Combatant Ship Engineering, A Different Approach

■ Charles Gallagher

Abstract

In 1989, Ingalls Shipbuilding contracted to design and construct three Sa'ar V Class corvettes for the Government of Israel. The available funding was considerably less than would have been needed to design and build equivalent ships for the US Navy. As a result, the Israeli Navy (IN) and Ingalls Shipbuilding, working closely together, implemented significant innovative systems engineering and design practices and the ships were delivered within the budget. Some of the key innovative design and engineering methods used during that program are described in this paper.

Nomenclature:

AOA: Analysis of alternatives

ASSET: Advanced surface ship evaluation tool

CAD: Computer-aided design

CODAG: Combined diesel and gas turbine

CODOG: Combined diesel or gas turbine

ICAM: Integrated computer-aided manufacturing

IDEF0: ICAM Definition language

OEM: Original equipment manufacturer

QFD: Quality function deployment

SI: International system of units

SWBS: Ship work breakdown structure

TLR: Top-level requirement

UML: Unmodified modeling language

Historical Background

The name Sa'ar—storm or gale in Hebrew—was chosen by the Israeli Navy (IN) for its new strike boats. The program began in 1965 with an order for two batches of six boats. Lűrssen Werft of Bremen designed the boats and they were built by CMN in its Cherbourg shipyard. The first 12 boats had various combat systems, which resulted in evolutionary designations—Sa'ar I, II, and III. The Sa'ar IV was once again designed by Lűrssen, but the ships were built by Israeli Ship Yards in Haifa. The two Sa'ar 4.5 boats are modified Sa'ar IVs that can carry a helicopter.[1,2]

[1]Commander Uzi Tishel, Israeli Navy, United States Naval Institute Proceedings, March 1992.

[2]See also "The Boats of Cherbourg" by Abraham Rabinovich for a thrilling tale of intrigue, diplomacy, and daring related to the design, construction, and delivery of five of the boats.

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The Sa'ar V Contract

Sa'ar V, although based on the Sa'ar 4.5, was to be larger and better. The preliminary design was accomplished by John J. McMullen in Arlington, Virginia. Ingalls Shipbuilding International was awarded the detail design and construction contract May 1, 1989 under the Foreign Military Sales program but using the less common feature of a commercial contract with the Government of Israel. The first ship delivery was scheduled for November 1993. The GOI Contracting Officer remained in New York City. The IN engineering team that worked with JJMA in Arlington, Virginia, relocated to Pascagoula, Mississippi, when the design and construction contract was awarded.

The Team

The IN team consisted of naval officers with graduate engineering backgrounds. It was led by a Captain and included four Commanders to handle the seven Ship Work Breakdown Structure (SWBS) groups, and a Lieutenant Commander for Logistics. All were married with families and had a previous tour in the United States. They were a close-knit integrated group and made all the decisions together, including program management, engineering, and subcontract management.

The Ingalls team was led by a lead engineer for each major SWBS plus one for the Ship Monitoring and Control System, and one for Logistics. They were collocated in an office "bull pen" environment to facilitate communications. Their charter was to keep the costs down by doing everything they could by themselves before calling upon other engineers and designers. The Ingalls Program Office had 10 personnel: the program manager, a deputy, a technical director, one scheduler, one financial analyst, two administrative support personnel, and three technical support personnel. Interface was primarily between the Ingalls engineering team and the IN team. The Ingalls Program Office would become involved with some of the more difficult technical questions and contractual scope questions.

Systems Engineering

Of the many definitions of systems engineering, the one that best describes this effort is that it is an interdisciplinary field of engineering that focuses on the development of complex systems. Typical systems engineers are aware of tools such as UML, QFD, IDEF0, the waterfall model, the VFE model, and more. A systems engineer working on a US Navy warship would have some familiarity with the AOA, TLR, ASSET, mission needs statement, and more. On the Sa'ar V program, many of the systems' engineering tasks were followed but with a huge difference in that in order to hold down the program costs, the analyses were largely performed in oral discussions between the IN and Ingalls.

