Submersible propulsion and energy:

FROM LTS-7 TO UKWIA£

Key words: motion, submersibles, propellers, sources of energy, .

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Abstract:

There is nothing exceptional in underwater technology except for environment. But this single factor means very difference, that creates many problems to underwater system designers and operators. For many years Department of Underwater Technology has been involved in design and construction of various submersible crafts. They ranged from 35 kg diver towing vehicle to 1500 Mg manganese nodule mining vehicle. All the vehicles designed require a kind of propulsor and adequate source of energy. Different solutions were exploited for every considered application. In most cases several prototypes were built and modified before fully acceptable solution was found. Experience gained during 30 years of work with live systems gives the University substantial capabilities in new developments and education. Paper describes most significant vehicle designs and outlines principal problems encountered in the area of interest of this conference.

1. INTRODUCTION

For the purpose of better understanding of the subject of this paper, it is important to define what is understood as propulsion and source of energy in a submersible system. To find the definition it is wise to turn to a long- term goal of The Department of Underwater Technology as academic institution. This is constant development of submersible design procedures and important technologies. Final expression of this work is an idea of the design procedure and computer program named DVCAD. It is generally an expert program that we want to offer to underwater community. Our experience as well as information available from other sources is offered to a designer or student in various forms. The procedure has been developed with the following assumptions in mind:

- A submersible is designed to fulfil defined mission tasks,
- It is composed of several hierarchically dependent subsystems,
- The subsystems are designed using information regarding well-proven products and principles. Non-existing components or additional parameters are evaluated using physical phenomena, dedicated design methods and reference products,
- The algorithm structure is open to allow design procedure to be customized,
- Arrangement of components in three-dimensional space and evaluation of external shape is a final step of design process and is purpose driven.
- Design process requires several iterations for whole system as well as subsystems and components.

The base for systematic approach is a submersible system break down that was adopted following careful analysis. Considering list in Table 1. it is difficult to completely separate maters of propulsion (or rather motion control) and source of energy, from other subsystems of hypothetical submersible. These are usually cross-interlinked on different levels. For this reason it is understood that one must be aware of these correlations while considering various designs that we adopted in our systems. This allow us to concentrate on very specific matters.

1. LTS-7

The LTS-7 "Grzeœ", a submersible manned by 2 persons, was our first serious underwater project. She has mass of approximately 3000kg and operating depth of 200m. She was built during best years of manned systems era. Designed as observation tool, to be used in research of active fishing gears, she is able to operate in two different manners. Principal "propulsion" used during observation of fishing gears under tow, is a steel towing rope. This solution gives high speed capability, unlimited by energy source. Another factor, important in observation of towed systems, is precise and stable position against the object of observation (net). Position in a plane, perpendicular to direction of movement of the craft, is controlled by means of vertical and horizontal hydrodynamic planes.

While operating in autonomous manner she uses substantial size lead-acid accumulator battery and 1.5kW DC electric motor. The battery and motor are oil filled and pressure compensated. A chopper was initially designed for speed control but this solution has been abandoned due to electrical instability. Simple switching of three 12V sections of the battery proved to be adequate and much less complicated, although very conservative. Located at stern, the motor is used to propel the vehicle in horizontal plane. This was the first time we attempted to submerge an electric motor. We had immediately found that oil filling creates many problems at commutator and brushes. The latter were drilled axially to avoid cushioning on layer of oil. Finally brush problems were solved and motor works well.

Of course, as any serious autonomous manned craft LTS-7 has surface buoyancy tanks and variable buoyancy system, with oil as working medium. These are supplemented by mercury based trim system. Three gear pumps used to supply three separate, hydraulic

