The Efficiency of Reverse Engineering in the Design of the ORCA XI Autonomous Underwater Vehicle

by

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Submitted to the Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degree of

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Abstract

Reverse engineering is the process of determining how a system works to aid duplication, maintenance, or redesign. Applications of reverse engineering include mechanical, electrical, software, and process systems. Although it has been known for centuries in the vernacular as tinkering with things to see how they work, reverse engineering has only recently been recognized as a systematic process valid for study. Reverse engineering can be applied to both simple and complex systems. The MIT ORCA team applied reverse engineering to build ORCA XI, the first autonomous underwater vehicle (AUV) to issue forth from the ORCA Project in several years. In addition to college-level systems, reverse engineering can be applied to navies, aiding in the prototyping of individual vessels as well as the manufacturing of entire fleets. There is evidence that China is using reverse engineering in this manner to develop a regionally-capable navy. The effectiveness of reverse engineering on the ORCA Project is compared to that of the Chinese navy to determine how a reverse engineering method could be expected to scale from a simple system to a more complex one. To quantify the relationship between the complexity of the system and how effective reverse engineering that system is, a reverse engineering efficiency based on the time necessary to complete a project with reverse engineering and the time necessary to complete the same project without reverse engineering was used. The efficiency values obtained from this comparison show that applying reverse engineering to an AUV can be just as effective as applying reverse engineering to a naval vessel, but that designing the production line necessary to manufacture a fleet of vessels decreases the efficiency of reverse engineering. These results suggest that new reverse engineering methodologies can be tested for efficiency on simple prototypes before being applied to time-consuming, complex projects.

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1. Introduction to Reverse Engineering

1.1 What is Reverse Engineering?

Ingle [3] is the major source for this introduction, because reverse engineering has only recently been considered a valid field of study. Despite being only newly studied, for centuries the concept of reverse engineering has been known informally as tinkering. The principle underlying tinkering and reverse engineering is learning how a mechanical system works by breaking it down into its component pieces, studying how each piece was made and how it works within the whole, and then building the system back up again. However, using reverse engineering to copy a product and sell it as one's own is a form of design theft, and led to the concept of patents. Patents appeared in Italy around the 15th century as a way to protect designers from tinkerers who could copy their products for a profit. Eventually patent laws spread to the new world, appearing in the United States around 1790.

The two main legal concerns for modern reverse engineering are patent infringement and design infringement. If a mechanical component is patented, then using reverse engineering to duplicate the component constitutes patent infringement. However, if only part of a component is patented, then duplicating that component is acceptable under patent laws. Design infringement is using reverse engineering to steal the design for a mechanical component or system, as the design can then be used to produce the component or system for a profit. However, reverse engineering a design to replace missing maintenance documentation or to improve some aspect of the design is legal.

1.2 The Systematic Process

Recently reverse engineering has been transformed from the object of garage tinkerers to a valid field of study. It has been elevated from the haphazard job of the curious hobbyist to a recognized method for developing technical data for a system, for replacing any obsolete parts of a system, and for improving a system's design. The change from "tinkering" to "reverse engineering" occurs when we apply a systematic process to the teardown, documentation, and rebuild of a mechanical system. Ingle proposes a four-stage method for reverse engineering that involves data evaluation, data generation, design verification, and design implementation. An outline of this process is shown below in Fig. 1.

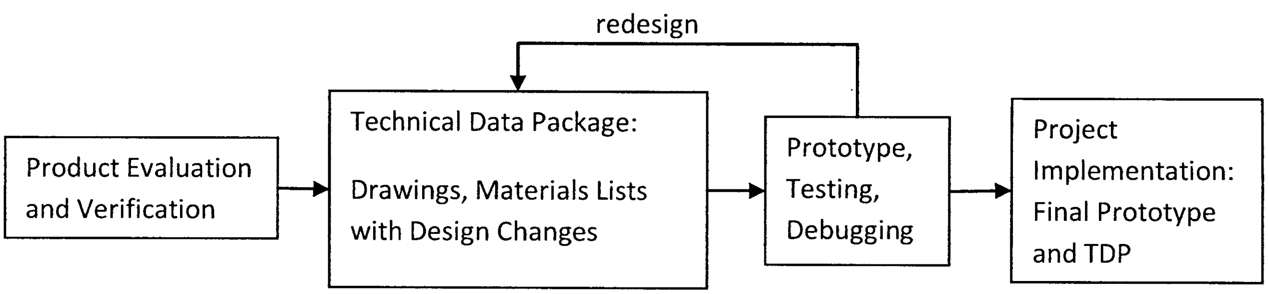

Figure 1 Ingle's four-stage systematic process for reverse engineering.

The first step of Ingle's reverse engineering process is evaluation and verification of the component or system that is to be reverse engineered. Evaluation includes visual and dimensional inspections, disassembly and reassembly, material analysis, operational testing, and failure analysis. Visual inspection yields the object's condition in terms of reproducibility, quality, and wear. Dimensional inspection determines the size, shape, and weight of the object, and any associated tolerances. When disassembling the object, a list documenting the pieces and the order in which they were disassembled helps the engineer better understand the product's design and its assembly process. Nondestructive disassembly, in which components retain joins such as welds and epoxy bonds, is often used. The disassembly and reassembly process is where the engineer answers a lot of "why's" and "how's," such as "why was this part a more difficult to manufacture L-shape instead of a rectangle?" and "how did they manufacture that plastic squiggle?" Some answers will be for design reasons, and others will be based on material availability. Spare or worn out parts are useful for material analysis, as it sometimes requires destructive disassembly to determine a part's material composition. For instance, plastics are often burned and their composition determined from the resulting appearance or smell, and metals can be bent or pulled to the breaking point and their composition determined based on fracture patterns and the load necessary for failure. During operational testing, one examines moving components and compares their movements to the object's operating parameters. Determining the modes of a product's failure through failure analysis is particularly important if the product tends to fail a lot during normal use. Verification involves comparing the data obtained from the evaluation to the data available from sources such as specification sheets and assembly drawings. If data is unavailable for comparison, one can take or measure the necessary data from multiple sample parts and compare the results. Any major discrepancies between the obtained and the available data need to be explained through further testing and observation.

The second step in a systematic reverse engineering process is technical data generation. The verified data from the evaluation step is used to create a technical data package that is complete enough for fabrication, including material and part procurement. The data package includes dimensioned drawings and solid models with tolerances. Any alterations to the design, be they substitutions for obsolete parts and materials or changes that might improve the design, are listed in this technical data package.

The rest of the process is typical of engineering design. The third step is design verification, which involves prototyping and comparing the prototype to the operational criteria. Both design and prototype undergo bench testing, environment testing, and system testing. If the system fails in any way, a failure analysis must be performed, the prototype redesigned, and the adjustments made to the technical data package from step two. After a few prototyping cycles, a deliverable prototype and a final technical data package will result in completed project implementation, the fourth and final step of the reverse engineering design process.

Very few modern products are completely new inventions; oftentimes they are simply an improvement on previous systems. At its best, reverse engineering is an iterative process for improving present designs. An engineer can take something apart, determine a small change that would improve some aspect of the design, and then rebuild the system with the small design change.

