which it might be applied. Secondary goals were (1) the ability to capture and invoke standard Navy requirements and best practices for knowledge capture purposes, and (2) the introduction of a rational measure of merit that would permit objective comparison of competing arrangement designs. ISA represents a new paradigm in naval ship arrangements design.

The surface ship arrangements problem has been approached as two essentially two-dimensional design steps as shown schematically in **Figure 1**. In Part 1, the spaces are *allocated* to Zone-decks on the ship's inboard profile. A *Zone-deck* is defined here as one deck within one vertical zone as illustrated in **Figure 2**. On the damage control (DC) deck where the decks are split by the main longitudinal passages, these overall Zone-decks are split into three (port, center, starboard) Sub-Zone-decks for the purposes of the allocation. Similarly, two Sub-Zone-decks would apply port and starboard of the well deck on an assault ship. Consideration at this level is given to the overall (global) location needs, adjacency,

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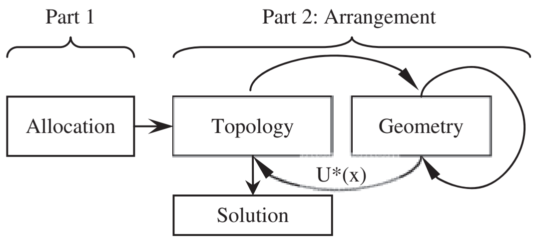

Figure 1: *Structure of the General Arrangement Optimization Process*

separation, area requirements, efficient area utilization, and relative importance of each space.

In Part 2, the assigned spaces are arranged in detail on the deck plan of each Zone-deck in a priority order beginning at the middle of the damage control deck. Consideration at this level is given to the area requirement, adjacency, separation, access, and shape features of the individual spaces. The methodology can produce rectangular, C-, T-, L-, and Z-shaped spaces as need to fit around each other, stair towers, vent trunks, weapons modules, etc.

The ISA system can also recognize complexes, the aggregation of spaces or Zone-decks, as needed to define medical complexes, food service complexes, watertight zones, electrical zones, fire zones, IT data zones, collective protection system zones, etc. The relative adjacency and separation constraints can be expressed relative to these complexes, as well as any spaces or locations, to address higher level design requirements.

Optimization Methods

The optimization of surface ship general arrangements is a challenging, complex problem characterized by an extremely large search space and a high number of often conflicting goals and constraints. It was, therefore, necessary in this effort to investigate and develop new optimization methods to achieve the goal of effective solution on a standard PC-level computer. This research has been documented in Nick et al. (2006), Daniels and Parsons (2006), Daniels and Parsons (2007), Nick and Parsons (2007), and Nick (2008). An overview of these methods, as necessary to comprehend arrangements design using ISA, will be presented here.

FUZZY OPTIMIZATION

As noted, the arrangements problem is characterized by a very large number of often conflicting design goals and constraints that are commonly quite subjective. An ideal way to treat this type of problem is with fuzzy optimization. The use of this approach was first proposed in Nehrling (1985) and then utilized in other arrangements design efforts such as Cort and Hills (1987) and more recently in Slapnicar and Grubisic (2003) and Ölçer et al. (2006). Fuzzy optimization has been adopted here as well.

In fuzzy optimization, fuzzy membership functions or fuzzy utilities $0 \leq U(x) \leq 1$, are defined for each goal or constraint. The independent variable x is selected to appropriately reflect each issue. A typical fuzzy utility, as might be used to express a requirement for separation in the longitudinal x-direction, is shown in **Figure 3**. The region with $U(x) = 0$ is clearly unacceptable to the designer and region with $U(x) = 1$ is fully acceptable. The fuzzy region between the minimum threshold x_ℓ and the design goal or target x_u is a subjective, fuzzy quantity between 0 and 1. This is similar to the approach used by Brown and Salcedo (2003) to define naval design measures of performance (MOPS).

If each design goal and constraint is expressed by an appropriate utility function U_i(x) that depends on the design choices x, then a fuzzy optimum using minimum correlation inference (Kosko 1992), for example, is given by the maximization of the optimization objective (cost) function or total utility $U(U_i$(x)),

$$U^* = \max_{\mathbf{x}} U(U_i(\mathbf{x})) = \max_{\mathbf{x}} [\min_i (U_i(x))] \quad (1)$$

Figure 2: *Definition of a Zone-Deck*

This seeks the design x that maximizes the worst (minimum) satisfaction of any of the applicable goals and constraints i. This approach yields a multicriterion compromise among all of the conflicting goals and constraints and treats them all in a similar manner. It has the search advantage that there is always a "feasible" solution that can be improved.

Allocation Optimization

The allocation of spaces to the Zone-decks is a complex problem. It is a combination of the classic Bin Packing problem (Lodi et al. 2002) and, with relative adjacency and separation constraints, the Quadratic Assignment problem (Loiola et al. 2007). This falls in the class of NP-Hard problems for which there is no known exact solution method, except the enumeration of all possible solutions. Further, the allocation is a combinatorial problem that seeks a set of numbers that are not part of a surface from which shape and slope information can be used in the optimization search strategy. It also has a very large search space that can have multiple local minima.

ALLOCATION DESIGN VARIABLES *x*

In the allocation problem, the unknown design vector **x** is the assignment of each space $i = 1, \ldots, I$ to one of the Zone-decks $k = 1, \ldots, K$ as follows:

$$\mathbf{x} = [x_1, x_2, \ldots, x_I], \quad 1 \le x_i \le K \qquad (2)$$

Thus, a 3 in the second entry x_2 would assign space 2 to Zone-deck 3. This independent variable vector is in the form of an integer (rather than binary) *chromosome* in the jargon of Genetic Algorithms. This formulation has the advantage that it ensures that each space is assigned to a Zone-deck and to only one Zone-deck without additional constraints. The number of possible solutions for this problem is K^I so 100 spaces being assigned to 25 Zone-decks on a corvette-size vessel will have a theoretical search space of 6×10^{139}.