Table 1. Submersible subsystems break down

Group 1. Work systems and instrumentation
1.1. Observation equipment
1.2. Manipulators
1.3. Hydroacoustic space Visualization equipment
1.4. Oceanographic instrumentation
1.5. Communication equipment
1.6. Navigation equipment
1.7. Emergency equipment
Group 2. Diving and personnel transportation
2.1. Divers and transferred personnel
2.2. Tools
2.3. Diver life support
2.4. Diving chambers
2.5. Mating skirts
Group 3. Control system and crew
3.1. Control system
3.2. Crew
3.4. Control panels
3.5. Isobaric compartments life support system
3.6. Pressure vessels for crew and controls
Group 4. Motion control
4.1. Surface buoyancy
4.2. Variable ballast
4.3. Trim
4.4. Propulsors
4.5. Hydroplanes
4.6. Anchors
Group 5. Energy supply
5.2. Main primary sources of energy (Heat engines, fuel cells nuclear sources)
5.1. Main secondary sources of energy (accumulator batteries)
5.3. Umbilical
5.4. Emergency sources of energy
5.5. Power distribution and energy transformers
Group 6. Externals
6.1. Frame
6.2. Fairing
6.3. Bumpers
6.4. Floats
6.5. Ballast

subsystems (manipulators, variable ballast and trim) are powered by means of the same type of electric 1,5kW DC motor. Also placed in oil filled container for pressure compensation.

While reliable vertical (ascend) propulsion is of critical importance in emergency, different means are provided for this purpose.

These are as follows:

- Breathing oxygen can be used to blow buoyancy tanks instead of compressed air.

- Lead ballast weight, accumulator battery and trimming mercury can be jettisoned.

It follows the principle that different physical phenomena are to be used to generate ascending capability in critical situations.

ZKR – JETTISON LIFE SAVING CAPSULE

The jettison emergency capsule is a special device designed for rescuing life under the most adverse weather and technical conditions. Principal application is high level deck of drilling rigs. The idea is built around pressure resistant capsule. After being manned by rescuees it is launched horizontally using high pressure air or pyrotechnic device. While launched it drops freely from heights up to 40-50m and submerges to 50 m below surface. To stop around 50m depth the capsule is equipped with a 3Mg anchor weight and automatic winch. By means of careful design of gears and pressure controlled friction breaks it is possible to automatically release the anchor and keep capsule at required depth while the anchor still submerges toward seabed. The intention was to keep the capsule and rescuees far off rig structure, possible fire and bad weather. For safety and operational reasons the anchor can be released or detached to allow capsule to surface and if required float free. To return below the surface it was possible to power the winch manually or by means of small electric motor. As mentioned above in this simple design several unique propulsion systems were provided to allow fast response to threats, reliability and safety. In experiments performed most of ideas were proved. Due to high investment costs the idea was not used in practice.

2. NODULE II

Never built, but well looking concept of the manganese module mining system is one we are very proud of. The project, initiated by Szczecin based, Interoceanmetal organisation, have stimulated several new ideas. Our concept of the system is based on large size autonomous underwater vehicles used for collecting of nodules at seafloor as well as for vertical transport of nodules to surface and transporting ships. Commercial system with output of 5 million tonnes of dry nodules (14 000 tonnes a day) requires really big pieces of equipment and unusual solutions. The size of the vehicle length exceeded 20m and width was 20m, while it was 5 m high. Total weight of the vehicle while ballasted or filled with nodules exceeds 1200Mg. But not the size is most exotic but source of energy provided .

To assure reliability and fast revitalisation of the vehicle after each dive, simple principle of underwater "boomerang" was adopted for the system. Principal source of energy for vertical and horizontal relocation of the vehicle is a potential energy of ballasting matter. At the surface, the vehicle is ballasted using high density matter (rocks). With slightly negative buoyancy, it glides toward a seabed 4-6 km below. This phase takes 1 – 2 hours and vehicle goes to precisely indicated point at nodule field. To collect assumed 500Mg of nodules per dive it must crawl 3600m only. That means 1 hour at 1m/s speed. During collecting phase, it collects nodules and releases ballast to keep itself negatively buoyant, but not excessively heavy. At the end of a bottom trip, rest of the ballast is released and vehicle glides up with positive buoyancy. To this point nothing new except for size of the "boomerang" can be found. The most interesting is an idea of use of high pressure water for vehicle propulsion. Pressure of water at the bottom is really high (40 – 50MPa) and can be directly utilized to generate mechanical energy. For this purpose, a water flowing through hydraulic motor was allowed to empty pressure resistant tanks. Volume of these tanks is approximately 50m^3. The system provides 200kW of mechanical energy used to drive tracks, pumps, manoeuvring thrusters and electric generators.

