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Engineering Aspects of Manned and Remotely Controlled Vehicles [and Discussion]

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Phil. Trans. R. Soc. Lond. A 1978 **290**, 135-152
doi: 10.1098/rsta.1978.0078

Phil. Trans. R. Soc. Lond. A. **290**, 135–152 (1978) [135]
Printed in Great Britain

Engineering aspects of manned and remotely controlled vehicles

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Mushrooming activities in offshore oil and gas developments have produced a wide variety of manned and remotely controlled vehicles which are conducting many tasks traditionally performed by surface craft and/or ambient-pressure divers. Trends in present underwater vehicle design and work requirements of both vehicles and divers indicate that direct and remote viewing, manipulative dexterity equal to the diver, and diver lockout support are deep-water work requirements. Diver lockout submersibles capable of operating to 2000 m are technically feasible, but saturation decompression schedules at this depth are not foreseen within the next decade. Substitution of mechanical means for human capabilities to perform diver-equivalent work will require major improvements and technological break-throughs in the areas of manipulation, wireless signal transmission and power sources. Individual or combined application of manned and remotely controlled vehicles offer the most immediate solution, but environmental factors and technical deficiencies combine to reduce their effectiveness. Design of future undersea hardware for manipulation by mechanical devices and inspection/testing by mechanical means can significantly narrow the performance gap between human and mechanical devices.

Introduction

Deep water is no stranger to the ocean engineer. The technical problems involved in reaching and operating at 2000 m with manned and remotely controlled vehicles were met and surmounted in the mid-1960s. New materials, life support systems and components for deep submergence have been continually developed since Trieste I reached 10911 m in 1960. From the point of view of technical feasibility, reaching and operating at 2000 m depth presents no problems. However, transferring the full range of 300 m work capabilities now available to a depth of 2000 m and, by necessity, replacing the manipulative dexterity, responsiveness and agility of the ambient-pressure diver with a manned or remotely controlled vehicle does present a wide range of engineering problems. The potential solutions are not only hardware-orientated, but they involve design philosophy and employment techniques as well.

The substance of this paper is to predict or anticipate engineering problems likely to be encountered by manned submersibles and remotely controlled vehicles at 2000 m depth. It is therefore appropriate to identify first what is now available in these vehicles, what tasks they perform in offshore oil, and what trends are seen in design and capabilities. Further – and this is a perilous undertaking – the likelihood of support from the ambient pressure diver at 2000 m must be predicted, for if he cannot be employed, then the potential problems increase by more than an order of magnitude.

Vehicle status

Manned submersibles

In 1970 the manned submersible was fast becoming an endangered species. With the advent of North Sea oil and gas discoveries its numbers multiplied. For comparative purposes table 1

Table 1. Submersible construction and buyers/users 1970–1976

year	submersible	buyers/users
1970	Cyana	government (civil)
	Nekton Beta	industrial
	PC-9	industrial
	SDL-1†	government (military)
1971	Burkholder	industrial
	Hakuyo	industrial
	Nekton Gamma	industrial
	PC8B	industrial
	Sea Otter	industrial
	Johnson-Sea-Link I†	research
1972	Mermaid II	industrial
	Pisces IV	government (civil)
	PS-2	industrial
	Globule	industrial
1973	Griffon	government (military)
	Pisces V	industrial
	Sea Ranger	industrial
	Vol-L1†	industrial
	Skadoc 1000†	industrial
1974	Diaphus	academic
	Aquarius I	industrial
	Moana I	industrial
	Johnson-Sea-Link II†	research
1975	PC-1201	industrial
	PC-1202†	industrial
	PC-14C-2	government (military)
	Argus	government (civil)
	Pisces VII, XI	government (civil)
	Pisces VIII, X	industrial
	Mermaid III†	industrial
1976	Leo	industrial
	Moana III, IV, V	industrial
	PC-1203	industrial
	PC-1204	industrial
	Vol-L2, L3†	industrial
	PC-1801†	industrial
	PC-1802†	industrial
	PC-16†	industrial
	Taurus†	industrial
	Mermaid IV†	industrial
	PRV-2†	industrial
	URF†	government (military)

† Diver lockout capability.

is included, which shows the growth in vehicle production during the past few years. The major customer for submersibles today is industry, and the major user of industrially owned submersibles is the offshore oil and gas industry. An inventory in 1976 of worldwide manned submersibles showed that there were a total of 91 vehicles; their status was as follows: operational/sea trials, 57; under construction, 16; undergoing refit, 7; inactive, 11. Because the field is dynamic, these values can change quite rapidly. Not included are perhaps 15–20 shallow-diving, one-man vehicles built for recreational use.