2. ORCA XI

2.1 Introduction to the ORCA Project

For several years MIT had a strong autonomous underwater vehicle (AUV) team. The AUV team, also known as the ORCA Project, had repeatedly performed well at the annual Association for Unmanned Vehicles System International (AUVSI) competition for AUVs, winning first place multiple times and being the first and often only team to complete the entire mission. The team was composed of graduate students from various fields who were so familiar with their technology that they could construct a competition vehicle in the three months preceding the July competition. Because the ORCA team's work focused only on the summer months when most undergraduates were off campus, the team was not successful in recruiting or retaining any undergraduates who could continue the team's work. When the ORCA team members graduated or became too busy to devote the long hours necessary to build a vehicle in a short time frame, the project died out and became dormant for a few years. In the fall of 2008, I decided to resurrect the ORCA project and use it to develop a year-round AUV team for any student interested in autonomous robotic technology.

After the initial recruiting was over, the new team consisted of myself, a sophomore electrical engineer, and four freshman interested in mechanical engineering and robotics. None of the team had ever built an AUV before, or indeed anything similarly complex, so we set a modest goal for ourselves: we wished to build a competition vehicle, ORCA XI, from scratch, take it to the summer 2009 AUVSI competition in San Diego, and qualify for the competition by driving straight, submerging and passing through a gate, and surfacing on the other side of the gate. The finished vehicle is shown below in Fig. 2.

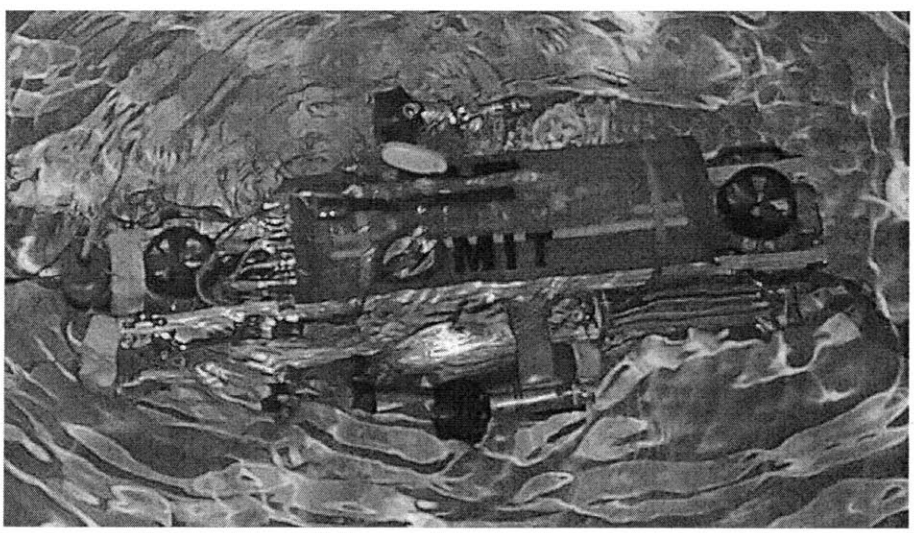

Figure 2 ORCA XI, the first AUV built by the inexperienced new ORCA team using reverse engineering. Source: http://web.mit.edu/orca/www/

2.2 Reverse Engineering the Subsystems

Since the new team had so little experience with underwater vehicles, the first step was to examine the available resources. In the old ORCA workspace we found batteries and electronic components galore, most with very little documentation. There was an unfinished vehicle with a frame, hull, thrusters, and no electronics; most of a spare vehicle frame; and much to our advantage, the ORCA IV, a sophisticated AUV built during the previous team's heyday. The previous team had kept documentation for the vehicle and some of the various components found in the lab on a wiki, but determining which piece of documentation went with which unlabelled component was difficult, resulting in many holes in our knowledge.

As a result of the difficult to understand documentation and our own inexperience, the team decided to reverse engineer the ORCA IV and other available vehicle components to aid the design of ORCA XI. The ORCA team followed a modified version of Ingle's reverse engineering process, as shown in Fig. 3.

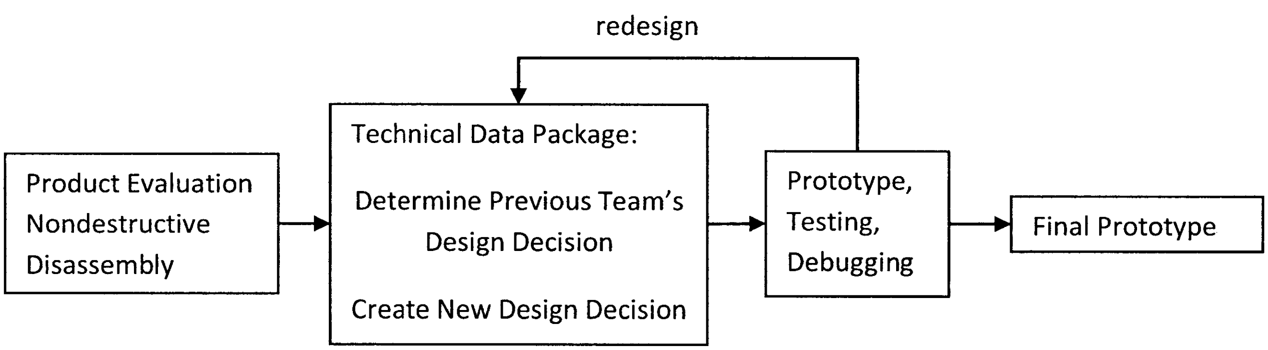

Figure 3 Modified version of Ingle's four-stage systematic process for reverse engineering as used in the MIT ORCA project.

For the initial evaluation step, we developed our own process. When information was needed to make a design decision, we would first observe a previous iteration of the component or subsystem in question. We would then take the component apart using nondestructive disassembly, and from the component's construction and how it interacted with the rest of the vehicle we determined the reason behind its design. During the data generation step, we did not generate a full technical data package of the ORCA IV or other components that we reverse engineered. Instead, we took notes on the design decisions behind the other vehicles and incorporated this reasoning into our own design. From there, we followed the rest of the prototyping and testing parts of the design process.

Six major subsystems of ORCA XI were the waterproof main hull, the waterproof battery housings, the vehicle frame, the thruster mounts, the waterproof wiring connections, and the buoyancy and ballasting system. These six subsystems are identified in Fig. 4.