During the detailed design and construction period, there were virtually no systems engineering analyses on paper. All of the analyses were performed by acquiring the data and discussing the approach. Sometimes, this was done within the Ingalls team but more often than not, the more significant matters were handled by the IN team. The remainder of this paper will describe some of those decisions. In each case, these decisions involved a matter that was within the general scope of the ship specifications but otherwise not defined to the level needed for detailed design.

Also, in each case, the engineering approach used was to resolve each matter without resorting to detailed paper analyses. Round-table discussions of the integrated team were the order of the day. The IN decisions were typically made around a table with ample discussion about all aspects of the situation until a consensus was reached.

The same result might have been achievable by a traditional USN approach, but at a much larger cost that included paperwork, studies, analyses, and travel. The IN team would first acquire all of the available facts and then the decision analysis process was normally one of joint discussions.

Another relevant factor was that each IN engineer owned his own budget for his portion of the ship. Before this contract, Ingalls engineers were not permitted to participate in subcontract negotiations. Engineers set requirements. Subcontract administrators conducted the negotiations. Technically, this rule was maintained on the Sa'ar V program, but only technically. The IN lead engineer would be in the negotiating room listening but not commenting unless invited. Only he knew the allocated budget. At appropriate times, there would be a break for sidebar discussions with the Ingalls Shipbuilding Subcontract Administrator to discuss and clarify some aspect of the requirements in order to reduce the costs.

The IN made the distinction between technical discussions, which can involve the cost of items, and price negotiations, which involve commercial matters such as insurance, the escalation factor, patent rights, and more.

This proved to be a very successful effort as numerous technical agreements and adjustments were made during these negotiations. As a result, the cost was controlled by eliminating the traditional paper process of engineering changes.

Example Design Decision Making

One of the most expensive cost drivers for the first ship of any class occurs during the construction period when physical interferences are discovered and must be corrected.

Implementation of Three-Dimensional Computer-Aided Design (3D CAD)

Following internal discussion with senior Ingalls Shipbuilding management, the decision was made that for the first time the entire design of a major warship would be checked for interferences using three-dimensional computer programming. While this was an exceedingly complex process, it did alleviate the prohibitively costly normal documented systems engineering approach and thus constituted a significant systems engineering decision.

In hindsight, the computer programming aspects proved more difficult than envisioned, in particular due to the extensive computer processing times; however, potential physical interferences were discovered and corrected in the 3D CAD environment with their associated cost savings. An unexpected benefit of the Sa'ar program was that it launched Ingalls Shipbuilding into the increased use of CAD (Lindgren et al. 1992).

Combat Systems Procurement

The combat system was planned to be the largest procurement on the program. Originally, it was planned to use the traditional combat system integrator approach. Due diligence was spent preparing the statement of work and technical specification with an emphasis on reducing costs including a bidder's conference to ensure understanding.

Unfortunately, we received a traditional combat system integrator proposal with all responders quoting prices far in excess of the available budget. At this point, the IN team regrouped and approached Ingalls with a different concept proposal; a combat system integrator would not be hired, and instead, Ingalls Shipbuilding would take that responsibility along with admittedly an increased risk. Ingalls Shipbuilding accepted this new shared responsibility with much of the pressure and responsibility residing with the IN.

The procurement of some equipment was delayed and some equipment would be installed in Israel rather than at Ingalls. Also, some equipment would be refurbished, used equipment rather than new. All possible cabling, some equipment, and certain other provisions would be incorporated into the delivered ship. For example, the original Phalanx Close-In Weapon System was actually a refurbished unit with some unique changes invented by and installed by the IN.

Logistical Support

The IN, as a cost-savings and maintenance-independent effort, chose to perform maintenance and repair on all of its electronic circuit cards. Ingalls Shipbuilding would negotiate for the design rights and computer program information at a level that allowed repair.

The IN already had an extensive in-house repair capability but did elect to purchase some additional repair and test equipment to maintain circuit cards that would be new to the IN inventory. This innovation allowed the IN never-before-known circuit card maintenance independence and reduced the probability of electronics-related equipment down-time. While the USN would consider this an example of life-cycle cost reduction, the IN considered it a standard requirement, reflecting the reality that in battle things need to be fixed immediately, on site.