ZONE-DECK AREA UTILIZATION UTILITY

The allocation goals and constraints include efficient space utilization, adjacency, separation, and global location within the ship's inboard profile, which capture most of the strategic arrangement considerations. Efficient space utilization is a continuous constraint. Each space i has a required area A_i and each Zone-deck has an available area A_k. Zone-deck k area utilization can be defined as $U_{Uk}(\mathrm{x}) = \Sigma A_i / A_k$ where the i in this case are only those spaces i assigned by the design x to Zone-deck k. The continuous Zone-deck area utilization utility U_k is defined using two halves of a Normal distribution for mathematical convenience as shown in **Figure 4**, where the desired utilization in this illustration is 95% allowing for lockers and other smaller features not included in the allocation. The designer can select different σ_ℓ and σ_u as shown. The implementation used in ISA also includes an optional finite $U = 1$ plateau between the two halves of the Normal distribution shapes. Typically, the tolerance for under utilization (spaces have excess area) is more relaxed than over utilization (spaces will be crowded in) as shown in Figure 4, where $\sigma_\ell = 0.4$ and $\sigma_u = 0.2$.

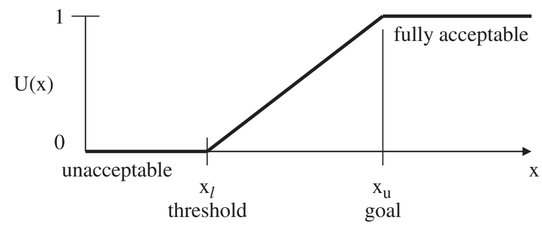

Figure 3: *A Typical Fuzzy Utility U(x)*

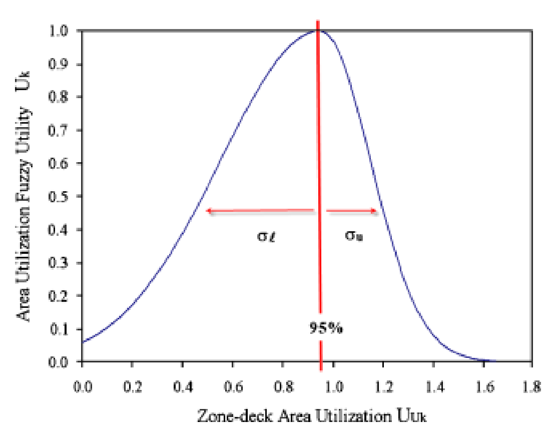

Figure 4: *Zone-Deck Area Utilization Utility U_k*

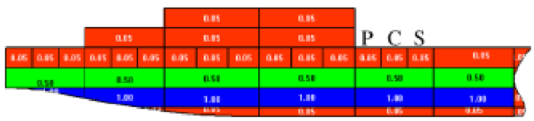

Figure 5: *Example Allocation Global Location Goal*

GLOBAL LOCATION GOALS

The remaining space allocation goals and constraints are discrete, rather than continuous, in nature. The global location utilities for each space express the design's preference relative to general location within the ship. Because the Zone-decks are discrete, this consists of an array of values $0 \leq U_{ik} \leq 1$, one for each Zone-deck for each space. This can be displayed intuitively as a color-coded array of values on the schematic inboard profile of the vessel as shown in **Figure 5**. This example could be for a space that the designer wants in the hull below the DC deck with the goal anywhere on the hold level (1.00, blue) and an acceptable solution anywhere on the 1st platform (0.50, green).

ADJACENCY/SEPARATION CONSTRAINTS

The adjacency and separation constraints are relative location constraints that relate the Zone-deck position of space A to any other space, location, or complex B. In the allocation, they relate to the Zone-deck location of B versus A and, thus, are also discrete. Because the relative positions desired in a design may vary depending upon whether space A is on the damage control (DC) deck, above the DC deck, or below the DC deck there are three conditional constraints. These can be displayed intuitively on a color-coded Zone-deck array with the current Zone-deck location of space A at the center origin (0, 0) as illustrated for an adjacency goal in **Figure 6** where space A wants to be close to space B on the same deck.

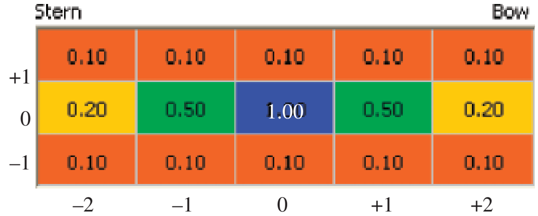

Figure 6: *Example Allocation Adjacency Constraint*

In this illustration, the utility $U_A(B)$ is 0.50 (green) when space B is one zone forward or aft on the same deck as A. There is no automatic reciprocity between spaces A and B.

OVERALL ALLOCATION UTILITY

The allocation cost function found to be the most effective is a follows:

$$U(\mathbf{x}) = U_1 \times U_2 \times U_3 \leq 1$$

where

$$U_1 = \min(U_k)$$

$$U_2 = \frac{\sum_{k=1}^{K} U_k}{K} \tag{3}$$

$$U_3 = \sum_{i=1}^{I} \frac{W_i}{\sum_{j=1}^{I} W_j} \min(U_{i1}, U_{i2}, \ldots, U_{N_i})$$

The U_1 uses minimum correlation inference and seeks to raise the lowest Zone-deck utilization utility. U_2 seeks to raise the average of all the Zone-deck utilization utilities. U_3 seeks to raise the weighted average of the lowest of the N_i goal and constraint utilities for each space i. The weights $0 \leq w_i \leq 20$ express the relative importance of each space and are normalized by the sum of the weights so that the maximum possible overall utility remains at 1. These three components are blended by product inference.

The overall utility $0 \leq U(x) \leq 1$ expressed in equation (3) provides a rational measure of merit for the assessment of the quality of any candidate general arrangement from the viewpoint expressed in the goals and constraints captured by the space utilities $U_{i\ell}$. Such a measure of merit can provide an often-needed discipline over proposed arrangements changes in latter design.

HYBRID AGENT/GENETIC ALGORITHM (GA)

As already noted, the allocation problem is a combinatorial optimization problem with a large search space. This type of problem is a natural candidate for solution using a GA

(Goldberg 1989; Michalewicz 1999; Gen and Cheng 2000; Deb 2001). Experiments with an integer-coded Genetic Algorithm using the chromosome equation (2) yielded very effective solutions (Nick et al. 2006). Nick used a two-round tournament selection algorithm (Michalewicz 1999) and elitism for the convergent elements and mutation, Simulated Binary Crossover (Deb 2001), simple crossover, and two-space swapping for the divergent, global search elements. A population of 50 candidate designs was used.

Because the overall utility in equation (3) has components directly associated with the various Zone-decks and spaces, the allocation problem is also amenable to treatment using an agent-based algorithm. An agent is an element of code or object that has prescribed behavior. A group of individual agents working in parallel can often evolve an effective solution to a problem. Daniels undertook experiments with an agent-based approach modeled on a human design team that yielded effective solutions using the same chromosome equation (2) (Daniels and Parsons 2006). The results were comparable with that achieved with the GA solution and the speed was greatly improved. A population of 10 candidate designs was used for the agents to attempt to improve.