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It is very difficult to generalize when discussing design and capabilities of manned submersibles. Only a handful are identical and even within these there are variations. However, to gain an appreciation of the industrial field at large the following characteristics are given:

(*a*) The average maximum operating depth is 572 m; the deepest is 3000 m (the French submersible *Cyana*); the average length, beam and height are 6.2, 2.3 and 2.7 m respectively.

(*b*) All use lead acid batteries.

(*c*) Crew complement is from two to six.

(*d*) Dive working duration is from 6–8 h.

(*e*) The average cruise speed and endurance is 1 knot for 7.9 h.

(*f*) The average payload is 480 kg.

(*g*) Dry mass is from 2–26 t.

(*h*) About half of the newly constructed vehicles have diver lockout capability.

(*i*) Approximately 80 % carry at least one manipulator; 40 % of these carry two.

(*j*) Launch/retrieval can be generally conducted in sea-state 4 and, in some instances, sea-state 7.

The major exception to the above is the 'Auguste Piccard'. Being 29 m in length and 168 t in mass and having a life-support duration of 90 man-days, it is in a class by itself.

Navigation or positioning capability of submersibles varies from company to company, but position accuracies of ± 1 m within an area of 130 km^2 are attainable relative to bottom-mounted transponders.

Manoeuvring characteristics vary widely but thrust, yaw, heave and pitch control are general capabilities. Mid-water hovering is also common, but to stabilize the vehicle when working on a fixed structure it is a general practice to grasp the structure with one manipulator and work with the other.

Work tools – e.g. drills, wrenches, grinders, brushes, etc. – are available to varying degrees on all vehicles. The most dominant work capability is direct viewing coupled with t.v. video documentation.

Unlike many other industries, the major submersible builders do not produce a fleet of similar vehicles on the speculation that buyers will be found. Each vehicle is generally built under contract, and each one is somewhat different from its predecessor. The difference might be in depth, lockout or non-lockout capability, size, instrumentation and crew. The result is that each vehicle reflects the buyer's idea of present and future capabilities required to meet the needs of the offshore customer (i.e. offshore oil and gas). Consequently there is little likelihood that a fleet of obsolescent vehicles will exist in the near future, such as the next five years.

A further consequence of this one- or two-at-a-time purchasing is that the size of the submersible fleet keeps pace with the demand for vehicle services. No operating company intentionally orders more vehicles than it can see a need for, and all operators are keenly aware of offshore activities that may provide a market for their services. The present situation therefore is one where vehicle supply and demand is equal, and will probably remain so unless there is a major change in underwater work requirements.

Remotely controlled vehicles

There are several types of vehicles which fall into this category: tethered, free-swimming vehicles; tethered, bottom-crawling vehicles; towed vehicles; and untethered, free-swimming

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vehicles. This discussion is limited to the tethered, free-swimming vehicles of the RCV-225 variety.

Undoubtedly the most dynamic growth in a particular underwater platform has been exhibited by the remotely controlled vehicles (herein they will be called RCVs; RCV is a registered trademark of Hydro Products, San Diego, CA.). In 1974 there were approximately eight RCVs; today there are at least 40. A listing of these vehicles and their depth capability is contained in table 2.