Supportability is a systems engineering principle that the IN elected to handle in a unique manner. Each original equipment manufacturer (OEM) was requested to guarantee support for 10 years at no additional cost. If the OEM declined or wanted reimbursement for this effort, then typically another source was found.

Another common procurement approach was to merely repeat back to the OEM a copy of his advertising literature. This proved to be quite efficient and occasionally resulted in some unusual OEM feedback when it was realized that the brochure had not undergone a rigorous technical review.

Equipment Testing

A fundamental engineering principle is to inspect the equipment at the factory, especially if it has new design features or is something that is not often produced. All significant Sa'ar V procurement contracts had a provision for factory acceptance testing with prior notification in the event the IN wanted to witness.

A traditional USN approach would have a test plan and detailed test procedures. These would be prepared, reviewed, and updated, all at significant expense.

The IN approach was to discuss factory acceptance testing with the OEM before contract award and include whatever was agreed to in the purchase order. Typically, this was whatever a manufacturer declared to be the approach he had bid as his standard; this is something that would ensure his quality product but would not cost more. It was based on common sense and good engineering practice. The manufacturer would merely agree to invite us to send an engineer to witness the testing. The IN would attend those events considered appropriate, and here another new experience occurred.

The IN engineer would examine the equipment in great detail based on his extensive experience and sound engineering judgment. This inspection was not simply a matter of checking off items on a test procedure. In every single case, save one, where the IN engineer elected to participate in factory acceptance testing, deficiencies were noted.

The experience is similar to an Admiral Rickover observation about a good engineer: "He was one of the breed of men taught by experience. These engineers—and I proudly and with no false humility class myself with them—could walk through an engine room and, through the din and uproar, catch the slight sound of a component out of adjustment. They could touch a jacket of metal and feel from the vibrations whether the machinery inside was operating well. They would taste boiler water to see if it were pure, and would dip their fingers into the lubricating oil to find out if a bearing was running hot" (Rickover 1974). Admiral Rickover would consider the IN team to be good engineers.

English or Metric Units

A key engineering challenge was the use of the international system of units (SI), the modern metric system of measurement. Again, the round table convened, first with the IN team and then with the Ingalls team. The IN team decided that they were comfortable with either system of measurement. While metric was preferred, there could not be a cost increase to implement the change.

The Ingalls team convened with the IN and recognized that the use of metric was being emphasized nationally and it would benefit Ingalls Shipbuilding to be on the leading edge of the adoption of SI. Ingalls engineering was consulted and indicated there would be no additional cost for using the SI system.

The Ingalls team rapidly decided that the ship would be designed in metric and then addressed the ship construction documentation and the work force. It was then decided that the risk of issuing the construction data packages in metric would present too much of a cost risk.

The ships would be constructed using work packages in English units. Ingalls then addressed the fact that most equipment was coming from six countries, five of which used the SI system. The decision was again to use the least cost approach. If the equipment was designed in English units, English units would be accepted. If it was designed in SI units, Ingalls would accept SI units. In this manner, the craftsmen would be introduced to the SI system but on a manageable level. Mounting hardware stock was added for the SI equipment as were pipe adapters; it turned out that the adapters were readily available.

Backup Power

Critical equipment was required to have the capability of operating from one of the three DC backup power systems.

Once again, key equipment was located. In most cases, it already had the DC power option built in. There were several exceptions. One option was to pay the equipment manufacturers to modify their equipment. This would have been an expensive approach and after one of the systems engineering brainstorming sessions, the decision was made to procure two inverters instead as this would be the less costly approach.

Because of cost constraints, the inverters would be commercial units. Based on an inspection of the units, the engineers decided to make modifications to harden them for the shipboard environment. This was accomplished by Ingalls in the yard.