The agent approach uses K Zone-deck agents that sequentially propose a prioritized list of changes to a randomly selected candidate design that will improve its own area utilization utility U_k. The Zone-deck agents can propose to add a space, divest itself of a space, or swap spaces with another Zone-deck. These are evaluated by a design review agent and the first, if any, that improves the overall arrangement design as expressed in equation (3) is accepted.

The agent approach also uses I space agents that simultaneously and sequentially propose changes to randomly selected candidate designs that will improve their own part of the cost function; i.e., $\min(U_{i1}, U_{i2}, \ldots, U_{iN_i})$. The space agents can propose to move to a new Zone-deck or swap places with a space in another Zone-deck. These are evaluated by the design review agent and the first, if any, that improves the overall arrangement design as expressed in equation (3) is accepted.

In the agent-based approach, the agents can only improve what is already present in the current small population of candidate designs, which is initialized using a random assignment algorithm. Some form of global or divergent search is also needed for maximum performance. Because each of the proposals from the agents is attempting to improve some part of the overall utility U, the agents are similar in function to the convergent (tournament, roulette) part of a GA. It was natural then, at least in retrospect, for Daniels to attempt a combination or hybrid agent/GA solution in which the convergent part of the GA was replaced by the Zone-deck and space agents, with the elitism preserved. To our knowledge, this was the first time in any field that such a hybrid optimization approach has been attempted.

Experiments with a hybrid agent–GA solution using mutation, crossover, and two-space swap elements for the divergent search part of the algorithm yielded solutions with superior overall utility (Daniels and Parsons 2006, 2007). A population of 10 candidate designs was again used. The solutions were also significantly faster than obtained with the more complex GA. This powerful, hybrid agent/GA algorithm has been developed further for use in the ISA allocation.

Arrangement Optimization

Following reasonable success obtained in architectural arrangement optimization problems (Medjdoub and Yannou 1999; Michalek et al. 2002), the detailed arrangement of each Zone-deck has been approached as a two step process as depicted in Figure 1. The outer loop is the optimization of the topology, the relative fore and aft position of the centroid of the spaces within the Zone-deck. The geometry is the detailed arrangement of the joiner bulkheads for any particular topology. Because more than one geometry can result from a given topology, an inner loop stochastically creates a number of geometries for each input topology using a Stochastic Growth Algorithm. The one with the best design utility is used for $U(x)$. The geometry growth algorithm operates on a discrete grid of 1 m, one frame spacing or some other appropriate scale.

A GA is used for the topology fuzzy optimization. Nick has developed and implemented a custom GA using roulette selection, crossover, and two-space swapping (Nick 2008).

As noted above, the detailed arrangement process is performed for each Zone-deck in a priority sequence starting near the center of the DC deck. This is done because this is usually the priority real estate and it is reasonable to fix the stair tower locations on this level. The stair towers then become fixed objects for the upper and lower decks. The DC deck also contains the major fore and aft passageways forming two or three Sub-Zone-decks in each Zone-deck, which makes their design more restrictive.

THREE BOX ELEMENT

Because real compartments must be able to be arranged not only as rectangles, but T, L, C, and Z forms in order to fit around each other, stair towers, machinery trunks, etc., a three-box element is used to define each space. Each space has a centroid rectangle (C) and then it can grow two optional appendage boxes (A and B) as needed within the geometry generation algorithm. Two spaces on a Zone-deck on the DC deck are shown in **Figure 7**. This consists of Port and Starboard Sub-Zone-decks outboard of the main longitudinal passageways and then a Center Sub-Zone-deck to which spaces will be allocated separately. Two spaces are shown in the aft portion of the Center Sub-Zone-deck. Space $J+1$ consists of just its centroid box C. Space J consists of its centroid box C and one appendage box A that has grown in order to fit around space $J+1$. The two elements of space J form a single L-shaped compartment.

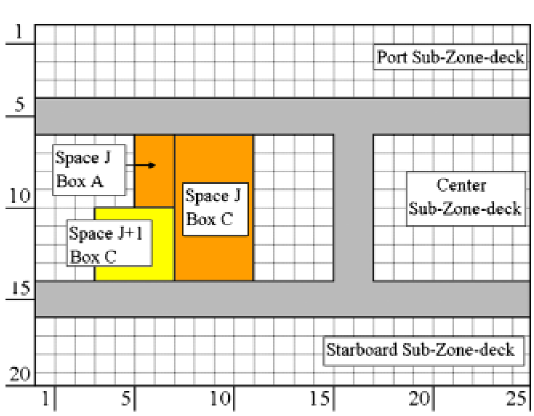

Figure 7: *Three-Box Elements on Damage Control Deck*

TOPOLOGY CHROMOSOME

The topology chromosome for a Zone-deck on the DC deck will be illustrated here. The location of the main longitudinal passages and the existence of stair towers (inboard or outboard of the main passageways) and the possible existence of an athwartship passage are set initially by the designer. The allocation algorithm then allocates spaces optimally to the three Sub-Zone-decks, perhaps spaces 1, 2, 3 to port; spaces 4, 5, 6, 7, 8, 9, 10, and an athwartship passage to the center; and spaces 11, 12, 13, and 14 to starboard. The topology optimization then establishes the best fore and aft ordering of the centroids of the allocated spaces within each of these Sub-Zone-decks as defined by an integer-coded chromosome such as the following:

$$\mathbf{x}_t = [3, 1, 2, \mathbf{PP}, 7, 10, \mathrm{CP}, 8, 5, 4, 6, 9\ \mathbf{SP}, 13, 14, 12, 11] \quad (4)$$

The **PP** and **SP** are placeholders designating the location of the port and starboard main passageways, respectively, as set by the allocation. The CP designates the location of an arrangeable athwartship passage that is required in this Zone-deck. This chromosome indicates that spaces 1, 2, 3 are arranged in the order 3, 1, 2 fore to aft in the port Sub-Zone-deck, etc.

SPACE GEOMETRY CONSTRAINTS

The space generation is subject to a number of space size, shape, and access constraints. Constraints are included for the required area, minimum overall dimension, minimum segment width, aspect ratio, and perimeter. For each of these, a simple, logical, piecewise linear default utility is included and they can be edited as desired by the user. **Figure 8** shows the default space required area utility where the independent variable is the ratio of the actual area (AA) to the desired area (DA) for the space.