TABLE 2. UNMANNED, SELF-PROPELLED, TETHERED VEHICLES

vehicle	depth/m	builder
Angus	300	Heriot-Watt University, Edinburgh, U.K.
Angus 002	300	Heriot-Watt University, Edinburgh, U.K.
Consub 1	610	British Aircraft Corp. Ltd Bristol, U.K.
Consub 2	610	British Aircraft Corp. Ltd Bristol, U.K.
Cord	457	Harbor Branch Foundation Ft Pierce, Fla., U.S.A.
Curv II	762	Naval Undersea Center San Diego, Calif., U.S.A.
Curv II	762	Naval Undersea Center San Diego, Calif., U.S.A.
Curv III	3048	Naval Undersea Center San Diego, Calif., U.S.A.
Cutlet	305	Admiralty Underwater Weapons Establishment, Portland, U.K.
Deep Drone	610	Supervisor of Salvage Washington, D.C., U.S.A.
Eric	500	French Navy Toulon, France
Eye Robot	100	Mitsui Ocean Development & Engineering Co., Ltd Tokyo, Japan
Manta 1.5	1500	Institute of Oceanology Moscow, U.S.S.R.
RCV-150†	1829	Hydro Products San Diego, Calif., U.S.A.
RCV-225‡	2012	Hydro Products San Diego, Calif., U.S.A.
Recon II	457	Perry Ocean Group Riviera Beach, Fla., U.S.A.
Ruws	6096	Naval Undersea Center Honolulu, Hawaii, U.S.A.
Scarab I, II	1829	Ametek Straza El Cajon, Calif., U.S.A.
Sea Surveyor	220	Rebikoff Underwater Prod. Ft Lauderdale, Fla., U.S.A.
Snoopy	457	Naval Undersea Center San Diego, Calif., U.S.A.
Snoopy	457	Naval Undersea Center San Diego, Calif., U.S.A.
Snurre	600	Royal Norwegian Council for Scientific Research Oslo, Norway
Telenaute	1000	Institut Francais du Petrole Paris, France
Trov	366	McElhanney Offshore Survey & Engineering, Ltd Vancouver, B.C.
Trov OI§	366	McElhanney Offshore Survey & Engineering, Ltd Vancouver, B.C.

† Three vehicles total: Martech International, Houston, Tx., U.S.A., Scandive, Stavanger, Norway; Deep Sea Resource Dev. Corp. Taiwan, Formosa.

‡ Eight vehicles total: Seaway Diving, Bergen, Norway (2 vehicles); Martech International, Houston, Tx., U.S.A. (2 vehicles); Sesam, Paris, France (2 vehicles); Taylor Diving & Salvage, Belle Chasse, La., U.S.A. (1 vehicle); Esso Australia, Ltd, Sale, Australia (1 vehicle).

§ Two vehicles total: Underground Location Services, Glasgow, U.K.; British Petroleum, Middlesex, U.K.

RCVs are as varied in design as are manned vehicles, and generalities regarding their characteristics are attended by numerous exceptions.

The basic tethered, self-propelled vehicle system consists of the vehicle itself (and sometimes an underwater clump or launcher), a cable and a shipboard control/display console. Supporting equipment includes a launch/retrieval device, a cable winch, an enclosed area for the vehicle operators and shipboard components and, if shipboard power is not available or suitable, a power supply unit.

Vehicles owned by industrial users range in depth capability from 200 m to 2000 m; the average is 1300 m. Depth *per se* presents no problem to the RCVs. Control of the vehicles at great depths is a problem which is discussed later.

Most vehicles are constructed of an open metal framework that supports and encloses (for protection) its various components. Buoyancy is generally positive by a few kilograms when the vehicle is submerged; this provides a fail-safe assurance that the vehicle will surface in the event of a power failure. Generally, but not always, syntactic foam blocks mounted atop the framework provide the required buoyancy.

TABLE 3. WORK INSTRUMENTS

	viewing/photography				manipu-lator	sonar		current meter	ther-mistor
	t.v.	still	stereo	cine		search	homing		
Angus	×	.	.	×	.	.	×	.	.
Consub 1	×	.	×	.	.	.	.	.	.
Consub 2	×	.	×	.	.	.	.	.	.
Cord	×	.	.	.	×	×	.	×	×
Curv II	×	×	.	.	×	×	×	.	.
Curv III	×	×	.	.	×	×	×	.	.
Deep Drone	×	×	.	.	.	×	×	.	.
Eric	×	×	.	.	×	.	.	.	.
Manta 1.5	×	.	.	.	×	.	.	.	.
RCV-225	×	.	.	.	.	.	.	.	.
RCV-150	×	.	.	.	×	.	.	.	.
Recon II	×	.	.	.	×	.	.	×	.
Ruws	×	.	.	.	.	×	×	.	.
Scarab I and II	×	×	.	.	× (2)	.	.	.	.
Sea Suveyor	×	.	.	.	.	.	.	.	.
Snoopy	×	.	.	×	.	.	.	.	.
Telenaute	×	.	.	×	×	.	.	.	.
Trov	×	.	.	.	× (2)	.	.	.	.