Stealth Hull Design

It is noticeable from the shape of the Sa’ar V that it is designed for a reduction in its radar cross section signature. One result was the creation of some small oddly shaped internal compartments. These immediately became rooms for the installation of electronic equipment. None of these compartments were scheduled to be manned and so another round-table discussion resulted in relaxing some of the criteria that would normally be applied for the satisfaction of standard human engineering criteria and making the need for the human to bend over or crouch down perfectly acceptable.

CODOG Power Plant

The Sa’ar V is a combined diesel or gas turbine (CODOG) configuration with an LM2500 for high-speed operation. The IN desired to have the maximum power available if needed for an emergency and to get the maximum power on line rapidly, again, only for the most unusual circumstances.

Three innovative changes were made to the then standard CODOG configuration. First, the team met with GE and CAE[3] to figure out a way to get more than the standard 25,000 hp. This was not an easy task but could be done, provided the IN was willing to accept the fact that operating a gas turbine above its normal limits will decrease its life expectancy.

The IN carefully explained that there are times in war when the extra power may be needed and so they wanted it designed into the ship machinery control system (SMCS). Once the

[3]The organization is now part of L-3 and is known as MAPPS. They continue to design and manufacture ship monitoring and control systems for numerous countries.

issues of the previously impenetrable wall of proprietary concerns were resolved, implementation was not all that difficult. GE provided the technical data for operating the engine at 30,000 hp and CAE developed the extended control algorithms.

As with most major machinery packages, there was on-plant software capable of full control as well as the off-plant software imbedded in the SMCS. Sensor limits were established as were sensing frequencies to ensure that the data needed for the critical decisions would always be available.

A second aspect of this emergency operating mode was the desire to have the capability to ramp up to the maximum power in the minimum time. This also was not too difficult with the GE, CAE, and IN engineers sitting around the table. GE also provided a second power curve that could be used in an emergency, provided that the technical risks were accepted. This second curve was programmed into the SMCS software and can be activated from whichever SMCS console is in control.

The teams then got into the subject of CODOG or combined diesel and gas turbine (CODAG). Clearly, the LM2500 so overpowered the two diesels that it was the mode for high-speed operation. However, in the speed ramp-up CODOG practice required a plateau while the diesels were brought off line and the gas turbine was brought on line.

For this discussion, Ingalls also had to deal with Falk and Renk, who designed and manufactured the reduction gear. They essentially said that their gear did not mind if the plateau were eliminated. It was not a reduction gear issue; it was a control system issue. CAE decided they had enough technical information from Falk, Renk, GE, GasTOPS, and MTU[4] to make the emergency power application a smooth transition.

[4]GasTOPS provided the propulsion dynamic analysis algorithms embedded in the SMCS. MTU provided the diesel engines.

This meant that for a brief period of time, the propulsion system would be in a CODAG configuration in order to eliminate the period of time on the change-over plateau.

Thus, the Sa'ar V has an SMCS that permits the conning officer to implement full emergency speed with one console command. The control system takes over and brings the full 30,000 hp to bear in the shortest time.[5] There is one instance when the consensus of the engineering teams did not prevail. It involved one aspect of the SMCS. This extensive system was in the early test stages at the CAE facility outside of Montreal. We reached the conclusion that we could control the ship heading quite well with either a joy stick or a small knob on the ship control console. As with other significant ship design decisions, the matter was taken to the Captain of the IN team as the team leader he was the final authority on any controversial matters. The matter was explained technically and demonstrated. He replied that he agreed—but—there is a matter of naval tradition to uphold and therefore we must have a traditional helm wheel.

Accordingly, Ingalls proceeded with this one departure from the engineering recommendation. A standard helm wheel was chosen; then CAE designed a mechanical friction feedback device to give the helmsman the feeling that he was turning a mechanism of some substance while in fact he was turning a potentiometer about half the size of one's thumb.

Hull Stability

How would the ship roll? The tow tank testing provided the basics, and yet uncertainties remained. Was additional (and expensive) testing needed? One of the key times when rudder roll stabilization might be helpful would be during helicopter operations.