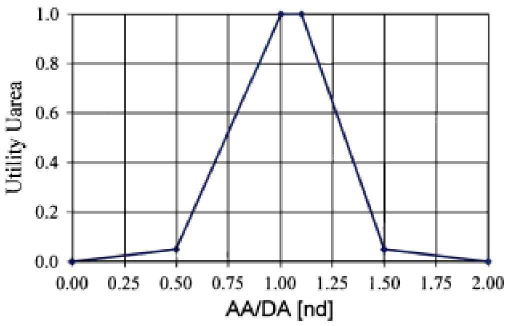

Figure 8: *Default Space Required Area Utility*

Figure 9 shows the default space adjacency constraint. The default parameters are related to the scale of the vessel through the beam, mean Zone-deck length, and ship length. The continuous adjacency/separation constraint distance variable *d* can be calculated either as a Euclidean distance $d = (\Delta x^2 + \Delta y^2)^{1/2}$, as might be used for a nuclear exclusion zone, or as a Manhattan distance $d = \Delta x + \Delta y$, as might be used for a radar wave guide length limit.

The user can specify that a space should have internal access from another space or that it is to have one or two accesses to passageways. On the DC deck, the access can be to the port, starboard, either, or both of the main passages (or athwartship passage, if present). If two accesses are required, an additional constraint is included to ensure that they can be far enough apart that they can functionally be considered two separate accesses in an emergency.

TOPOLOGY OBJECTIVE OR COST FUNCTION

The topology fuzzy optimization objective or cost function is determined for each topology's best geometry using minimum correlation inference and the fuzzy utilities for each space *i*'s constraints and then averaging over all spaces so that a single unsatisfied space will not drive the whole solution,

$$U(\mathbf{x}_t) = \frac{\sum_{i=1}^{I} \min(U_{Cj})}{I}, \quad 1 \le j \le N_i \qquad (5)$$

The U_{ij} are for the required area, minimum overall dimension, minimum segment width, aspect ratio, perimeter, adjacencies, separations, and, if two accesses are required, the access separation. Note that multiple adjacency and separation constraints can be present for any space *i*. The perimeter constraint was added to disadvantage complex two-box spaces with minimal connection between the two elements. Additional constraints dependent upon the number of corners could also be introduced to discourage complex spaces.

TOPOLOGY GENETIC ALGORITHM

The topology optimization is performed by a custom GA that determines the chromosome equation (4) that optimizes the cost function equation (5). The schematic of the algorithm is shown in **Figure 10**. The convergent part of the algorithm is a roulette selection that operates on both the parents and the daughters from the genetic operations because a small population is used. The divergent genetic operations are crossover and two space swap. Elitism is utilized. On the DC deck, a two-point crossover is used to exchange whole Sub-Zone-deck allocations. No crossover is used below the DC deck because this would invalidate the allocation assignment.

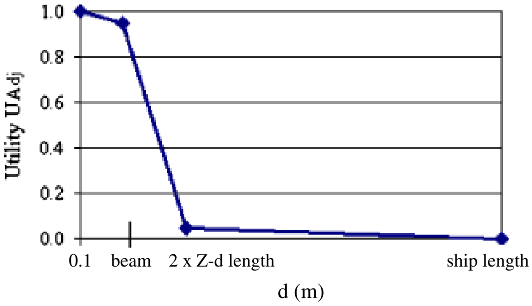

Figure 9: *Default Space Adjacency Constraint*

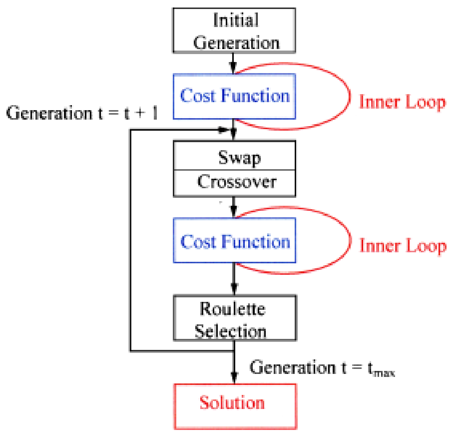

Figure 10: *Topology Genetic Algorithm Schematic*

STOCHASTIC GROWTH ALGORITHM

Because there can be more than one geometry for each topology, it is necessary to explore the possible geometries for each topology. This is accomplished by generating a number of different geometries in a Stochastic Growth Algorithm (Nick 2008) and then exhaustively selecting the geometry with the best cost function to associate with that topology.

The Port and Starboard Sub-Zone-decks have long narrow aspect ratios so the spaces are simply distributed along those regions according to their required areas. Any stair tower required is placed in the largest space.

The geometry development for the Center Sub-Zone-deck then begins with the placement of the athwartship passage, if one is required, accounting for the required areas of the spaces forward and aft of this passageway based upon the topology chromosome. The geometry development then operates on the area forward and then aft of this passage in succession. A required stair tower is placed in the region with the less constrained allocated area. If two stair towers are required, one is placed in each area. Unit-size centroid elements are placed in accordance with the chromosome with an approximate spacing based upon their required areas. The spaces are first extended for access to the designated main passageway, if one is specified, or to the side with the fewest attachments, if not. The end spaces are also extended to the ends of the region. These connections then become fixed to ensure that the access requirements are met. The stochastic growth part of the algorithm then follows the schematic shown in **Figure 11**.

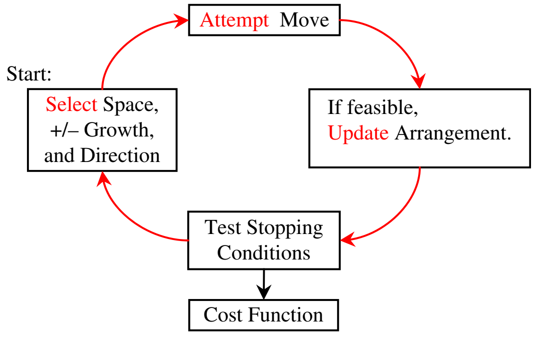

Figure 11: *Schematic of Stochastic Growth Loop*

A space, direction, and amount (±) of growth is randomly selected recognizing the change in area needed and the remaining unoccupied area. The growth can, with a lower probability, be negative even if the space has adequate area so that it can translate to make room for another space. A selected move is permitted if room is available. If a space needs to move the stair tower to make room for its growth, it can push the stair tower if room is available into which it can move. The spaces can grow or lose their appendage elements as needed to fit around other objects.