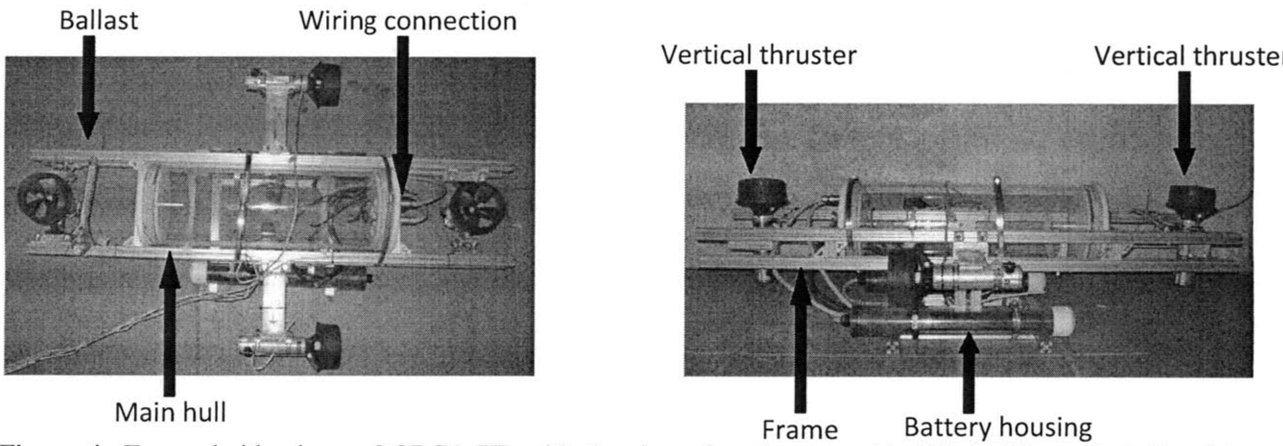

Figure 4 Top and side views of ORCA XI, with the six main subsystems identified. The main hull, wiring connections, and buoyancy/ballasting system are identified in the top view; the waterproof battery housings, vehicle frame, and vertical thruster mounts are identified in the side view. Source: http://web.mit.edu/orca/www/2009_orca4.shtml

Five of these six subsystems were reverse engineered from previous vehicles—that is, all except for the waterproof battery housings, which were found already built in a usable form in the lab. We designed these five subsystems for ORCA XI based on the information gleaned from varying degrees of nondestructive teardown that we performed on previous vehicles. An overview of which subsystems were reverse engineered and how closely design decisions for ORCA XI followed those made by previous teams is shown below in Table 1.

Section	Subsystem	Designed with RE	Same Design Decision
2.2.1	Waterproof main hull	yes	Yes
2.2.2	Thruster mounts	yes	No
2.2.3	Vehicle frame	yes	Yes
2.2.4	Waterproof wiring connections	yes	Yes
2.2.4	Buoyancy/ballasting system	yes	No
2.2	Waterproof battery housings	no	Yes

Table 1 The six major subsystems of ORCA XI, including whether or not the system was designed with reverse engineering and whether or not the team made the same design decision for the system as observed on previous designs.

All six subsystems were critical to our mission, and successful reverse engineering and design of five of these subsystems allowed us to achieve the competition goal of qualifying.

2.2.1 Main Hull

One of the earliest design decisions for ORCA XI was the construction of the hull. A survey of the vehicles and vehicle components in our workspace showed that all previous main hulls were composed of a clear plastic material, with two opaque plastic endcaps each with two o-rings that formed a double seal between the plug portion of the endcap and the inside of the hull. This observation led us to three conclusions about the choice of a clear material for the hull. A clear hull would let us add a bottom- or side-facing camera to the vehicle without the additional construction of a separate waterproof camera housing that would have to be connected to the main hull. In addition, the transparent hull would allow for visibility of the electronic connections of the main computer inside, thus decreasing troubleshooting time for any possible loose connections at the competition. Finally, if the hull had any problems with its waterproofing, or if the seals failed for any reason, the resulting leaks would be immediately apparent in the clear hull. If the hull were opaque, the leaks would not be detectable until the computer fried or the vehicle began to sink.

2.2.2 Thruster Mounts

A major design decision made early on during the design of ORCA XI was thruster placement. A study of ORCA IV revealed that the vertical thrusters were embedded into the nose and end cones of the vehicle, as shown in Fig. 5.

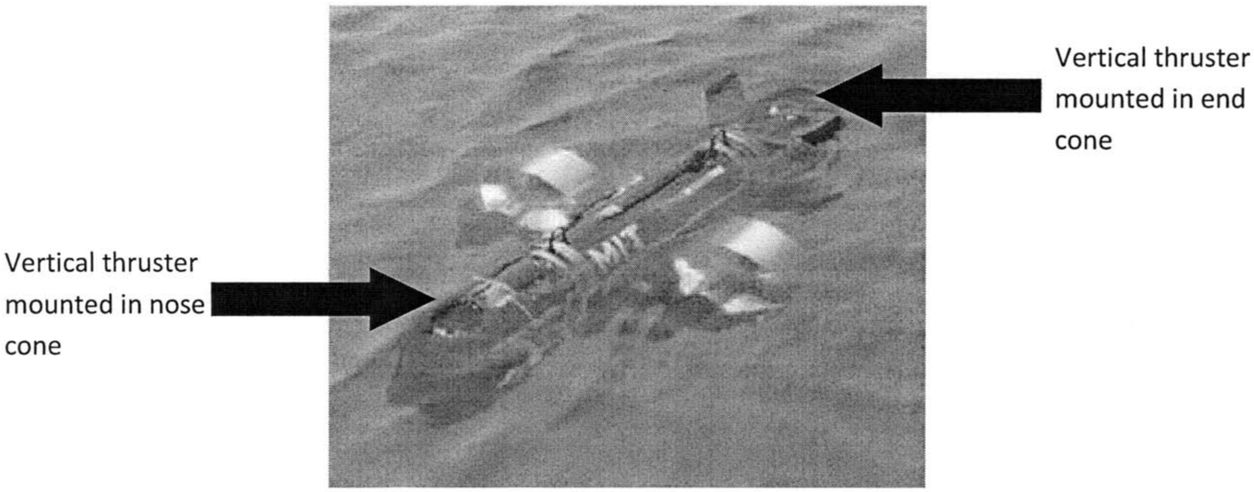

Figure 5 Thruster placement in the nose and end cones of ORCA IV. Source: http://web.mit.edu/orca/www/2001_orca4.shtml

We determined that the cones served primarily to streamline the vehicle, since otherwise the thrusters would protrude vertically at the ends of the vehicle and add extra drag forces. By removing the end cones and reverse engineering them, the team determined that the cone was constructed from a plastic outer shell over a shaped piece of pink foam. A hole had been cut through the top and bottom of each cone so that the thrusters were mounted completely inside the cones. We also found wooden forms in the shape of the cones, and decided that the outer shell had been thermoformed into its complex shape over the wooden form. With the team's limited building experience, however, we determined that the time and effort necessary to build the molds, thermoform the cones, and adjust the ballasting was not worth the slight reduction in drag force. As a result, the team's final design decision was to mount the thrusters directly to the vehicle's frame.

The thrusters themselves also caused a certain amount of aggravation during the testing of ORCA XI. Some of the thrusters made a high-pitched whining noise while running, indicating internal friction. Applying grease to the thrusters' bearings, however, proved to be more difficult than anticipated. The thrusters had been in storage for several years, and because of their age there was little maintenance documentation to be found for them. A few phone calls made in an attempt to find more documentation revealed that the company that made the thrusters had merged with another company, and that the thrusters were out of production. Because of the lack of documentation, we needed to reverse engineer the thrusters for maintenance purposes. By taking apart the end of the thruster, I was able to discover an opening to the gearbox through which I was able to apply the necessary grease.