Like all good naval engineers, the IN team was interested in the possibility of improving the sit-

[5]This was the first time that the LM2500 system was designed to 30,000 hp.

uation and the SMCS easily incorporated an existing inexpensive module for rudder roll stabilization, and so that was done. The rudders and their support system could handle the loads. But the only way to know for sure whether the helicopter could operate safely under adverse weather conditions was to wait until the ship was built and encountered those conditions. In order to accommodate this approach, the extra rudder control pumps were designed into the ship, but not procured. They could be procured and installed later if conditions warranted.

Ship Machinery Control System

The SMCS was the most advanced at the time and it still remains far ahead in many subtle and not so subtle aspects. The system engineers again caucused to determine those features most important to a reduced crew size.[6] Many features were incorporated. Only a few examples will be mentioned here. A significant danger on any ship is the risk of fire. With the quantity of unmanned spaces, it is important to have extensive fire and smoke detection capability. This was accomplished with several sensors, and with the small crew, it is all the more important to extinguish the fire rapidly.

Automated Damage Control

This was accomplished by permitting the system, under certain circumstances, to automatically trigger a fire suppression system in the affected compartment. Various types of sensors and extinguishing media were selected and the decision time came for what logic would be used to initiate the automatic suppression. The engineers were simply not happy relying on any single sensor or any single type of sensor. One of them suggested we use two different types of sensors as the criteria. This rather simple thought caught on immediately. There were nods around the room and so it was implemented.

[6]The ship is designed to operate easily on normal missions with a crew of 45. For extended missions, the crew can be increased to 61. If a helicopter or other special operations group is aboard, there could be 10 additional personnel for a total of 71.

Automated Acoustic Quieting

Another time, the teams were thinking about the overall protection of the ship during different combat scenarios. Invariably, the discussion turned to the ship's acoustic signature. In short order, it was realized that any effort to have the humans establish a quiet ship condition would take an unacceptable amount of valuable time. In addition, the process could be complex, depending on the condition of the ship at the time. And as humans would be relied on to take the necessary actions, there was the possibility of error. It was then realized that all of the pieces of machinery that were needed to be controlled acoustically were already under the control of the SMCS.

The solution became obvious. Quiet ship operation would be implemented through the SMCS, and to make it even simpler, all of the necessary sequencing logic would be in a single algorithm and activated by a single special-purpose button on the ship control console.

Automated Failure Mode Control

A final example from the SMCS lies in the failure mode. Failures were handled in the software and hardware design to fail set rather than fail safe.[7] If a propulsion shaft was turning, the failure mode was to keep it turning. If a motor was running, the failure mode was to keep it running. In this way, if the SMCS lost control, things would continue to function as they had been set until such time as the SMCS could regain control or until local control was taken.

Selection of Machinery Sensors

Sensors were of particular interest to the IN. The overarching requirement was for good-quality marine-grade sensors. The natural effort by the Ingalls team was to pull out the standard Military Specifications. The IN explained that the marine industry had developed just about every

[7]It is interesting to note that a Google search discloses nine definitions for fail safe but not one for fail set.

sensor we would need and generally had several classes of each sensor from the least expensive to the good quality to the explosion proof. Although some Military Specification sensors ended up in the design, it was not the primary consideration.

Machinery Repair Considerations

It turns out that a primary consideration was the ability to repair equipment within the IN without recourse to the OEM. Part of the overall planning of the Israeli Defense Forces is to be ready when called upon, including the ability to repair anything rapidly and as close to the place of use as possible. As part of this sensor selection effort, every sensor was submitted to the IN for approval before it was incorporated into the design. This included those sensors built into and supplied as a part of an OEM item. In every case save one, good-quality repairable marine-grade sensors were located and selected. The one exception was the differential pressure sensors for the collective protection system (CPS). Perfectly good differential pressure sensors were available but their scales were large when compared with the CPS needs of only a few pounds per square inch.

Summary

The Sa'ar V was designed to achieve the greatest capability at the least cost. Many engineering principles were based on extensive open roundtable discussions among collocated engineers, but without the traditional systems engineering documentation. The IN was very pleased with the ships and Ingalls Shipbuilding earned a profit.

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Author Biography

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