SAMPLE TOPOLOGY OPTIMIZATION RESULTS

To illustrate the operation of the topology/geometry optimization an example of a DC deck Zone-deck will be presented. This Zone-deck has Port, Center, and Starboard Sub-Zone-decks to which 3, 7, and 4 spaces numbered 1–14 have been allocated, respectively. There is to be an athwartship passage in the Center Sub-Zone-deck and the stair tower is to be outboard on the port side and inboard on the starboard side. There is a fixed machinery trunk adjacent to the passageway in the Port Sub-Zone-deck.

The topology optimization was conducted for 25 generations using a population of four chromosomes and generating four geometries for each topology. One of the initial geometries, which resulted from the *specific* chromosome equation (4), is shown in **Figure 12**. This topology resulted in a total utility value $U = 0.7036$. Spaces 7, 8, and 10 have grown appendage boxes to complete the arrangement. All three boxes for space 7 are one compartment. Final joiner bulkhead locations could be adjusted by the designer if construction simplifications were desired.

The GA progress history is shown in **Figure 13**, which shows the best chromosome utility and the average of the utilities of the entire population. The elite (best) chromosome starts at about 0.757 and then makes three improvements converging to the final value of $U^* = 0.8165$ (an 8% improvement) by the 17th generation. The resulting optimum design, using these GA parameters, is shown in **Figure 14**. This is the best topology and geometry found to meet the size, shape, adjacency, separation, and access requirements for the spaces.

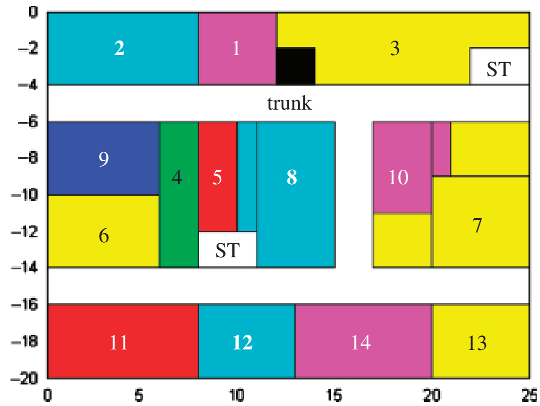

Figure 12: *One of the Initial Geometries (U = 0.7036)*

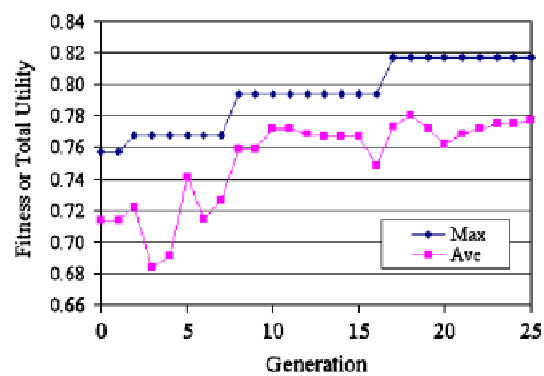

Figure 13: *History of Maximum and Average Utilities*

ISA System Organization

The ISA software system is an approximately 100,000 line, native C++ application that utilizes LEAPS (LEAPS 2006). LEAPS is an intelligent (NURBS geometry, attributes, and behaviors) product modeling system and central data repository that has been introduced as the central, coordinating database for naval ship design information. ISA is intended to be used following ship design synthesis using ASSET (2005). ASSET is a highly developed naval ship synthesis system applicable to surface monohulls that is being extended to submarines, catamarans, and trimarans. ISA is, thus, compatible with the current paradigm for US naval surface ship design.

The highest level schematic of the ISA system is shown in **Figure 15**. ISA begins by linking to the LEAPS database created as part of the ASSET synthesis to obtain the ship geometry information including the hull form, decks, bulkheads, and superstructure. It also links through SQL queries to a Microsoft (MS) Access library file that houses a ship type space list template that contains the spaces expected on that type of ship keyed to the Ship Space Classification System (SSCS). This library also contains default design goals and constraints for each space that reflect standard Navy requirements and best practices (NAVSEA 1992, etc.). The system has a designer's graphical user interface (GUI) and a second more comprehensive Administrator's GUI for use in debugging and managing the MS Access Library file. The XML Model file stores

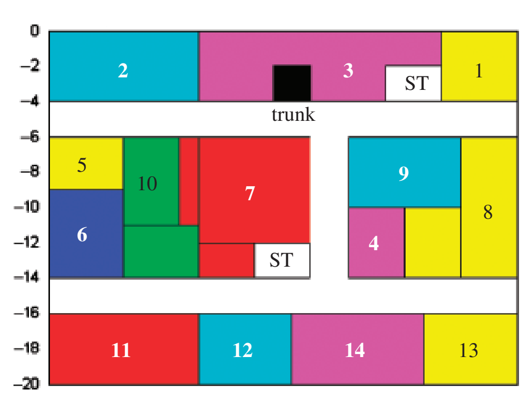

Figure 14: *Final Geometry (U* = 0.8165)*

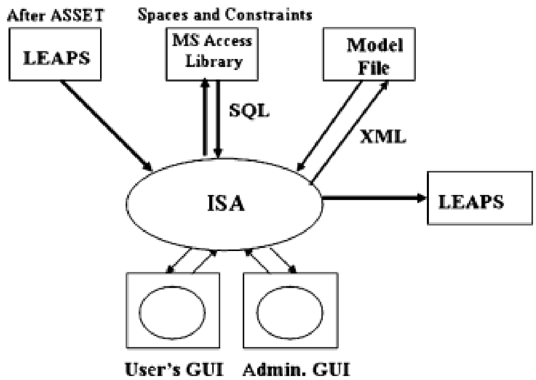

Figure 15: *Overall Schematic of Intelligent Ship Arrangements System*

ISA specific run files that support run recovery and restart.

ISA begins with the LEAPS definition of the hull, bulkheads, and decks as visualized in **Figure 16** to define the envelopes for the various Zone-decks within the ship. The designer then views the Zone-decks on the inboard profile as shown in **Figure 17** and identifies the DC deck upon which the main passageways will be defined. This is on a Zone-deck by Zone-deck basis so it can include a discontinuous DC deck.