2.2.3 Vehicle Frame

The biggest design concern for the vehicle's frame was design for assembly. Due to budgeting restrictions, the vehicle would have to travel as checked baggage on the flight to San Diego. The frame would have to be completely disassembled to fit inside the available crate, and would have to be easily reassembled with limited tools, since our only resources would be what we could take in our luggage on the flight. The ORCA IV was a highly complex vehicle, difficult to disassemble even for reverse engineering purposes, so we chose instead to examine an abandoned vehicle frame lying around in the lab. This frame was composed of 80-20, a highly modular material with a system of brackets and screws that required only a screwdriver and a nimble hand for assembly. An example of a previous iteration of ORCA with an 80-20 frame is shown below in Fig. 6.

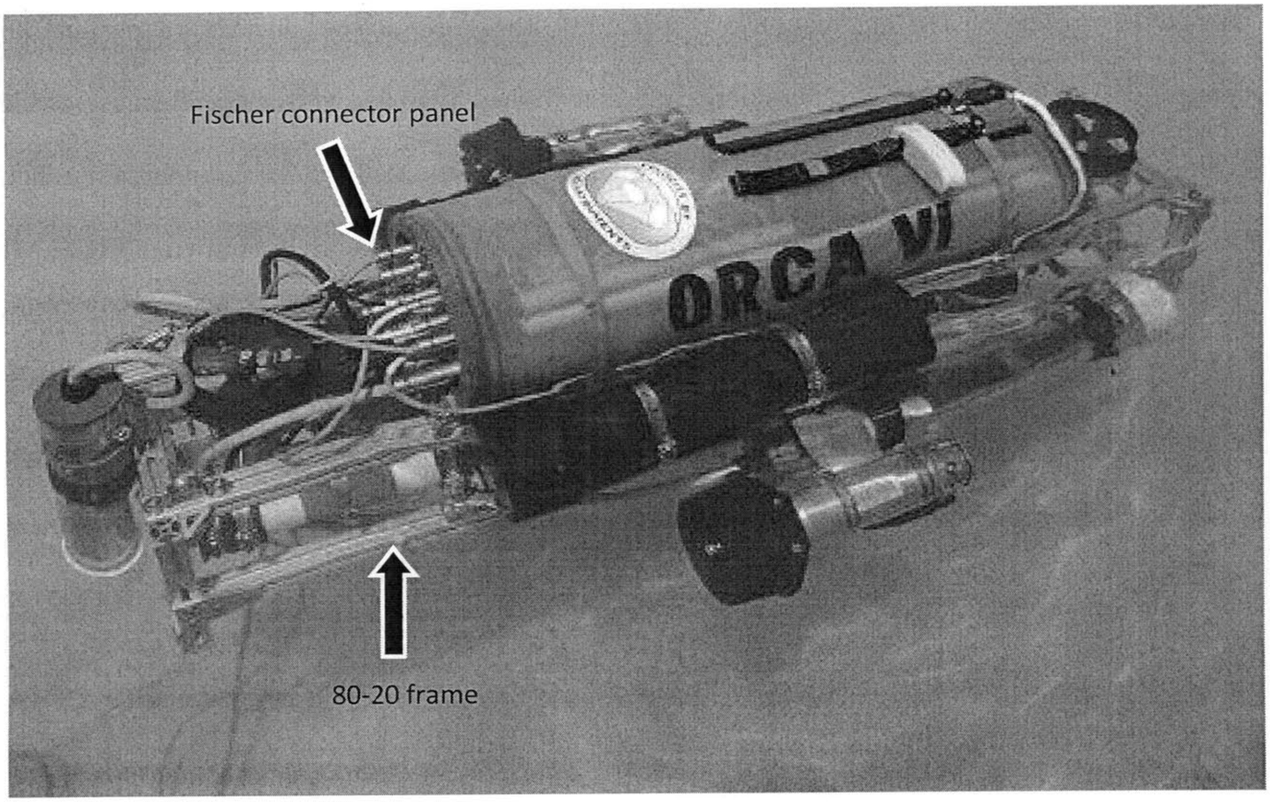

Figure 6 The complete ORCA VI, with the 80-20 frame reverse engineered for the design of ORCA XI. Source: http://web.mit.edu/orca/www/2004_orca7.shtml

By disassembling and reassembling the existing frame, the team was able to gain a hands-on feel for where best to place the 80-20 brackets and hinges for easy assembly. Otherwise, thrusters and hulls easily could have been placed in the way of a bracket, limiting access to the assembly screws. As a result of reverse engineering the existing 80-20 frame, we were able to design our own vehicle frame that was easily assembled in our hotel room with a minimal number of tools.

2.2.4 Waterproof Wiring Connections

Once all of ORCA XI's main components had been mounted on the frame, we needed a way to connect the thrusters, battery packs, and sensors to the main hull which housed the computer, without compromising the water resistance of any seal. All previous ORCA vehicles had Fischer connectors linking the various waterproofed electronics. Each connector had a small o-ring surrounding its base, which sealed the connector's hole in the endcap. Such waterproof connectors are expensive and can take six months to order, so we decided to design our connection panel around the Fischer connectors that we had available in the lab. Because of the layout of the electronics inside the hull, only one endcap could be used as a connection panel. By studying the placement of the Fischer connectors on previous vehicles, as shown in Fig. 7, we were able to determine the optimal placement of connectors on our own vehicle that prevented the multiple lengths of cables from becoming entangled as they were threaded towards the connection on the main hull.

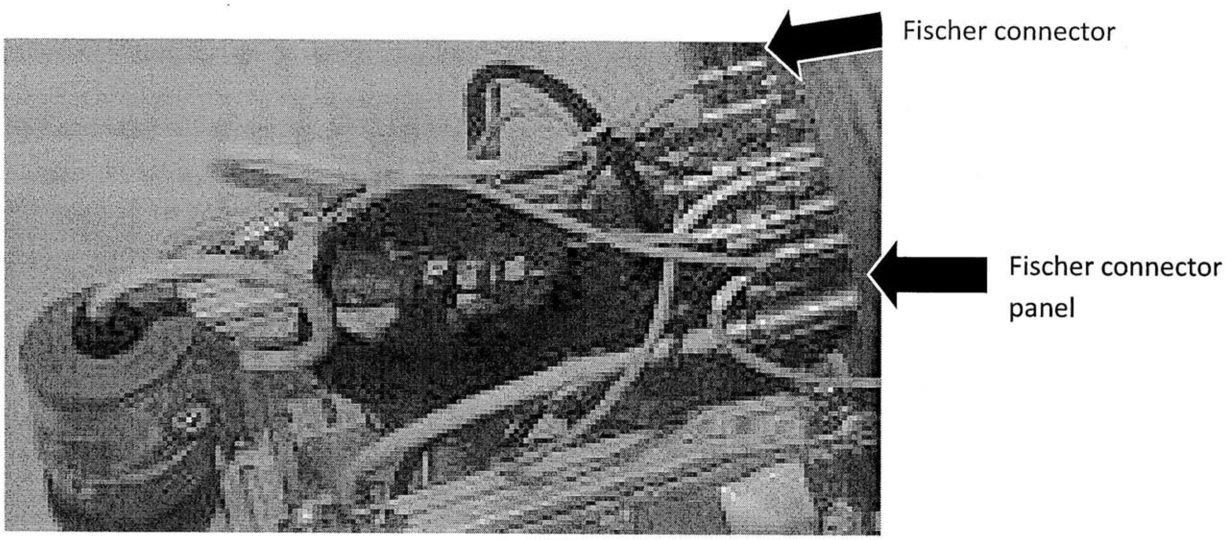

Figure 7 Close-up of the Fischer connector panel on ORCA VI. Source: http://web.mit.edu/orca/www/2004_orca7.shtml

2.2.5 Buoyancy and Ballasting

The last subsystem to be added to the vehicle was the ballasting and buoyancy subsystem. According to competition rules, ORCA XI needed to be very slightly positively buoyant, so that if the vehicle lost power it would float to the surface where it could be easily retrieved, instead of sinking to the bottom of the pool arena where it would be more difficult to locate. Because the vehicle was not perfectly symmetric around the front and back ends, we needed extra buoyancy and ballasting to keep the vehicle level with respect to the water. ORCA IV, an extremely heavy vehicle, used pink foam to add buoyancy. The foam had been cut into shapes that could be tucked away discreetly on the vehicle, such as the molded nose and tail cones in Fig. 8, thus not detracting from its sleek outline.

