Advances in the Design of Energy-Efficient Submersibles

Part I : The Design Problem

by

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The Concept of Limited Power as a Driver of Technical Innovation

The Kremer challenge, first issued in 1959, inspired engineers over a period of 18 years to seek advances in aeronautical engineering design. The challenge was to design an aircraft, propelled solely by human power, which would complete an airborne figure-of-eight course around two markers located half a mile apart. With the evolution of lightweight, high strength structures, efficient propulsion systems and research into human exercise physiology, the prize was finally awarded to Paul McCready and his craft "Gossamer Condor" in 1977.

On a similar theme, but in a different fluid medium, how many naval architects would consider applying their skills to the design of an "underwater bicycle"? In 1989, the HA Perry Foundation in the USA offered a prize of $5,000 to the winner of a design competition for submarines, which were to race round a 400 m oval course, at 7 m depth in the ocean, propelled solely by human power. The "International Submarine Races" were born at Riveria Beach, Florida on 23 June that year.

The event had been envisaged primarily as a student design competition, with the objective of encouraging students from different engineering disciplines to enter the field of underwater technology, by presenting them with a challenge which was both technically demanding and fun. In fact, about 50% of the competitors were teams of professional engineers.

A second important objective of the competition was to foster advances in the hydrodynamics, propulsion and life-support systems of small subsea vehicles. The specification of a human power source deprives designers of the easy solution to achieving greater speed (i.e. by using a bigger engine). The teams are therefore forced to focus on improvements in other vehicle subsystems, seeking (for example) minimum hull drag, maximum propulsion efficiency and precise ballast and trim control.

The 1st International Submarine Races attracted 17 entries and proved so popular, that subsequent competitions were held in 1991 (34 entries) and 1993 (42 entries).

The Design Brief

In order to encourage innovation, the rules of the competition are kept to the minimum required within the constraints of safety. Those rules which significantly impact vehicle design are:

- Each vehicle must carry two crew, of whom only one may generate propulsive power while the other is responsible for navigation, steering and safety.

- All vehicles must be wet (free-flooding), with primary and back-up SCUBA on board for each person.

- All propulsion systems must be human-powered. Stored power systems are not permitted.

- Vehicles must be positively buoyant in the heaviest condition, so as to ascend safely and float in a stable fashion if disabled.

Competing vehicles are judged in three categories: Speed, Innovation and Cost-Effectiveness. For the Speed category, time trials are conducted through a 100 m underwater straight course, in order to establish a seeding order for the contestants. The vehicles then race in pairs around an oval course in a series of elimination races.

Innovation is evaluated by a judging panel consisting of experts in the field of marine technology. Innovation covers every aspect of the vehicle's design, from the major subsystems such as propulsion and control, to non-essential yet thoughtful details, such as the method of exhausting the exhaled SCUBA air from the submarine.

The third category of Cost-Effectiveness is rated by a formula containing a factor of speed per dollar of construction cost for each vehicle. Labour and materials for fabrication are included in the cost, but design time is free. This judging category aims to discourage the use of expensive design solutions which give only marginal improvement in performance.

The grand prize of $5,000 for overall performance is awarded to the submarine which achieves the highest combined score for each of the above categories (Speed, Innovation and Cost-Effectiveness). Many other prizes are awarded for achievements in specific areas of submarine design, such as Launch and Recovery, Use of Composite Materials and Safety; this upholds the competition's objective to foster advances in subsea vehicle technology.

The design of a human-powered submarine involves various engineering subsystems (see Figure 1). Concepts developed for the competition pertain to the design of small commercial and research submersibles, for missions such as inspection and maintenance, oceanographic data collection or diver delivery. In particular, the technology applies to subsea vehicles where energy efficiency is paramount, such as long-distance untethered submersibles [1]. There are also applications for surface craft, for example in the design of low-drag underwater appendages on grand prix racing yachts, as demonstrated by the Americas Cup contenders [2].