The underwater component(s) or 'vehicle' of these systems weigh from 68 kg to as much as 2268 kg. The sea-state limitations on launch/retrieval are controlled by the nature and sophistication of the shipboard handling equipment. Some indication of sea-state limits can be gained from the following operator statements: Consub 1 can be launched/retrived up to sea-state 4; Deep Drone is designed to be handled up to sea-state 5 if 'normal' handling equipment is available which is generally employed to handle manned submersibles. These two are not the heaviest vehicles operating, but they do fall around the average vehicle mass of 961 kg.

The speed of RCVs is similar to that achieved by manned vehicles, and ranges, at the surface, from 1 to 5 knots (1.8–9.3 km/h). There is a decrease in speed with depth and/or with increase in currents which may range from 20 to 84 % of the surface speed. The reduction is caused mainly by cable drag, but can be alleviated by different modes of vehicle deployment. The Scarab vehicles are designed to cruise along the bottom while (in conjunction with the surface ship) they tow the entire length of cable. The RCV-225 is deployed from a launching cage and works around the launcher on 120 m of tether cable; hence, cable drag is substantially reduced. For this reason, many of the RCVs employ a launcher or clump.

All but a few vehicles are capable of two translation motions and one rotational motion; these are thrust (forward/reverse) and heave (up/down) and yaw (left/right heading changes) respectively. These motions are provided by the arrangement of two horizontal or forward thrusters and one vertical thruster. By adding a fourth lateral or side thruster a third translational motion is obtained: sway or sidle. If the lateral thruster is mounted forward, it is used to augment yawing, rather than providing a sideways translational motion.

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For routine operations the support crew complement ranges from one to seven; three to four is average.

The instruments listed in table 3 are those which are standard onboard equipment. All RCVs carry underwater lights. British Aircraft Corporation's Consub 1 has a manipulator-held rock drill which has successfully operated in the field, but is not listed in table 3. The majority of RCV manipulators are simple devices which can do no more than extend and open/rotate the claw. The limited orientator and locator motions are not a liability because the vehicles themselves can provide several more degrees of freedom to the manipulator by virtue of their excellent manoeuvring capability.

Navigation or positioning is similar to that used on manned vehicles with variations in capabilities from company to company.

Also like their manned counterparts, RCVs are generally built to order, but the variation in design or capability between vehicles of a particular series is slight. Payload, or the ability to carry additional submerged mass (i.e. work tools), is very small and without modifications, generally limited to no more than 1 or 2 % of the vehicle's mass.

Work tasks and trends

Submersible and RCV support for offshore oil and gas is arbitrarily divided into two categories: (1) tasks historically performed by divers, and (2) the provision of observations and measurements of the bottom or hardware which require details that conventional over-the-side surface techniques cannot attain. The categories are further divided into three functional tasks: (i) observational/documentation; (ii) observational/manipulative and (iii) observational/measurement/sampling. The 'observational' function is included in each task to emphasize that without some degree of visibility, the tasks now performed by undersea vehicles could not be conducted. The need for visibility is significant because, as is discussed later, the ambient diver performs a great deal of work by feel on objects he cannot see clearly.

Following are various tasks which have been performed by manned submersibles and RCVs for offshore oil and gas.

submersibles	RCVs
Observational/documentation tasks	
pipeline route inspection	geological observations
pipeline arc observation	cathodic protection inspection
video/visual survey of installed pipelines	pipeline inspection
cathodic protection inspection	tank and buoy inspection
platform site inspection	bottom reconnaissance
platform jacket inspection	marine fouling assessment
pipeline inspection	
pipeline burial inspection	platform inspection (pre- and post-installation)
inspect/videotape manifold and hose of spar buoy	subsea completion system inspection
inspect/videotape legs, bracings, members, anodes and scour on drill platform	anchor dragging assessment
inspect/videotape chains, ancisors, anodes and transponders of drill platform; assist in change of hose string	wreck identification
pre-burial pipeline inspection	
inspect/videotape loading platform	
locate/inspect/videotape pipeline	