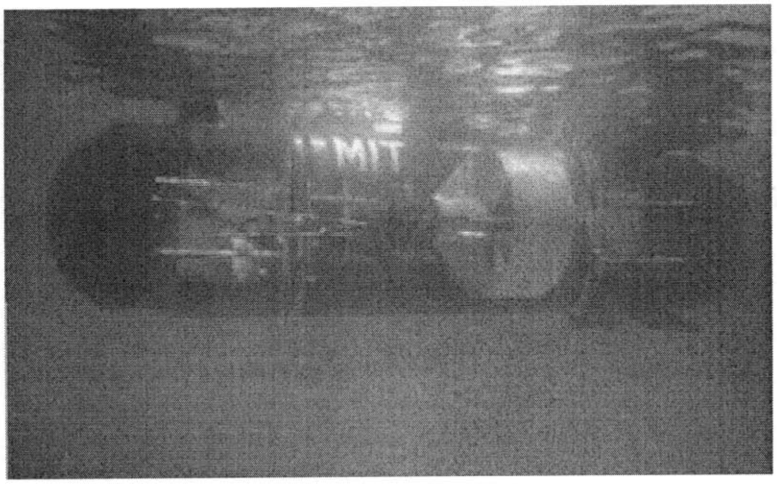

Figure 8 The pink foam used for buoyancy on ORCA IV was calculated and shaped to fit inside the complex molded shape of the vehicle's nose and end cones. Source: http://web.mit.edu/orca/www/2001_orca4.shtml

Since we had to completely disassemble our vehicle for travel and then reassemble it for competition, however, such definite locations and quantities of buoyancy were not practical for the ORCA XI. Instead, we trimmed the vehicle for our test runs using pink foam for buoyancy and small, dense objects such as lead weights and certain hand tools for ballast. The foam and the weights were attached to the vehicle's frame with plastic zip ties, which were simple to attach and remove, thus facilitating adjustment. This modular method of ballasting, while not as compact as that of the ORCA IV, enabled us to quickly re-trim the vehicle to adjust to any slight changes that occurred during reassembly.

3. Naval Power in China

3.1 History of Reverse Engineering in China

The reverse engineering process used to design the ORCA XI is relevant not only to budding college-level ocean engineering teams but also to the navies of rising countries. China in particular has been on the rise as a world power in the latter part of the twentieth and the beginning of the twenty-first centuries. Is it possible that China, like the ORCA team, has used some form of reverse engineering to bring their fledgling navy up to speed with other major world powers?

Reverse engineering western technology played a key role in the industrialization of China. In 1864 China began sending engineers abroad to study manufacturing processes and buy weapons and other industrialized equipment. Over the next two decades, China continued this program, reverse engineered the purchased equipment, and used the knowledge gained for industrialization and for developing military resources. Although some of the first ships developed were mostly pieced together from foreign-made components, including British, German, and American guns, China was soon able to manufacture the necessary parts for future ships. The program fell, however, when a series of wars between 1884 and 1894 destroyed both the northern and southern Chinese fleets [6].

Reverse engineering western technology does not stop at military or naval applications. In 1986, China launched the 863 Program for the acquisition and development of technology in most fields of modern research, ranging from biotechnology to energy technology. All of these areas of research, however, have dual use in civil and military applications. The program is similar to the one begun in 1864—engineers and students are sent abroad to study and acquire technology. Unfortunately, China does not have many of the same ideas about copyright and patent infringement. According to Larry Wortzel, one 1988 research lab "consisted of several technicians carefully dismantling Nokia and Motorola cellular phones and then diagramming and cataloging their parts and design," without the slightest suggestion of awareness that copying the phones would constitute design theft [6].

3.2 Methods for Naval Development

Clearly, China has a long history of more or less successful attempts at industrialization and militarization through reverse engineering. Could these skills be used to reverse engineer a navy? If so, is there a more efficient way to build a navy than by reverse engineering another country's obsolete naval equipment? The following discussion is based on Yung's [7] analysis of China's potential naval power. To begin, consider three major ways of building a navy. The first method is for a country to build its navy from the ground up, using its own engineers' designs and pouring money into research to develop technologies. The second method is to import more advanced naval equipment from other countries, reverse engineer the equipment, and then use the data to mass produce naval systems. The third way is to buy a navy by buying vessels from other countries and using them as part of the fleet. The time and monetary costs of each of these three methods are outlined below in Table 2.

Acquisition Method	Purchase Expense	Time
Build, no RE	1	3
Reverse engineer	2	2
Purchase	3	1

Table 2 Three methods for a country to acquire a navy, comparing monetary expense and time required. Purchase expense and time are measured on a scale of 1 to 3, where 1 is the smallest amount and 3 is the largest.

All three methods have their advantages and disadvantages. The first method of building a navy would stimulate the research and production sectors of the economy, but the resulting ships would most likely always lag significantly in capability behind those of other world powers who have spent centuries developing their technologies. Most of China's naval technology designed from the 1950s until present has lagged thirty to forty years behind the other leading world powers. As only 3 to 4% of the Chinese population were enrolled in higher education in the 1990s, a large increase in higher education is necessary for China to have enough engineers and technicians to develop their own navy without reverse engineering or much foreign assistance.

The second method of buying a navy is possible, but the initial monetary investment is much higher than that of buying vessels to reverse engineer. Assuming that China spends about 5% of its GDP, China could obtain a regional navy by 2010 if its economy grows 8% every year for fifteen years. This would give China $83.6 billion in funds for purchasing its navy and accompanying technical maintenance. If the economy grows by only 4% every year, a much more modest amount, China would only have $59.21 billion to fund the purchase of its navy, not enough to acquire a regionally active naval force. Even if purchasing a navy did not require such a hefty up-front investment, the relative lack of people with higher education would also pose a problem for the technical knowledge necessary to maintain and operate the navy. In addition, suddenly starting to buy the vessels necessary to assemble and equip a regionally capable naval could make China's neighbors uneasy and increase strain between China and nearby countries.

3.2.1 Reverse Engineering a Navy

Research practices over the last 40 years suggest that China is in fact pursuing the third method of reverse engineering and then mass producing the vessels necessary for a regional navy. This process requires less time than building a navy from the ground up, as well as less money for the initial investment. In 1994, China spent roughly $50 billion on its defense budget. Dedicating just $5 billion of this annual budget would allow China to purchase enough vehicles to reverse engineer and begin mass producing a regional navy within 15 years. An estimate of what China could purchase on such a budget is shown in Table 3, taken from Yung's analysis of China's naval prospects.