The price for this simple form of energy source is equivalent amount of ballast loaded at the surface and released at depth. To revitalize vehicle after dive the only operation required, is to open and drain the tanks of high pressure water and take ballasting material. Again there is no need to waste accumulated energy. This energy is used to propel the vehicle the surface to transporting ship that take nodules and loads ballast again. There is no need for charging (20 hours) or replacement of accumulator batteries. No chance for shorts. It seems to be very smart, purely mechanical solution.

Table 2. Principal parameters of energy sources and propulsors of submersibles developed by Department of Underwater Technology of Technical University of Gdansk

Year Vehicle name	Vehicle purpose Working depth [m]	Dimensions L x B x H [m]	Principal capacity of energy source	Propulsion power	Vehicle mass [Mg]
1974 Czapla	Diver observation sled 60	2.5x 1.2x0.8	Compressed air	Towed	0.030
1976 LTS-7	Fishing gear studies 200	3.5x1.8x1.8	Accumulators lead-acid 10kW	Towed and electric DC, 1.7kW	3,000
1984 BURZYK	Mine neutralisation 200	3.0x 0.8x 0.8	Accumulators Diesel engine	Electric AC, 20kw	1,200
1986 Jettison Emergency Capsule	Drilling rig life saving device 50	4.0x4.0x.7.0	Gravity	Compressed air, free fall and free dive	20,000

1990 KORAL	Observation and simple manipulation 400	0.6x0.6x0.6	Umbilical 4kW, 50Hz 800V	Electric DC, 5x 0.1kW	0,150
1990 KONKRECJA I	Nodule deposits observation and simple manipulation 6000	4.0x1.0x2.0	Accumulators lead-acid 20kWh	Electric DC, 1.0kW	3,0
KONKRECJA II	Industrial Nodule mining 6000	20.0 x 20.0x5.0	Ballast and potential energy of water column	Hydraulic 200kW	1500,000!!!
1990 HOLONUR 1	Diver Towing vehicle 50	0.7x 0.4x0.3	Accumulators lead-acid 0.6kWh	Electric DC, 200W	0,035
1995 KORAL AT	Observation and simple manipulation 400	0,9x0,7x 0,7	Umbilical 4kW, 1200Hz 800V	Electric AC, 5x 0.5kW	0,070
1995 HOLONUR 2	Diver Towing vehicle 50	0.8x0.4x0.3	Accumulators lead-acid 0.6kWh	Electric DC, 300W	0,035
1995 AUV	Oceanographic measurements	3,0x100x500	Accumulators lead-acid 10 kWh	Electric AC, 6x 0.1kW	0,700
1997 Holonur 3	Diver towing vehicle 50		Accumulators lead-acid 1.5kWh	Electric DC, 550W	0,035
2000 Ukwia[3]	Sea mine neutralisation vehicle 200	1.5x0.7x0.75	Umbilical 6kW, 600Hz 800V	Electric AC, 6x 0.7kW	0,200

3. DIVER TOWING VEHICLE HOLONUR MARK II AND MARK III

Our diver-towing vehicle is quite old development now. It was started at 1990 when first prototype has been built. Its performance was not impressive so next model was developed soon. It can be described as standard design with brushed DC motor, supplied with low voltage, lead acid accumulator batteries. Motor is switched on and off only. LED indicators inform a diver of battery condition. Some test vehicles were built as Mark II. They were further upgraded to obtain reliable underwater equipment. Exceptional feature of the vehicles were a ball bearings used as 2.5:1 reduction planetary gears. Their performance and reliability were proved during years of intensive exploitation with exception for some problems with hydrogen build up. After two blowups the problem has been solved by means of low temperature catalytic burners.