The award structure of the competition encourages differing objectives amongst competitors. For example, experience in the events held to date shows that a vehicle designed for the Innovation award is unlikely to score highly in the speed category. This leads to a rich diversity of design solutions, which will be analysed in a subsequent article. The present article will discuss the technical difficulties of designing an energy-efficient submersible and examine the options available for their solution.

Hull Design and Construction

The primary consideration for these areas are low hydrodynamic drag, but other important factors include ergonomics, and ease and cost of construction. The latter is particularly significant since the vehicles are prototypes, often built by teams with limited knowledge of boat building and operating on tight budgets.

The components of hydrodynamic drag are skin friction and form drag. Skin friction drag $\left(F_{D_{sf}}\right)$ is given by the formula:

$$F_{D_{sf}} = c_f \rho V^2 A$$

where c_f = friction coefficient, ρ = water density, V = vehicle velocity and A = wetted surface area. To decrease skin friction, the designer should aim to minimise c_f and A, for which feasible options include the application of surface treatment, prolongation of a laminar flow regime around the hull and reduction in wetted surface area.

Labour-intensive measures can be taken during fabrication to ensure a fine surface finish on the hull, but a more sophisticated approach is through the application of "riblets" (which were thought to be of dubious benefit on yacht hulls during Americas Cup trials) and the injection of polymers or other friction-reducing substances around the hull. The permissible substances are limited by US Federal and State Pollution Regulations.

The skin-friction associated with a laminar boundary layer is typically an order of magnitude lower than for a turbulent boundary under equivalent conditions [3]. Body shaping to extend the laminar boundary layer is a technique which was developed for the aerospace industry and has been successfully applied to underwater vehicles, where drag reductions of 50–60% have been achieved [1, 4]. A hull form which is a natural laminar flow body of revolution (see Figure 2a) is a more energy-efficient solution for delaying turbulent transition than "active" techniques, such as boundary layer suction or wall heating.

The form drag of a body immersed in a flowing fluid results from flow separation, leading to low pressure in the wake. The cross-sectional area of the wake can be minimized if flow separation at the rear of the vehicle is delayed, through optimum design of the after body and propeller. A small projected frontal area is also advantageous.

For reduction of both the skin friction and form drag, vehicle size should be minimized, but herein lies the first engineering dilemma. Figure 1 clearly illustrates the problem of encasing two people, their life support and the propulsion system, to form a hydrodynamically-efficient shape. The submarine "engine" is a human athlete, who must be permitted to produce power at optimum efficiency; this cannot be compromised by cramped conditions. Equally the pilot will be aided in the tasks of precise navigation and vehicle control, if some degree of physical and mental comfort is provided. A compromise between optimum ergonomic and hydrodynamic design must be made.

If ease and/or cost of fabrication is an over-riding factor, a simple torpedo-shaped hull (Figure 2c) may be selected. However, significant drag reduction can be achieved by using a body of revolution formed from an efficient wing profile (Figure 2b). If this option is selected, grp or carbon/Kevlar lamination over a prefabricated mould may be the only feasible construction method. Use of lightweight composites, such as laminated foam sandwich, will not offer the benefits which are apparent for surface craft, because the ballast weight required to offset the material buoyancy will be a disadvantage during launch and retrieval operations.

The Human Engine: Transmission and Propulsion

The conversion of human power to propulsive power is a challenging design problem, since the well-proven bicycle technology of the terrestrial environment may not be the most efficient underwater. Questions to be addressed include:

a) which are the most powerful muscles of the human body for external power production?

b) what is the most energy-efficient motion for the power-producing stroke underwater?

c) what position should the "prime mover" adopt in order to produce power most effectively?

d) how much useful power can be produced?

e) how can that power be converted most efficiently to mechanical power and then transmitted to the propulsor?

It is generally accepted that leg cranking alone is the most efficient form of power production; significant increases in power output can be achieved, but for a limited period, if a combined arm and leg system is used. This will be followed by a drop in power to a value well below that of simple pedalling.