Year	Purchase Cost	Purchase	Purchase Description
1996	$4.5 billion	2 Su-27s 2 Kilo subs 2 AWACs equivalents 2 Aegis equivalents 2 MCM	Soviet fighter jet Russian diesel-electric submarine Airborne early warning and control radar system Radar search, tracking, and missile guidance system Mine countermeasures ship
1997	$5.7 billion	1 carrier Carrier refit 2 E-2C equivalents XJ-10 assist. 2 UNREP	Aircraft carrier ship Upgrade to current aircraft carrier Surveillance aircraft platform for AWACs Improvements for indigenously designed aircraft Underway replenishment system for refueling and restocking of stores and munitions
1998	$6.7 billion	Ship modernization Gas turbine engine J-8 upgrade	Upgrades to currently existing ships Gas turbine engine Improvements to indigenously designed supersonic interceptor fighter

Table 3 Yung's estimate of what technologies China could purchase for reverse engineering a navy, well within a reasonable defense budget.

Examples of these purchases are shown in Fig. 9. In the past, China has successfully reverse engineered purchased vehicles, including the Russian MiG-19 and the F-6 attack aircraft, going so far as to mass produce the latter. In addition to reduced up-front cost compared to buying a regionally capable navy, the gradual buildup of naval power by the slower process of reverse engineering and designing for mass production would be less unsettling to China's neighbors.

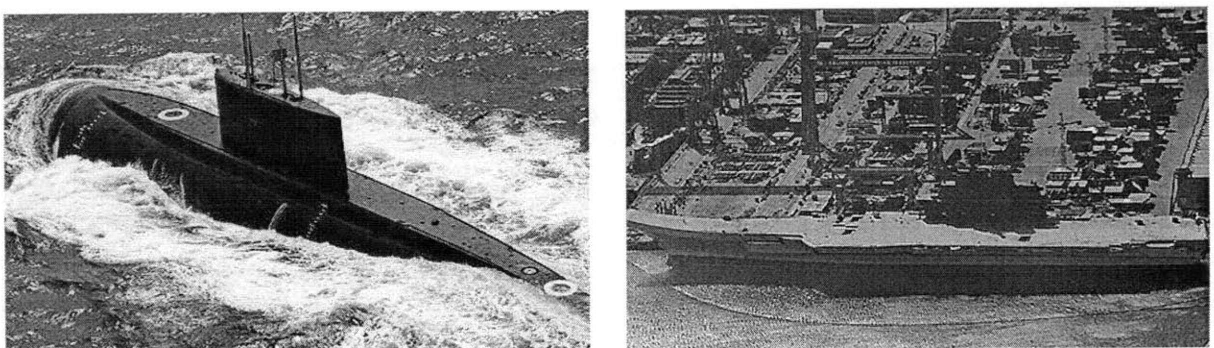

Figure 9 Kilo class diesel-electric submarine and *Varyag* aircraft carrier. Both are examples of Soviet –era technology that can be used to reverse engineer a Chinese navy. China has already acquired the Kilo class submarine; the aircraft carrier is a potential purchase. Sources: http://www.sinodefence.com/navy/sub/kilo.asp and http://www.sinodefence.com/navy/surface/varyag.asp

Given China's history of successful reverse engineering of Western technology and its current research trends and defense budget, it seems likely that China is in the process of reverse engineering a regional navy. According to Yung, it would take China about 15 years to go from the acquisition of the vessels to be reverse engineered until the beginning of series production. Yung's timeline of defense production is reproduced below in Fig. 10.

Acquire technology Disassemble Learn how items work and are made	Develop design specifications Build equipment and line for mass production Build prototype	Mass produce Fill inventories Train users
→	→	→
10 years	12-15 years	5+ years

Figure 10 Yung's timeline of how long it would take for China to develop a navy using reverse engineering.

According to Yung's timeline, about ten years would be spent on the acquisition, disassembly, and documentation of the vessels, and another fifteen years would be spent designing the prototype and building the equipment necessary for mass production. As of 2009, it was estimated that China's navy consisted of 8 nuclear submarines, 58 diesel-electric submarines, 26 destroyers, 51 frigates, and approximately 100 corvettes and fast attack craft. China still does not have any aircraft carriers as part of their naval forces [5].

4. A Comparison of Reverse Engineering Effectiveness

Building a college-level AUV at first seems completely different from building a seaworthy vessel, let alone an entire navy. The number of interactions between subsystems and components, the total capabilities, and the resources necessary for building all contribute to the complexity of a system. Using this definition, it can be shown that both the navy and its component vehicles are much more complex systems than the AUV. The many interactions between all of the subsystems and components of a navy, a single naval, or an AUV must flow seamlessly in order for the whole system to work. However, since the AUV is much simpler than a navy or a naval vessel, there are fewer subsystems and components that must interact, thus decreasing the likelihood that an error will occur. In addition, a naval vessel also has more capabilities than a simple AUV. For instance, the AUV can be programmed to shoot ping-pong balls upon sensing a certain shape, whereas a submarine can do serious damage with a torpedo. Finally, because the AUV is smaller and simpler than a naval vessel, it can be built with resources that fit comfortably into a basement or large garage. Navies, however, require industrialized machinery to mass produce vessels that will form their fleets.

In addition to the mismatched levels of system complexity, the purpose of the ORCA Project differs greatly from that of China. As part of an educational institution, the prime purpose of the ORCA Project was to provide MIT students with an opportunity to explore hands-on underwater technology. Winning the competition is simply an added incentive for work on the project. The real goal of designing AUVs for ORCA, either from scratch or from reverse engineering, is to gain knowledge and foster interest in the field of underwater technology. However, China's goal in reverse engineering a navy is not education but long-term profits. The purpose of reverse engineering a navy is to build a force that will enable the country to enforce its power and thus have greater impact on world affairs. In addition, developing an industry around these naval projects would help stimulate sectors of China's economy.

Despite this disparity in complexity and purpose, the principles of reverse engineering can be successfully applied to both AUVs and seaworthy naval vessels, as shown by the ORCA Project and the Chinese navy, respectively. This study sought to determine a relationship between the complexity of the system and the effectiveness of reverse engineering on the design and manufacture of that system.

4.1 Reverse Engineering Efficiency

To quantify the impact of reverse engineering on the design and manufacture of a system, I defined a reverse engineering efficiency. This efficiency value is based on the time necessary to design and build a system indigenously and the time necessary to design and build the same system with the aid of reverse engineering. I define reverse engineering efficiency as

$$\eta = \left(1 - \frac{T_{RE}}{T}\right) * 100\% \quad (1)$$

where T_{RE} is the time necessary to reverse engineer, design, and build a system, and T is the time necessary to design and build the same system without reverse engineering.