New requirements and technological development resulted in totally new approach to vehicle propulsion. Principally new requirements called for longer range, higher speed, lower noise and improved reliability. To achieve this we have adopted well proven synchronous AC motor technology, previously used in remotely operated vehicle KORAL AT. A prototype was built using permanent magnet AC motor with sinusoidal magnetic field. Main differences against brush motors are: no brushes, speed reduction planetary gears, slide bearings and oil pressure compensation of propulsion motor. This solution offers higher reliability and substantial noise reduction, with slight increase in weight and motor diameter. Two years later, however, this has been abandoned for it complexity and replaced with simple brushed, low speed DC motor.

Table 1. Mark III and Mark II diver towing vehicle technical data

	Mark III	Mark II

1. Nominal thrust	250 N	120 N
2. Maximum speed - 1 scuba diver	1.5 m/s	1 m/s
5. Operating time at nominal thrust	1.4 - 3.5 hours	2 hours
6. Range (maximum)	11000 m	4500 m
2. Nominal battery power drain	550 VA	300 VA
3. Nominal battery voltage	144 V	24 V
4. MTBF calculated	2000 hours	800 hours
6. Continuous speed control	Yes	No
7. Compass	Flux gate	Magnetic
8. Battery diagnostics	LCD, plain text	3 LEDs

4. AUV FOR OCEANOGRAPHIC STUDIES OF BALTIC WATERS.

Being significant source of pollution of Baltic Sea, Poland is heavily involved in its monitoring as well as investments devoted to protection of the environment. One of the tasks is environment monitoring. It means the need for periodical trips to selected points using various surface ships. While at location, oceanographic equipments are being lowered and required measurements performed. AUV mission task is identical with exception for continuous measurement on route. It is expected that introduction of the new technology will substantially reduce costs of monitoring and will make it whether independent.

The mission profile is comparatively simple. A vehicle is intended for delivery by road and launched at one of Polish ports located along Baltic south coast. After a launch, vehicle leaves the port controlled by radio means. While at sea, it descends and begins its trip along planed route. Normally it will cruise at given speed and depth to first point were oceanographic measurements are to be done in vertical. Measurements are made twice - during ascent and descent. While at the surface, actual position is being measured using satellite (DGPS) navigation receiver. If a distance between measurement points exceeds allowable maximum, vehicle surfaces between these points and corrects it's position using the same means. While at the required depth, the vehicle reassumes cruise to next measurement point or if a mission task is achieved, to recovery point. This point can be located at the same port or any other place at a range of 200km from the launch point.

The vehicle has been designed to carry hypothetical “payload” of oceanographic equipments, described by the following parameters:

Volume:	200mm x 200mm x 1000mm
Negative buoyancy:	1000N
Power requirements:	24V/50VA (average)
Energy:	2500Wh (50 hours)

To give above equipments possibility to work according to assumed parameters they must be accurately located in water space. This accuracy was assumed as ± 50m at a range of 200 km.

The cruise speed of the vehicle has been assumed to be in range from 1 - 2 m/s depending on particular mission. The move system has been initially designed with a different ballasting and trimming subsystems, supplementing propulsion components. After detailed study this has been reduced to set of 6 electric propulsors, arranged to meet motion requirements. They are built around proven solution with permanent magnet synchronous motor powered by DC/AC frequency inverter. The design has been modified to reduce complexity while compared with other designs. At a penalty of slight diameter and weight increase, the planetary gear has been removed. Principal advantage of the modified device is increased reliability but a noise has also been reduced substantially.

Powerful, simple, reliable and inexpensive energy source for AUVs is our target and we still wait for it. For the time being we have adopted well known and proven lead-acid hermetically sealed accumulators tested in diver delivery vehicles. Their parameters are suitable for the vehicle prototype and it is assumed they can be easy replaced with more advanced source in near future.

An energy source Lithium ion accumulator cells are currently considered for AUVs under development.. This type of comparatively modern accumulator is difficult to operate but it offers excellent specific capacity and power factors. Even specific cost do not exceeds acceptable level. Table 3. gives quite recent comparison of cells and batteries considered for small battery powered vehicle.

Tabela. 1. Specifications of selected types of modern D size primary and secondary electrochemical cells.

Nominal battery requirements: capacity 500Wh, voltage 24V, current 20A.