Observational/manipulative tasks

object removal prior to pipeline trenching
loosen and tighten bolts with impact wrench
drill holes in steel structures
collect hard rock core samples
stud insertion (explosive embedment)
close/open pipeline valve handwheel
wire brushing for inspection and maintenance
torch burning (acetylene) and concrete chipping
cable inspection and burial
assist in trenching operation
inspect and help disconnect and hook up an experimental oil storage tank
cable and repeater burial
drillship guideline change out
preparation of an abandoned wellhead for re-entry (template alignment; guideposts; install new guidelines)
maintenance of buoy moorings and offshore platforms

small object retrieval
rock fragment collection
hard rock drilling
benthic organism collection
drill bit recovery
assist in connecting surface retrieval line

Observational/measurement/sampling tasks

submersibles

pipeline route survey and sampling (side scan sonar, echo-sounder, rock and sediment sampler)
platform site surveys
establish/document/measure length and height of suspended pipeline sections
post-pipeline entrenchment profile (echo-sounder)

This is not an all-inclusive list of the tasks manned submersibles and RCVs are now conducting in the offshore fields, but it is a representative sample. The last category is a relatively new, but promising, rôle, i.e. acoustic mapping in conjunction with sampling and observations. Various attempts were made in the middle and late 1960s to use submersibles as undersea mapping platforms, but these were experimental exercises. With increasing depth, details of bottom topography are more difficult to obtain from a heaving, pitching vessel than from a stable, submerged vehicle. This task can be expected to become more frequent as production proceeds into rough, deep areas. There are no reported efforts whereby RCVs have been used as acoustic mapping platforms; possibly the present lack of payload to accommodate required instrumentation is at fault. The British Aircraft Corporation, however, does include in its new Consub design the capability to exercise such options. In spite of the dynamic growth of RCVs, they are still feeling their way and have yet to realize their full potential.

Trends

Manned submersibles

If consideration in design and capabilities is only given to submersibles currently used by industrial firms, then the following trends can be seen: diver lockout and dry transfer is an increasing capability (8 out of 14 vehicles built in 1976 offered diver lockout); plastic bow domes for increased viewing are mandatory; greater electrical (i.e. battery) power is sought and the dry mass of vehicles has increased (the newly built Taurus weighs 26 t). In short, industrial submersibles are now larger, more powerful and offer a wider range of instrumentation and diver support than did the vehicles of the 1960s and early 1970s. The weight increase is a reflexion of greater depth (stronger materials) and battery capacity. Less obvious is the shape of the pressure hull. In vehicles operating in depths greater than 600 m the pressure hull is spherical because it is the most efficient shape for dealing with pressures below this depth. A sphere, however, is the least efficient shape for capitalizing on layout within a particular volume: the cylinder is the most effective for this.

A very recent trend in submersible design is Oceaneering International's Arms (Atmospheric Roving Manipulator System) and the two subsea completion diving bells of Comex. Both systems are manoeuvrable spheres connected by a lift/signal transmission cable to the surface and equipped with sophisticated manipulators. Significantly, these systems were designed for employment from specific drillships and for conducting inspection and manipulative tasks. Guide rails affixed to the blowout preventor stack allows the Arms to be secured to a rail and then move circumferentially around the stack by means of a built-in friction drive system.

Both systems depart from the typical manned submersible in that they have forsaken extended bottom cruising for precision manoeuvring and control. Arms, for example, is designed to maintain position within 1 m of any part on the outside surface of the blowout preventer. A further emphasis has been placed on manipulative dexterity. The Arms manipulator is the most sophisticated in that if offers a force-feedback capability which is intended to allow the operator to 'feel' the task being performed. Both systems were built in late 1976 and scheduled for operations in the spring of 1977.

RCVs

The industrial operational life of these vehicles has been so short that major trends are hard to discern. Indeed, in many instances the techniques of employing these vehicles are still in what might be termed the development stage. As with any new capability, there is a period of trial and error to see where the vehicle offers its best application. It has become obvious that the RCV is an excellent viewing and t.v. documentation platform and can be used to perform straightforward manipulative tasks, but under what environmental conditions and with what surface support have not been precisely defined.