The designer then views a default arrangement for the main passageways on the DC deck and edits this arrangement as desired. A typical result is shown in **Figure 18**. This also shows the Zone-deck location of the athwartship passageways and the stair towers. These are still arrangeable items, but the designer can edit the Zone location of the athwartship passageways and the placement of the stair towers inboard or outboard of the main passageways. With the main passageways defined, the Zone-decks and Sub-Zone-decks on the DC deck are defined. The designer can also declare Zone-decks as exclusion zones at this time if they are outside the scope of the arrangements problem; e.g. machinery rooms, tankage or voids.

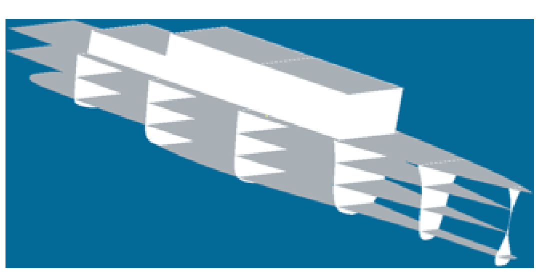

Figure 16: *Visualization of Zone-deck Envelope*

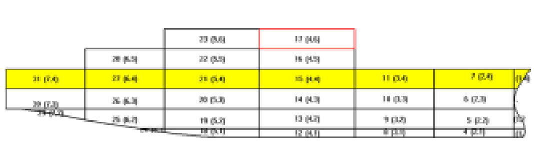

Figure 17: *Designation of the Damage Control Deck Zone-decks*

The designer next links to the MS Access Library file to obtain the SSCS-based ship space list and the default constraints for these space types. The designer then edits these to reflect the specific unique requirements for the particular design. At this point the number and capacity of the various staterooms, etc. are created resulting in a unique space requirement for each compartment. Spaces can be designated by gender and other detailed use specifications at this time. Spaces, such as the bridge or chain locker, can also be fixed to a particular Zone-deck at this point if the designer knows where they must be and they are, thus, not included in the allocation optimization.

With the Zone-decks and the required spaces and their characteristics and constraints specified, the designer can instantiate the objects for these elements, and the arrangements design proceeds with the optimal allocation. The results of the allocation can be evaluated by the designer through visualization of the inboard profile, as will be shown in the example below, or by studying the design model tree in which the results for each Zone-deck, space, and constraint can be interrogated in detail. Following acceptance of the Zone-deck allocation, the designer edits a priority order for the Zone-deck detailed arrangement. The Zone-deck topology and geometry optimization can then proceed. The designer can edit the default optimization parameters and constraints as desired at each level.

When the designer is satisfied with the final results, they will be returned to the design's LEAPS database automatically. This requires the use of an automated re-GOBERIZER that can replace the ship definition granularity as shown in

Figure 16 with a more detailed definition of each of the arranged spaces while maintaining the integrity of the LEAPS relational geometry representation.

Example Allocation

The example vessel presented here is an artificial demonstration design that the ISA team has named the Habitability Ship. It has its origins in a non-US Navy 3,150 tonne, 109 m Notional Corvette design (Figure 2). This was a two-gender design using an Officer, PO, and Specialist (enlisted) nomenclature. Because there is publication sensitivity associated with this design and with the default constraints associated with the combat related spaces, the ship was reduced for demonstration purposes to just contain the propulsion and habitability aspects of the original design. All combat spaces, one superstructure deck, and six vertical WT zones were eliminated from the vessel and the hull form was scaled to enclose this reduced size. One engine room was eliminated. The net result is a vessel with an abnormally large fraction devoted to habitability spaces.

The Habitability Ship is the example shown here in Figures 5, 16, 17, and 18. The design consists of 103 spaces, 14 of which are fixed including the bridge; bridge-related electrical equipment rooms (2); steering gear (2); anchoring and mooring, mooring area and gear storerooms (3); enclosed RIB stowage area, boat gear locker, main machinery room (2 levels); and auxiliary machinery room. There are a total of 1,307 goals and constraints.

The allocation for the Habitability Ship was optimized using the parameters listed in **Table 1**. A population of 10 was run for 1,500 generations. A generation here is one round of GA operations and one cycle of space and Zone-deck agent proposals that can produce up to five changes each. The Zone-deck area utilization used a "mean" plateau from 0 to either 0.95 (above the DC deck) or 0.90 below. Thus, there was no penalty for underutilization of the Zone-deck. The mean time per generation was 6.59 seconds

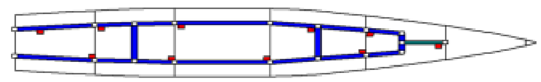

Figure 18: *Main Passageway Arrangement and the Placement of Athwartship Passageways and Stair Towers on the Damage Control Deck*

on a 2 GHz Intel Pentium Mobile PC with 1 GB RAM.

The resulting fitness (total utility *U*) history is shown in **Figure 19**. The maximum utility exceeds 0.75 within about 40 generations. The best solution was essentially reached in 181 generations requiring about 20 minutes. No further improvement was found out to 1,500 generations. The mean utility of the 10 chromosomes in the population is highly variable as the GA operations continue to introduce new allocations into the population.

The mean fitness dropped whenever the lower solutions were reseeded because the best solution was unchanged for 100 generations. This feature was included to give greater assurance that the solution had not settled on a local maximum. The resulting allocation is shown on an inboard profile schematic in **Figure 20**. The gray Zone-decks are not arrangeable. The fixed spaces are listed in red. The aft five Zone-decks on the Second Deck, the DC Deck, contain Port, Center, and Starboard Sub-Zone-decks. In total

TABLE 1: Allocation Optimization Parameters

Parameter	Value
Population	10
Generations	1,500
Utilization left mean	0.0
Utilization left sigma	Irrelevant
Utilization right mean	0.9 or 0.95
Utilization right sigma	0.2
Crossover probability	0.2
Mutation probability	0.2
Two-space swap probability	0.8
Two-zone-deck swap probability	0.2
Mean CPU time per generation	6.59 s
CPU time standard deviation	0.85 s

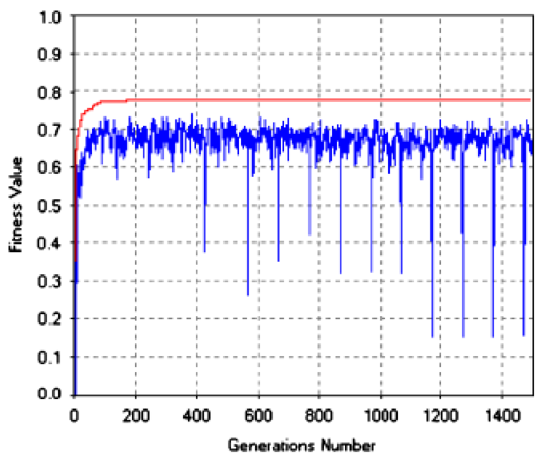

Figure 19: *Allocation Maximum (Red) and Mean (Blue) Fitness (Overall Utility) History*

there are 29 arrangeable Zone-decks and Sub-Zone-decks into which the 89 arrangeable spaces are allocated. This results in a theoretical search space of $29^{89} = 1.4\times10^{130}$ possible allocations.