Linear or rotary (i.e. conventional bicycle) foot cranks are options for converting human power to mechanical power. Linear cranking may be more efficient at a low cadence and requires a smaller swept volume for the lower leg, but this must be offset against the convenience of using off-the-shelf bicycle components if rotary cranks are selected. Compatibility with the final propulsion mechanisms (see later) is also a factor; for example, linear cranking is well-suited to a fin propulsion system [Figure 3].

The streamlined shape of a submarine restricts the posture of the human propulsor to either a recumbent (as in Figure 1) or prone (lying face down) position. Historical evidence from the terrestrial environment suggests that a recumbent position is preferable, but research has shown [5] that the prone position permits a higher power output for a given heat rate and ventilation rate of a human subject underwater. This can be explained by the hydrostatic pressure imbalance between the regulator which delivers air to the subject and the centroid of the lungs. Additional work must be done by the respiratory muscles to overcome this imbalance in the recumbent position, where ambient pressure at the regulator is lower. The effect is imperceptible in air, but is of major importance to diver performance [6].

The maximum workrate for a fit human under atmospheric conditions has been well researched and documented [7] but information regarding underwater workrates is scarce. Factors such as the increased drag of limbs moving through water, the effects of pressure and weightlessness and the restricted airflow through a SCUBA regulator may reduce the useful power output by up to 50%. Figure 4 illustrates the strong dependency of power output on duration of exertion. The average time taken for the 100 m sprint by the top 10 submarines in 1993 was 60 seconds, corresponding to a gross power output in air of 0.7 kW on the 'National Amateur' curve in Figure 4. This translates to 0.35 kW useful power underwater, confirmed by ergometer trials [8], but will fluctuate strongly for relatively small changes in the duration of the sprint.

The average time taken by the most competitive submarines for the elimination races in 1993 was $4\frac{1}{2}$ minutes. Figure 4 gives a gross power output in air for this duration of 0.35 kW, translating to 0.18 kW of useful power underwater. The propulsion system design must therefore accommodate a wide variation in available power, if optimum speed is to be achieved for both the time trials and elimination races.

Operating speed of the "prime mover" is also an important parameter for propulsion system design. Ergometer studies carried out in Florida on 14 subjects suggest that 50 rpm is optimum for a fit subject [9]. However, there may be reasons for the designer to specify a different value, such as the ability of the pedaller to maintain a constant cadence at a higher or lower speed [8].

Cranking cadence has important implications for the transmission system, where small energy losses equate to a high percentage of available power. Although variable gear ratios, such as the derailleur system for bicycles, may be attractive ergonomically, chain drives are associated with high hydrodynamic losses and are too fragile in an underwater environment. A better solution is to mount pedals directly onto a bevel gear box driving the prop shaft and to use a controllable pitch propeller rather than gears to reduce the required start-up torque.

For a human-powered submarine, the parameters which are needed to design a propeller, i.e. shaft power and speed, effective power and operating speed of the vehicle, will fall outside those on a conventional design chart. Therefore the propeller must be custom-designed for maximum efficiency, from first principles. Many competitors developed their own computer programmes, based, for example, on lifting line theory. In general terms, propeller efficiency increases with blade diameter and decreases as the blade area ratio and/or number of blades rises. The most efficient propellers for this application resemble those on aircraft, having long slender blades with narrow tips. There are also arguments in favour of using counter-rotating or ducted propellers.

The Submarine Races provide an ideal platform to demonstrate the feasibility of some innovative propulsion systems, such as oscillating fins, paddle wheels and mechanical pushers. These will be presented in a future article, where selected overall design solutions for competitive submarines will be analysed.

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Part 2 : Outstanding Design Solutions

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Background

The International Submarine Races, for small submersibles with a crew of two people operating in the open ocean and propelled solely by human power, were held biannually between 1989 and 1993, off the East Coast of Florida. An article in the March issue of S&B International described the objectives of this competition and the design options available to competitors.