4.1.1 The ORCA Project

For the purposes of this study, an iteration of the ORCA Project was deemed complete once the vehicle had finished participating in that year's competition. To determine the time required to build an AUV with and without reverse engineering, separate surveys were sent to the old and new ORCA team members, respectively, asking the team members to estimate how many man-hours went into developing a complete iteration of the project. These surveys and their responses can be found in Appendix A. The old ORCA team yielded two replies, one of which was an estimate of 4000 hours. The other response detailed a method to estimate the number of hours spent on the vehicle for any given year. For this estimate, I used the numbers from the ORCA team that attended the 1998 competition—20 team members with 16 people attending the AUVSI competition in San Diego. According to the method outlined in Appendix A, this team size broke down into 4 full-time members, 8 half-time members, and 8 quarter-time members. The 4 full-time members were estimated to work 55 hours per week for the first 7 weeks of the summer and 65 hours during the week before the competition. The 8 half-time members were estimated to work 20 hours per week for the first 7 weeks of the summer and 30 hours during the week before the competition. The 8 quarter-time members were estimated to work 10 hours per week for the first 7 weeks of the summer and 15 hours during the week before the competition. In addition, the 16 people who attended the competition were estimated to work 17 hours a day for the 4 days that the vehicle participated. These numbers yielded an estimate of

4928 hours to build an iteration of the ORCA AUV. This estimate was averaged with the 4000-hour estimate to yield 4464 hours spent developing an AUV without the aid of reverse engineering. The survey sent to the new ORCA team also yielded two replies. One team member estimated that he spent 500 hours on the project, and the other estimated that he spent 300 hours. The team consisted of 7 people, and as I was familiar with the work habits of the entire team, I estimated that 2 people spent 500 hours each and that 5 people spent 300 hours each working on the vehicle over the course of the summer. These numbers yielded an estimate of about 2000 hours spent developing an AUV with the aid of reverse engineering.

4.1.2 Chinese Naval Projects

For the time necessary for the Chinese navy to build a vessel with reverse engineering, the timespans to reverse engineer and prototype China's three most recent naval projects listed in Yung's tables were averaged. These naval projects and their timespans are shown below in Table 4.

Name	Capability	Date acquired	Mass production	Time elapsed
HQ-7	Surface-air missile	1978	1990	13 years
Z-9 Haitun	Maritime surveillance helo	1980	1992	12 years
XJ-10	Fighter	1988	2008	20 years

Table 4 China's three most recent reverse engineered naval projects, including the platform name, its capability, the date acquired, the date mass production began, and the time elapsed between acquisition and mass production. The elapsed times for these three platforms were averaged to represent the time necessary for China to reverse engineer and prototype a single platform.

The time necessary for China to develop a regional navy was taken from Yung's estimate of 25 years, as shown previously in Fig. 10. Since the technology of indigenously built naval vessels in China averages about 30 to 40 years behind Western technology, this number was used as an estimate of both the length of time it would take to build a single vessel and the length of time it would take to build up an indigenous navy, without reverse engineering.

4.1.3 Nuclear Reactors in France

Reverse engineering can be successfully applied to many other complex systems outside the naval and underwater fields. Nuclear reactors are an example of one such system. In 1971, France began building a series of six 900 giga-Watt reactors from a design that they purchased from the American nuclear company Westinghouse. After building two more series of this particular reactor design, France purchased the design for a new series of 1300 giga-Watt Westinghouse reactor in 1977, and in 1979 they began building another series of reactors based upon their own modifications to the Westinghouse design. Construction began on the first completely new French reactor design in 1984 [2]. The reverse engineering process can be observed at work in the development of the French nuclear power industry. France used a purchased technical data package and used the knowledge gained from building these Westinghouse designs to first modify the Westinghouse design and then develop their own original reactor designs. In 2001, the French companies that participated in the construction and modification of Westinghouse reactors combined to form AREVA, a nuclear power company based upon new French nuclear reactor designs [2]. AREVA is now one of the leading nuclear energy companies and has even expanded to have a branch in the United States, thus showing how reverse engineering can revolutionize the profitability and impact of a country's industry.

It is interesting to note that the French companies were able to build 12 reactors from their 1979 modified Westinghouse design over 90 month period, which averages to about 7.5 months per reactor, with reverse engineering. When France started building reactors from their indigenous designs, the companies took 126 months to build 4 reactors, which averages to about 31.5 months per reactor without reverse engineering [2].

4.2 Comparing the Systems

The results of the data estimates for the ORCA Project, for Chinese naval projects, and for a French nuclear reactor are shown below in Table 5.

	Build Time	
Vehicle Type	**Without RE**	**With RE**
ORCA AUV	4464 hours	2000 hours
Chinese naval vessel	35 years	15 years
Chinese regional navy	35 years	25 years
French nuclear reactor	31.5 months	7.5 months

Table 5 Data estimates for the length of time necessary to build an iteration of the ORCA AUV, a single Chinese naval vessel, a regional Chinese navy, and a single French nuclear reactor. Each project has a time estimate for building with and without reverse engineering.

Eq. 1 was then applied to the data in Table 5 to determine the reverse engineering efficiency for each vehicle type. The resulting reverse engineering efficiencies are shown below in Fig. 11.

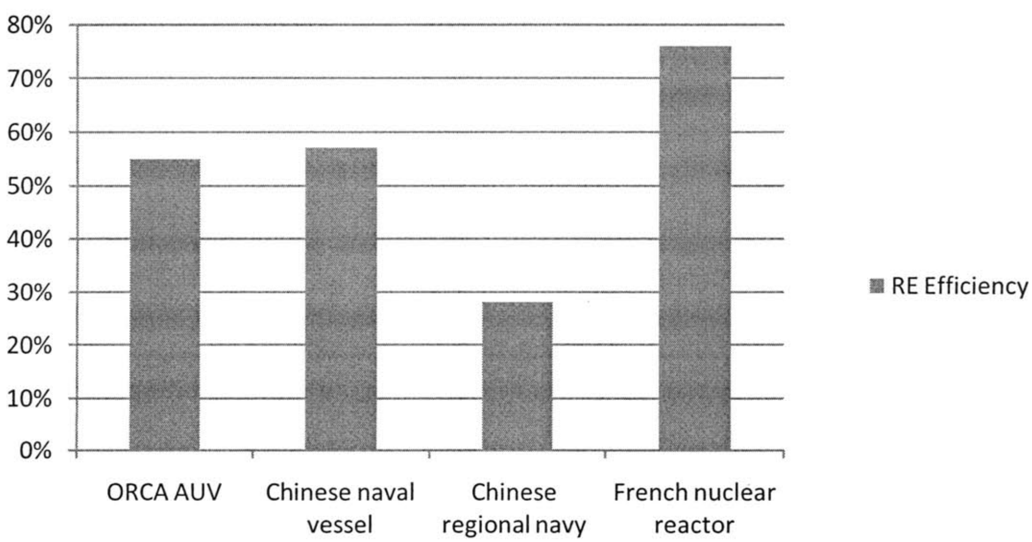

Figure 11 Calculated reverse engineering efficiencies for the ORCA AUV, a single Chinese naval vessel, a regional Chinese navy, and a French nuclear reactor.