In general, the arrangement is very satisfactory with a total utility of 0.778. This is composed of the three component terms in equation (3) with a minimum Zone-deck area utilization utility $U_1 = 0.987$, average Zone-deck area utilization utility $U_2 = 0.999$, and weighted average minimum space utility $U_3 = 0.790$. The U_3 value characterizes the amount of compromise necessary for a solution.

The least utilized Zone-decks are the center Sub-Zone-deck at the stern on the second deck (Zone-deck 39) at $U_{U39} = 0.636$ and the starboard Sub-Zone-deck at the stern on the second deck (Zone-deck 41) at $U_{U41} = 0.653$ indicating that there is unassigned area available in the vessel.

The least satisfied space is the Specialist Cabin (Male) (6) in the center Sub-Zone-deck in the second subdivision on the 2nd deck (Zone-deck 11) with minimum utility of 0.30. Of the remaining arrangeable spaces, a total of 34 spaces have a minimum utility of 1.0, 1 has 0.90,

	Subdiv 6 **STERN**	Subdiv 5	Subdiv 4	Subdiv 3	Subdiv 2	Subdiv 1 **BOW**
Level 01			ZONEDECK 29: RESIDENT SPACES: SPACE 29: Engineer Officer Cabin SPACE 36: Fan Room (Deckhouse) SPACE 48: Officer Cabin (Male)(2) & Bath GrpA SPACE 49: Officer Cabin (Male)(2) & Bath GrpA 1 SPACE 50: Officer Cabin (Male)(2) & Bath GrpA 2 SPACE 51: Officer Cabin (Male)(2) & Bath GrpA 3 SPACE 97: XO Cabin & Bath	ZONEDECK 21: RESIDENT SPACES: SPACE 12: Bridge SPACE 19: Electrical Equipment Room SPACE 20: Electrical Equipment Room 1 SPACE 52: Officer Cabin (Male)(2) & Bath GrpB		
Main Deck		ZONEDECK 36: RESIDENT SPACES: SPACE 7: Boat Gear Locker SPACE 11: Bosun Storeroom (MainDeck) 1 SPACE 22: Electrical Equipment Room 3 SPACE 30: Enclosed RIB Stowage SPACE 37: Fan Room (Deckhouse) 1 SPACE 57: Officer Cabin (Female)(2) & Bath 1 SPACE 68: PO Cabin (Female)(4) & Bath	ZONEDECK 28: RESIDENT SPACES: SPACE 6: BC Medical Facility SPACE 25: Electrical Equipment Room 6 SPACE 43: Medical Consultation Room SPACE 44: Medical Storeroom SPACE 56: Officer Cabin (Female)(2) & Bath SPACE 58: Officer Cabin (Female)(2) & Bath 2 SPACE 77: Sick Bay	ZONEDECK 20: RESIDENT SPACES: SPACE 10: Bosun Storeroom (MainDeck) SPACE 16: CO Cabin & Bath SPACE 17: CO Storeroom SPACE 28: Electrical Equipment Room 9 SPACE 53: Officer Cabin (Male)(2) & Bath GrpB 1 SPACE 54: Officer Cabin (Male)(2) & Bath GrpB 2 SPACE 55: Officer Cabin (Male)(2) & Bath GrpB 3		
DAMAGE CONTROL DECK 2nd Deck	ZONEDECK 40: Port RESIDENT SPACES: SPACE 35: Fan Room (Hull) 4 SPACE 46: Mooring Area & Gear Storeroom (Aft) ZONEDECK 39: Center RESIDENT SPACES: SPACE 8: Bosun Storeroom (Aft Mooring) SPACE 61: PO & Specialist Dining Room 1 ZONEDECK 41: Starboard RESIDENT SPACES: SPACE 23: Electrical Equipment Room 4 SPACE 47: Mooring Area & Gear Storeroom (Aft) 1	ZONEDECK 34: Port RESIDENT SPACES: SPACE 34: Fan Room (Hull) 3 SPACE 71: Daily Provision Room ZONEDECK 33: Center RESIDENT SPACES: SPACE 27: Electrical Equipment Room 8 SPACE 40: Galley & Scullery ZONEDECK 35: Starboard RESIDENT SPACES: SPACE 102: PO & Specialist Dining Room 3	ZONEDECK 26: Port RESIDENT SPACES: SPACE 15: Cleaning Gear Storeroom (Below Decks) SPACE 62: PO & Specialist Dining Room 2 ZONEDECK 25: Center RESIDENT SPACES: SPACE 33: Fan Room (Hull) 2 SPACE 72: Recreation Room SPACE 96: Wardroom ZONEDECK 27: Starboard RESIDENT SPACES: SPACE 21: Electrical Equipment Room 2 SPACE 60: PO & Specialist Dining Room	ZONEDECK 18: Port RESIDENT SPACES: SPACE 76: Ships Office SPACE 93: Training Room ZONEDECK 17: Center RESIDENT SPACES: SPACE 63: PO Cabin (Male)(4) & Bath GrpA SPACE 64: PO Cabin (Male)(4) & Bath GrpA 1 SPACE 65: PO Cabin (Male)(4) & Bath GrpA 2 ZONEDECK 19: Starboard RESIDENT SPACES: SPACE 26: Electrical Equipment Room 7 SPACE 32: Fan Room (Hull) 1 SPACE 90: Electrical Switchboard Room 1	ZONEDECK 12: Port RESIDENT SPACES: SPACE 9: Bosun Storeroom (Fwd Mooring) SPACE 24: Electrical Equipment Room 5 SPACE 31: Fan Room (Hull) SPACE 38: Foul Weather Gear Locker ZONEDECK 11: Center RESIDENT SPACES: SPACE 81: Specialist Cabin (Male)(6) GrpB ZONEDECK 13: Starboard RESIDENT SPACES: SPACE 94: Library	ZONEDECK 7: RESIDENT SPACES: SPACE 3: Anchoring & Mooring SPACE 45: Mooring Area & Gear Storeroom (Fwd)
1st Platform	ZONEDECK 38: RESIDENT SPACES: SPACE 5: Battery Locker and Charging SPACE 69: POL & Paint Locker (Storage) SPACE 70: POL & Paint Locker (Service) SPACE 75: Sewage Treatment Machinery Room SPACE 87: Steering Gear Room SPACE 88: Steering Gear Room 1 SPACE 92: Electrical Switchboard Room 3 SPACE 95: Trash Room	ZONEDECK 32: RESIDENT SPACES: SPACE 18: Cool Cold Dry Provisions SPACE 41: General Stowage SPACE 42: Linen Locker SPACE 59: Laundry (Officer & PO) SPACE 73: Refrigerator Machinery Room SPACE 86: Laundry (Specialist)	ZONEDECK 24: RESIDENT SPACES: SPACE 99: MMR Diesel (1stPlatform)	ZONEDECK 16: RESIDENT SPACES: SPACE 66: PO Cabin (Male)(4) & Bath GrpB SPACE 67: PO Cabin (Male)(4) & Bath GrpB 1 SPACE 74: SD Storeroom SPACE 78: Specialist Cabin (Male)(6) GrpA SPACE 79: Specialist Cabin (Male)(6) GrpA 1 SPACE 80: Specialist Cabin (Male)(6) GrpA 2 SPACE 85: Specialist Cabin (Female)(6) 1	ZONEDECK 10: RESIDENT SPACES: SPACE 82: Specialist Cabin (Male)(6) GrpB 1 SPACE 83: Specialist Cabin (Male)(6) GrpB 2 SPACE 84: Specialist Cabin (Female)(6)	ZONEDECK 6: RESIDENT SPACES: SPACE 13: Chain Locker SPACE 89: Electrical Switchboard Room
Hold	ZONEDECK 37: RESIDENT SPACES:	ZONEDECK 31: RESIDENT SPACES: SPACE 0: Aft Pump Room SPACE 91: Electrical Switchboard Room 2 SPACE 101: Mechanical Workshop (General)	ZONEDECK 23: RESIDENT SPACES: SPACE 98: MMR Diesel (Hold)	ZONEDECK 15: RESIDENT SPACES: SPACE 1: Air Conditioning Room SPACE 39: Fwd Pump Room SPACE 100: AMR	ZONEDECK 9: RESIDENT SPACES: SPACE 2: Air Conditioning Room 1	ZONEDECK 5: RESIDENT SPACES: SPACE 4: Auxiliary Propulsion Room SPACE 14: Chain Locker Sump
Doublebottom		ZONEDECK 30: RESIDENT SPACES:	ZONEDECK 22: RESIDENT SPACES:	ZONEDECK 14: RESIDENT SPACES:	ZONEDECK 8: RESIDENT SPACES:	ZONEDECK 4: RESIDENT SPACES:

Figure 20: *Allocation of Spaces to Habitability Ship (Gray Unarrangable Zone-Decks; Red Fixed Spaces; Black Outside Vessel)*

24 have 0.80, 1 has 0.75, 1 has 0.70, 4 have 0.60, and 23 have 0.50. The fact that all of the spaces were not able to achieve a minimum utility of 1.0 is evidence of the high degree of compromise necessary in typical arrangement design.

Conclusion

The ISA optimization algorithms and software system provides a new way to efficiently obtain a rational arrangement for naval surface ships. The design process remains under the control of the arrangements designer, who expresses the design needs and requirements in the form of simple, intuitive fuzzy constraints and goals. Once developed for a particular class of ships, these can be captured to facilitate knowledge retention and to ensure that all standard requirements are met in future similar designs.

When the ship arrangements geometry is captured within the software, future ISA enhancements could address distributive system design and redundancy issues, including component location, stores strike down analyses, General Quarters and evacuation routing analyses, etc. When coupled with a three-dimensional geometry and graphics capability, the optimization technology developed in this effort could also be extended and applied to topside arrangements design optimization and the arrangements of components and equipment within submarines. This three-development, as well as further development, extension and enhancement of the current ISA system, are now underway at the University of Michigan under Navy sponsorship.

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Author Biographies

Michael G. Parsons was the principal investigator for the ISA research and code development. He earned his B.S.E. (NA&ME) from University of Michigan, MME from the Catholic University of America, and Ph.D. (Applied Mechanics) from Stanford University. He served on active duty for 6 years at Naval Reactors–NAVSEA 08. He was an NA&ME faculty member of the University of Michigan for 35 years. He is a member of ASNE and Fellow, Honorary Member, and Webb Medalist of SNAME. He is now Professor of NAME Emeritus and Arthur F. Thurnau Professor Emeritus at University of Michigan.

Hyun Chung obtained his M.S.E. and Ph.D. (NA&ME) from the University of Michigan following undergraduate work at the Seoul National University. He has focused on object-oriented software and database development in addition to his specialization in tolerance analysis and control in the welding of assemblies. As a Post-Doctoral Scholar, he led the ISA code development.

Eleanor Nick earned her M.S.E. and Ph.D. (NA&ME) and M.S.E. in Mechanical Engineering from the University of Michigan following undergraduate work in ME (with a minor in architectural studies) at Tufts University. She had an undergraduate year abroad at University College London where she studied ME and basic NA subjects. Ellie was a National Defense Science and Engineering Graduate Fellow. She had a major role in the ISA design and developed the topology and geometry optimization algorithms, in particular, for ISA. She is a member of ASNE and SNAME. Upon graduation she joined The Glosten Associates, Seattle.

Anthony Daniels earned his B.S.E., M.Eng., and Naval Architect degrees in NA&ME and M.S.E. in Industrial and Operations Engineering from the University of Michigan. He worked for JJMA/Alion for 3 years before returning to the University of Michigan. Tony had a major role in the ISA design and developed the space and constraint database and its management system and the hybrid agent/GA algorithms and software for the allocation optimization, in particular, within ISA. He is now a research engineer at the University of Michigan where he is continuing the ISA development in collaboration with David J. Singer.

Su Liu earned his B.S.E. and M.S.E. in Computer Science from the University of Michigan. He served as a principal programmer for ISA code development. He is now employed at Microsoft.

Jignesh Patel, Associate Professor of Computer Science, University of Michigan, helped guide ISA code development. He earned his B.Tech. from Benaras Hindu University in India and his M.S. and Ph.D. (Computer Sciences) from the University of Wisconsin–Madison. His research focuses on various aspects of database management systems. He is member of IEEE. He recently returned to the University of Wisconsin–Madison.