In the present article, we will look at the design developments and performance trends over the history of the event, and examine some of the more successful vehicles which have participated.

Speed Trends

So how fast is a human powered submarine? What is the comparison with an Olympic swimmer, who will maintain 2.2 m/s over 100 m?

The submarine *FAU-Boat* (Plate 1), designed by students from Florida Atlantic University, clocked 2.42 m/s (4.71 knots) over a 100 m straight sprint in 1991. This is the record for operation in the open ocean. Higher speeds are achieved in a controlled, indoor environment; for example the vehicle, *Torpedo III* (Tennessee Technological University) achieved 2.76 m/s (5.36 knots) in December 1995, at the David Taylor Model Basin in Bethesda, Maryland. The improvement reflects the absence of wave action, cross-currents and poor visibility, which adversely affect both the human and vehicle performance in the ocean.

Over the history of the Submarine Races, the average speed of the vehicles has increased, as shown in Figure 1. Here, vehicles have been grouped according to their average speed for a 100 m sprint, within bands of 0.25 m/s. The mode (most frequently occurring speed band) rises from 0.75 – 1.0 m/s in 1989, up to 1.5 – 1.75 m/s in 1993. The corresponding mean values of speed for the whole fleet are 0.9 m/s in 1989 and 1.4 m/s in 1993.

But the International Submarine Races are not simply speed trials. An entry in the competition is a multi-faceted project comprising:

- the design and construction of a reliable vehicle, optimized for the judging criteria of speed, innovation and cost-effectiveness
- fitness training for the propulsor
- training in vehicle handling skills for the pilot
- teamwork between the submarine crew and their back-up supporters (engineers, technicians and divers)
- time for in-water testing and development
- logistics (transportation, travel, accommodation, access to local workshop facilities during the competition)
- presentation skills (for the judging process)
- fund-raising and publicity

A team must excel in all these areas to achieve success in the competition and therefore the technical quality of a vehicle's design is only one of the aspects which influence its final ranking. Each year, a significant number of entries fail in the basic task of completing a 100 m underwater time trial as shown in Table 1. There is a higher success rate for teams which have previous experience in the competition and therefore appreciate the importance of a robust, reliable vehicle. Many failures of potentially fast submarines result from insufficient wet testing prior to the competition, which is vital to identify mechanical weaknesses and to ensure accurate buoyancy and trim.

	1989	1991	1993
Total number of submarines	17	34	42
Number of submarines completing 100 m time trial	9	23	24
Number of submarines completing 100 m time trial, where the team had competed in previous event(s)	–	13	19

Table 1 Statistical Data for the History of the Submarine Races

The Shape of Fast Submarines

A low drag hull design is crucial to achieving good speed with limited propulsion power. Table 2 shows that the majority of the fastest submarines are symmetrical bodies of revolution, formed by rotating a wing profile around the longitudinal axis. Exceptions of note in 1993 are the MIT *Sea Beaver* (Plate 3), which comprises a Goertler 4165 series hull (optimized for enclosed volume versus drag) with an added cylindrical mid-section, and the "tuna-shaped" hull of *Pelagic Cruiser II*, which was shown in P45 of S&B, March 1996.

The two submarines from California Polytechnic in 1989 convincingly demonstrate the advantage of a fair hull form. *Speedstick* (0.84 m/s) was identical to *Subversion* (1.42 m/s), except that its internal mechanisms were mounted in a tube, upon which the crew rode broomstick-fashion (Plate 3). *Subversion's* hull was a conventional body of revolution.

FAU-Boat was the fastest submarine for two consecutive competitions, but surprisingly slower in the most recent. Modifications between 1991 and 1993 included smaller control surfaces (to reduce drag) and propeller redesign for a higher shaft power and speed: 0.75 HP at 70–80 rpm. These values were reported to have been measured in the Human Performance Lab at Florida Atlantic University, but the deterioration in submarine performance suggests that they are over optimistic.