The reverse engineering efficiency for an iteration of the ORCA AUV was calculated to be around 55%. The reverse engineering efficiency for a single Chinese naval vessel was calculated to be approximately 57%, and the reverse engineering efficiency for a Chinese regional naval was calculated to be about 28%. The reverse engineering efficiency for a French nuclear reactor was found to be around 76%. This high efficiency for the French reactor suggests that reverse engineering can be applied to such complex systems as nuclear reactors with excellent results. According to this data, there is no apparent correlation between the increasing complexity of a system and its reverse engineering efficiency. The efficiency for the ORCA AUV and the naval vessel were within a few percentage points of each other, thus supporting the notion that from a reverse engineering perspective a college-level AUV is simply a scaled-down version of a naval vessel. As a result, any developments in systematic processes for the reverse engineering naval vehicles can be first tested on simpler systems for efficiency before they are applied to larger, more complex projects, thus potentially saving time and money.

As seen in Fig. 11, the reverse engineering efficiency for the regional navy was far lower than that of either the AUV, the single vessel, or the nuclear reactor. This difference may be due to the design of the production line. Both the AUV and the single vessel can be seen as prototypes; their build times do not include all of the preparations necessary for mass production. Also, since France had the manufacturing equipment for nuclear components, turbines, and generators since 1975, and for the nuclear fuel cycle since 1976, they did not have to include the setup of their manufacturing processes in their reactor designs. Most of the components were already available, and France had had time to determine an effective procedure for using these components to construct a reactor from the building of the several preceding series. China, however, does not have such manufacturing plants and processes already in place. The production line for each class of vehicle in the navy requires not only the design and manufacture of massive production equipment, but also the design of an efficient production process. This study assumes that China is only reverse engineering the purchased vehicles and not their manufacturing processes. As a result, the application of reverse engineering to the efficiency of the design of production equipment, the production process, and the assembly lines is a possible topic for further consideration.

It should be noted that other factors, especially politics and economics, can affect the length of time necessary for a project to be completed. For instance, political objections to the potential risks of nuclear power could slow down construction on a series of reactors in France, while a year of slow economic growth could hinder China's defense budget and thus decrease work on naval projects. While these effects are most apparent for the French nuclear reactors and the Chinese naval vessels and navy, university politics and economics also affect student ventures such as the ORCA Project. Faculty must be found who support the project, and funding must be acquired both from university and corporate sources. Difficulty in either of these areas can adversely affect the progress of even a collegiate engineering project.

5. Conclusions

A four step systematic process for reverse engineering including product evaluation, technical data and design generation, prototyping, and final project implementation was outlined. The development of ORCA XI was then examined in light of this systematic process, thus showing how valuable reverse engineering can be to a project whose team members do not have much experience in the design or construction of a particular system. Reverse engineering was then taken from the university lab to the world stage, where it was shown that reverse engineering a regionally-powerful navy was both economically and chronologically feasible for China. A reverse engineering efficiency was developed to compare the effectiveness of reverse engineering on ORCA XI, a Chinese naval vessel, and a regional Chinese navy. The comparison of efficiencies for these three systems suggested that it was just as efficient to reverse engineer an ORCA AUV as it was to reverse engineer a single Chinese naval vessel, and that reverse engineering an entire navy was less efficient than reverse engineering a prototype because of the need to develop production lines and equipment. The constant efficiency with increasing complexity of system suggests that new systematic methods for reverse engineering naval systems can be tested on a simpler platform before being applied to large, expensive projects. The negative effect of the need to develop of production lines and equipment on the efficiency of reverse engineering a system suggests that a different reverse engineering could be applied to the development of the production process itself to increase overall efficiency.

6. References

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Appendix A: Data Surveys

Surveys sent to the old and new ORCA teams; the responses were used to estimate the number of man-hours each team spent on their vehicle.

The following quotations are the e-mail survey sent to the old ORCA team and the responses received. The responses were used to determine the number of man-hours needed to create an iteration of the ORCA vehicle without reverse engineering.

> "I am writing my senior thesis on my work with the 2009 ORCA team, and could use a little help from your collective memory. If you could e-mail me back with:
>
> 1) Which ORCA competition vehicles you worked on (competition year is fine), and
>
> 2) Your best estimate at the total number of man-hours from that went into the soup-to-nuts development of each vehicle listed in (1).
>
> Feel free to e-mail me if you have any questions."
>
> "I worked on the team from 1998 – 2006.
>
> Each competition season, we generally worked for about two months, ten people, probably 60 hours a week for 4 people and 20 hours a week for 6 people, plus then maybe 100 hr/wk for everyone at the actual competition, so something like 4000 man hours per season. Just a guess.
>
> Of course, there were years with more hours and year with less. We have a very dedicated effort in 1998, 1999, 2002, 2003, and 2004, less so in other years by my recollection."
>
> "I worked on Orca I-VII (Summer 1998-2004), although my work on Orca III was quite limited – I was working a full-time job in SF that year probably only putting in a couple hours a week of corresponding by email and then I attended the competition. In terms of work on the vehicles it was like this:
> 1998: Brand new vehicle from scratch, big team, lots of man-hours
> 1999: Brand new vehicle again, hull was built as a senior thesis by Ben Polito
> 2000: Significant modifications to the Orca II to handle a very different mission from previous years
> 2001: Again, significant modifications from Orca II to handle a different mission

2002: Again, significant modifications from Orca II to handle a different mission
2003: New vehicle with 80/20 frame built in parallel to making modifications to the 2002 vehicle. New vehicle was used for the competition.
2004: New motor controllers designed by John Edelson during the year, otherwise relatively minor modifications to 2003 vehicle, but there was a lot of work to getting the vision systems working and marker dropping system working since the mission was once again quite different from the previous year. Work was steady, spiked just before the competition, but we got everything working really well within the first day or two in San Diego and we actually didn't have a lot of work to do after that and got to spend a decent amount of time relaxing and sleeping a normal schedule.

In terms of calculating the man-hours, I think you could get a good approximation for each year as follows:
- Figure that each season's work started the week after MIT's final exams and ended the day of the competition. During those years almost no work was done between the end of the competition and the end of the following school year with just the couple of exceptions mentioned above.
- You can probably find each year's roster by looking through the web page archives and various documents on them.
- Work was pretty steady up until 1-2 weeks before the competition. Assume that 3-4 people were working full time+ (they had UROPs and were putting in extra hours as well) on the order of 50-60 hours/week. Of the remaining people, figure that ½ were working evenings a couple of nights/week + weekends on the order of 20-25 hours/week. And figure the remaining ½ were probably putting in 10 hours/week.
3. For the 1-2weeks before the competition there was a major spike in the amount of work going on, with the full-timers probably putting in 60-70 hrs and probably all of the part-timers were putting in 1.5 times their normal hours. For the 3-5 days of the competition work was essentially non-stop, with everybody who went to the competition putting in 16-18 hour days, sleeping in shifts so that work went on around the clock."

The following quotations are the e-mail survey sent to the new ORCA team and the responses received. These responses were used to estimate the number of man-hours needed to develop the ORCA XI, an iteration of the ORCA vehicle that involved reverse engineering.

"If you were involved in ORCA any time leading up to the 2009 San Diego competition, you can really help me out by answering the following question:

About how many TOTAL hours did you spend working on ORCA XI?"

“Very rough guess but 500 hours”
“In answer to your question, probably in the 300 hour range. Of course, if I had to redo everything I did right now, it would probably take 20% of that time...”