Cell type	Cell price	Dimensions	Cell mass	Cell voltage	Cell capacity	Max. discharge current	Cell energy capacity	Battery no of cells	Battery capacity	Battery mass	Price
-	PLN	mm	kg	V	Ah	A	Wh	szt	Wh	kg	PLN
Sonnen-shine 12 V battery	133	1 34x67x60	1,5	12	3,5	10	42	6	252	9.0	798

Lead-acid Cyclon D	26	34,2x67,6	0,200	2	2,5	10	5	48	240	9.6	1248
Alkali LR20/D	4	34,2x61,5	0,100	1,5	18	0,4	27	320	8640	32	1280
LiSO/ LO26SHX	38	33,8x59,0	0,085	3	7,5	4 (30)	22,5	28	630	2,38	1064
NiMH Varta VH4500D	73	33,5x58,0	0,150	1,2	4,5	4 (40, 4-5min)	5,4	60	324	9,0	4380
NiCd Varta RSH4	63	33,5x61,0	0,147	1,2	4,0	4 (15-20)	4,8	60	288	9,0	3780
Li - Ion	130	33,8x59,0	0,085	3,5	4	4 (30)	14	28	392	2,38	3640

5. KORAL, KORAL AT AND UKWIA£

The KORAL family of vehicles has been created to meet requirement of the approaching era of unmanned systems. To design remotely operated vehicle during time of industrial autarchy it was not an easy task. We were able to utilize some technologies developed for previous projects but many adequate materials and components were not available. One must also remember that high power microcomputers of that time were based on Z80 and 8086 running at 1MHz. Control system of the KORAL was based on this type of processor also and it was very modern solution. Finally, the vehicle was developed and prototype has been build. It worked according to assumption with exception for excessive weight. This was result of selected power supply. The vehicle was supplied and controlled using umbilical cable. To reduce umbilical conductor size the voltage at the surface was increased to 800V. This was good decision. Bad decision was to use standard frequency of 50Hz. While surface located step-up transformer can be heavy, the vehicle transformer should be kept as light as possible. With 50Hz working frequency it was difficult problem. In spite of application of sophisticated aluminium tape windings, it was not possible to get the transformer mass below 30kg. As a result, instead of assumed 60kg the vehicle mass was 120kg.

It worked, however, and first important practical step toward ROVs has been made.

Couple years later we were lucky to test very modified version of the vehicle named KORAL AT (for advanced technology). Thanks to very social changes we faced, really advanced technologies were utilised. These included rare earth electric motors, fibre optic data and video transmission, advanced computers and many others. In this design, to supply the vehicle, a frequency inverter generates AC current of 1200Hz and 1000V. In spite of increased power, mass of step down transformer can be reduced to 4kg, that means ten times drop. Also rare earth magnet synchronous motors application o was great step forward. This reduced mass/power ratio and allowed to fill the motor with compensating fluid. In fact, a motor of this type is very primitive and reliable. Connected to frequency inverter it gives possibility to continuously control speed of rotation and resultant thrust.

KORAL family was further extended with UKWIA£ vehicles. The latter uses principally the same technology and general arrangement of KORAL, but was modified to meet an owner specification. It is 1.5m long and its mass exceeds 160kg (two times the KORAL mass). An 500m umbilical with two 1mm^2 conductors is used to supply adequate energy. Using the same type of motor, 6 thrusters and 5 manipulation drives are built. They are supplied using advanced frequency inverters that allows precise speed control and remote diagnostics. Different planetary gears are used for different applications with different shaft speed and torque. It is interesting that all 5 manipulation drives are supplied by single inverter and bank of relays. Many modifications of inverter – motor – gear – shaft - seal – propeller chain has been tested to achieve required reliability of these highly loaded components. Laboratory and field tests lasted 3 years.

7. SUMMARY

Looking back at our achievements, one can easy find, that long and painful process of research and development is required to obtain reliable and smart submersible propulsor.

The solution adopted in specific application is always a difficult compromise between several factors. A magnitude of applications is very stimulating, however, and requires creative teams of designers and researches.

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