Table 2 Time Trial Speeds for Fastest Submarines

1989		
Team *Vehicle Name*	Hull Form	**Speed: m/s**
California Polytechnic *Subversion*	Wing Profile	1.42
US Naval Academy *SQUID*	Teardrop	1.36
Applied Physics Laboratory *HumPsub*	Laminar Flow Wing Profile	1.32
Florida Institute of Technology *Sea Panther*	Torpedo	1.19
California Polytechnic *Speedstick*	Broomstick	0.84

1991		
Team *Vehicle Name*	Hull Form	**Speed: m/s**
Florida Atlantic University *FAU-Boat*	Wing Profile	2.42
Mare Island Shipyard *Sub-Human II*	Wing Profile	1.91
Benthos, Inc *Subsaurus*	Wing Profile	1.75
US Naval Academy *SQUID*	Teardrop	1.71

University of New Hampshire *SPUDS II*	Wing Profile	1.56

1993		
Team *Vehicle Name*	Hull Form	**Speed: m/s**
Florida Atlantic University *FAU Boat*	Wing Profile	2.19
MIT *Sea Beaver II*	Goertler Series + Cylindrical Mid-Section	2.05
Tennessee Tech *Tech Torpedo II*	Torpedo	1.83
Team Borborygami *Pelagic Cruiser II*	Tuna	1.73
Battelle *Subjugator*	Wing Profile	1.64

Novel Concepts for Hull Form

A handful for submarines have employed the drag reduction concept of natural laminar flow shapes, although the application of this technology in an environment of high ambient turbulence in shallow coastal waters is questionable. Plate 4 shows the laminar flow hull of the Applied Physics Laboratory's *Humpsub*, which was third fastest in 1989 (the best speed trial result for a laminar flow shape). This team's efforts to optimize hull form may well have been obrogated by a disappointing propeller design, which resembled an industrial fan. The vehicle was also large (4.9 m long) compared with its close rival *SQUID* (3.1 m), posing the question of how much its performance might improve should all subsystems be optimized.

The need to minimize surface area, for reduction of skin friction drag, was discussed in Part I of this article [S&B International, March 1996]. Since a sphere has the lowest surface area: enclosed volume ratio, this shape was selected by the renowned hydrodynamicist, Cal Gongwer, for his entry *Knuckleball* in the 1989 Races (Figure 7). His design philosophy was that the high form drag of a sphere can be reduced by preventing separation at the rear, through the acceleration of boundary layer flow into the propeller [1]. He had previously demonstrated the concept on a 13 inch diameter model. *Knuckleball* incorporated a hand-cranking mechanism for the propeller, with pilot and propulsor sitting side-by-side in the sphere [2]. Sadly, the vehicle proved directionally unstable in the Atlantic waves and the concept was never proven at full scale.

Novel Propulsion Systems

Propulsion is the area holding greatest potential for contestants with aspirations to the Innovation Award. As the method most commonly used by aquatic animals, oscillating fin propulsion holds a fascination for the marine engineer and indeed this is a topic of long term research at MIT [3]. In total, seven teams have designed fin propulsion for their vehicles, but only two have demonstrated successful operation at the event.

Gossamer Albacore (Lockheed Advanced Marine Systems) won the Innovation Award in 1989, with a triple foil propulsion system which drove the vehicle at 0.5 m/s (1 knot). The hull was a 4.2 m torpedo shape, 0.6 m in diameter, with stern-mounted foils, as shown in Plate 6. The fins and their drive mechanism are detailed in Figure 2. This arrangement [4], with a large central fin sweeping in the opposite direction to an upper and lower half-size fin, was designed to overcome the problem of body yaw which would be induced by the reaction to a single oscillating fin.

The vehicle was donated to Scripps Institution of Oceanography after the event, where the propulsion system was changed to horizontal oscillating foils, connected to the submarine by external arms at the vehicle's centre of mass. This location ensured the absence of a pitching moment on the vehicle and doubled the speed to 1.0 m/s (2 knots).

The performance of other novel propulsion systems, such as jet propulsion and paddle wheels, cannot be assessed due to operational failures. However, in 1991 *Spirit of Columbus* (Battelle Memorial Institute) successfully demonstrated a "frog-leg" propulsion system, known as the "articulated linear thrust engine drive". A hinged pair of plates were fitted in V-formation on the end of a drive rod protruding from the submarine's stern (see Figure 10). On the thrust stroke, the rod was pushed backwards, automatically forcing the plates apart, which thus presented a high drag profile to the water. The rod was retracted on the return stroke, when the plates folded flat to present minimum profile drag [5].

Spirit of Columbus (Plate 7) had a very fair and compact hull, with low resistance. Sadly, the linear thrust engine could drive the vehicle at only 0.8 m/s, whereas a more conventional 3-bladed propeller, as fitted for the 1993 races, doubled this value.

Thus single rotary propellers remain the system of choice for teams looking for good speed performance. Protective shrouds were popular in 1991 Plate 8, following reports of entanglement with lines and damage on the reef during the first event. By 1993, the shrouds had been abandoned, with blade shaping used to avoid entanglement (Plate 9) and improved launch systems to prevent damage in shallow water.

The submarine *Team Effort* in Plate 8 won the Innovation prize in 1991, for it's combined propulsion and altitude control system. This so-called 'tandem propeller system' permits individual blade pitch control. Collective blade pitch is used in the usual way to provide thrust, but cyclic variation in the pitch of individual blades via a swash plate (in a similar manner to the main rotor of a helicopter) will provide transverse and vertical forces to control pitch and yaw. Excellent manoeuvrability at low and even zero speed can be achieved, since forward speed is not required to produce the control forces [6].

A different type of combined propulsion and control system, utilizing vectored thrust, helped *Sub-Human II* (1991) and its successor *Sub-Human III* (1993) to rank highly in the Innovation category (2nd and 3rd respectively). Designed by naval architects and engineers from Mare Island Shipyard, California, the tail sections of the vehicles were articulated to sweep through ± 30° in the horizontal plane, providing yaw control. Both submarines boasted dual counter-rotating propellers, thereby eliminating the rolling moment on the vehicles which would be produced by reaction to the torque of a single propeller. Although this dual propeller system demands intricate engineering of the co-axial shafts and transmission, there is a beneficial efficiency gain through the partial recovery of rotational losses imparted to the fluid by the forward propeller. Furthermore, for a given thrust, the overall blade diameter is reduced in comparison with a single propeller, which is helpful in the potentially damaging environment of the Submarine Races, near reefs and the seabed. Plate 10 shows how the stabilizers of *Sub-Human III* are fitted on the articulated tail section, which allows the vertical fins to double as rudders for yaw control, should the propellers cease to operate.

Further Innovations

Ahead of *Sub-Human III* in the Innovation category for 1993 was *C-Scan II*, an individual entry by Gary Straughan (2nd) and the winner *OMER*, from the École de Technologie in Montreal. The emphasis of *C-Scan* (Plate 11) was on steerage, with a hull which articulated by 10° at 3 points, permitting a vectored thrust arc of ± 30°. Gary also designed a steerage system for his surface buoy (which each submarine was required to tow), an innovation not considered by other competitors.

OMER was one of the few non-US entries in a competition which is billed as 'International'; others came from Germany, the UK, the Bahamas and Canada. *OMER* evolved from an impressive development programme, incorporating wind tunnel testing of three candidate hull profiles and construction of a quarter-scale radio-controlled model for testing various subsystems. The vehicle geometry was unusual, with 3 fixed stabilizers at the stern in Y-formation and 3 forward moveable control surfaces, comprising two independent dive planes and a single, upward-pointing rudder (Plate 12). This rudder configuration was not efficient, due either to its size or location, causing the submarine to average an undistinguished 1.1 m/s (2.1 knots) as it meandered down the 100 m straight sprint. The submarine's innovative features included a planetary pedalling motion for the propulsor, which extended the lever arm for the push stroke, and computerised monitoring and control of the pitch angle of the propeller blades and of the air consumption of the crew.

The Secret of Success

So far we have examined submarines which are fast or innovative; but these are not the overall winners. Historically, the overall winners do well in each of the categories of Speed, Innovation and Cost-Effectiveness, to beat their rivals on cumulative score.

Winner of the 1st International Submarine Races in 1989 was *SQUID* from the US Naval Academy (Plate 13). The compact, teardrop-shaped hull was second fastest in the fleet at 1.36 m/s, driven by counter-rotating propellers with surrounding Kort nozzle which were designed and developed through advanced potential flow analysis and computer modelling of the propulsion system. Research had been conducted into ergonomics and the human-machine interface, to optimise the pedalling position and internal layout. The Academy's extensive background in submarine operations was augmented by two weeks of dedicated testing in the Gulf of Mexico, prior to the competition. Thus, the most successful team based their campaign on thorough preparation and reliability.

Further refinement of *SQUID* in 1991 improved its speed to 1.71 m/s (Table 2), but it was nevertheless beaten by 3 other competitors, including the overall winner *Subsaurus* from the undersea systems company 'Benthos'. *Subsaurus* had aborted its time trial in 1989, due to failure of a propeller drive pin, but the team felt that their design was a viable contender and should be proven rather than changed for the next event. The hull form was based on a turbulent flow analysis by Myring [7] and the highly efficient, large diameter propeller was designed using lifting line theory. The stabilizers and control surface layout was distinctive, with two rudders and two horizontal stabilizers at the stern, fixed vertical stabilizers midships, plus a second set of rudders located forward of the moveable dive planes (Plate 14). The forward and aft rudders were counter-linked, to rotate in opposite directions. The comparatively large vertical fin area (0.57 m^2) was designed to counteract the submarine's inertia and thus reduce side slip during turns.

The Benthos team efforts for 1991 were concentrated on power training for the propulsor using an underwater ergometer and substantial hours of bottom time in the submarine for pilot and propulsor, which was facilitated by a Walkie-Talkie communication system to the surface support vessel, via the tow line to the surface buoy. Again, a campaign of thorough preparation and proven reliability paid off.

Speed improvements were less dramatic by 1993, but nevertheless the overall winner *Tech Torpedo II*, bettered *Subsaurus's* speed, although placing only third in that category. *Torpedo II* had a simple, cylindrical hull, with a hemispherical clear nose made of polycarbonate (providing excellent vision for the pilot) and a convexly tapering tail. It's control surfaces, comprising fixed leading sections with moveable trailing edge flaps, were located forward for the dive planes and at the stern for the rudders. An additional set of fixed, horizontal stabilizers were also located at the stern. The angle of the flaps was controlled via 4 hydraulic linkages to a single joystick, which contributed to a respectable ranking for the team in the Innovation category.

What each of the overall winners have in common is a solid vehicle design, with well-researched subsystems and good integration. Substantial in-water testing experience leads to a reliable vehicle and confident, welltrained crew, who can concentrate their efforts on winning during the competition, rather than fixing the submarine or learning how to operate it.

More than an Amusing Diversion?

Although the Submarine Races were conceived as a fun event to encourage students into the field of marine technology, one may speculate as to the possible applications and commercial spinoffs.

Energy efficiency is an essential component of the developing technologies for untethered underwater vehicles, where on-board power is limited. One example is the UK's current *Autosub* project, to build an autonomous long-range submersible for oceanographic measurements. *Autosub* incorporates a laminar flow hull.

There may be applications in covert military underwater operations, such as diver delivery, but whether there are benefits to be gained by extending the human powered submersible concept to sports diving remains to be seen.

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