The most obvious trend to date has been the incorporation of a launcher or clump into the umbilical cable. The launcher acts to keep the power/signal transmission cable taut and absorb the effects of heave imparted by the surface ship. With this arrangement the RCV is able to work, unhindered by surface motion, from a tether cable attached to the launcher.

A more recent trend is toward larger vehicles with greater payload capacity. The RCV-225 weighs 80 kg; the evolutionary extension of this vehicle, RCV-150, weighs 220 kg and is capable of accommodating a wide variety of instrument options. A similar trend is seen in follow-on vehicles to Consub 1. Additional equipment capabilities to the new vehicles are search sonar, vehicle tracking devices and manipulators. The RCV-150 also includes an option for head-mounted display and control. Much like the early proponents of manned submersibles, the proponents of RCVs now speak of multi-purpose vehicles equipped with a wide array of devices for surveying, sampling, inspection and manipulative work tasks (e.g. brushing, drilling, grinding, etc.). The attainment of such versatility is more complex, however, than merely attaching another instrument.

Paralleling the specialized design of the Arms and Comex diving bells are two RCVs designed by Hydrotech International and Exxon.

The Hydrotech system is still in the design state and is scheduled for completion by 1979. The system is designated as an unmanned deep water (1200 m) pipeline repair system, and consists of two vehicles: a work vehicle and a vertical transport vehicle. The work vehicle is designed for soil excavation, pipe coating removal, pipe cutting and end preparation; its dry mass is 49 t. The vertical transport vehicle is designed to transport and position replacement sections; its dry mass is 63 t. Both vehicles are cable-connected to the surface and both rely upon closed-circuit t.v. for real-time information. Since underwater visibility is mandatory in order to conduct work, a clear-water flushing capability is included on each vehicle. Model tests indicate that launch/retrieval is possible in sea-state 3.

The Exxon system has undergone limited field testing and is scheduled for near-future work in the Gulf of Mexico. The device is termed a Maintenance Manipulator System (M.M.S.) and is designed to perform routine maintenance on Exxon's Submerged Production System (S.P.S.). Failure mode prediction of S.P.S. components identified those likely to malfunction with wear or by external damage. These components were then designed for removal, replacement and pressure testing by the M.M.S. The M.M.S. is guided to the S.P.S. platform along a pop-up buoy line; it then mates with a cogged track on the platform which is routed to place the M.M.S. in position to work on the pre-isolated, faulty component. When replacement is completed, the M.M.S. transports the faulty component to the surface where the system is retrieved. Monitoring of the work is by closed-circuit t.v. Underwater visibility is therefore critical.

Table 4. Ambient diver work tasks

welding	.	rigging	×
drilling	×	bolting/unbolting	×
cutting	×	assembling	.
grinding	×	grouting	.
inspection (visual)	×	painting	.
measurements (dimensional)	×	site investigation	×
testing (non-destructive)	×	directing surface lifting/lowering	×
video documentation	×		

The ambient pressure diver

The variety and difficulty of potential problems encountered in working to 2 km by manned and remotely controlled vehicles will be determined by the depth to which the ambient diver can work. If the diver cannot support offshore oil to 2 km depth, then the problems will be of great magnitude. At present both vehicles are competing in many tasks with the diver. In several applications they are as effective and in some they are better. But in other tasks they cannot even approach the diver's performance.

Offshore oil diving can be, for convenience, placed in two categories: scheduled and non-scheduled. Scheduled diving is that where the diver's rôle is known before the dive. When, for example, a structure is planted on the seabed the diver's rôle is predetermined and he may have trained extensively to perform it. Non-scheduled diving is that where the diver responds to an accident or malfunction, for example, recovering a lost tool, repairing a broken structure, or tightening a loose nut. In both cases the job the diver performs may be similar (e.g. welding, cutting or rigging) but in the first instance the conditions under which it will be performed are controlled; in the second they are not. The difference is critical.

Table 4 is a general tabulation of the types of work performed by the offshore ambient diver. The × to the right indicates tasks which manned and remotely controlled vehicles have also performed.

There are several aspects of these tasks which are significant, the most important being that the diver can do these virtually anywhere on a structure, the vehicles are restricted by virtue of size or by their umbilical to working on the extremities. A second important aspect is that the diver can and does perform a number of these tasks by feel alone and can work in zero visibility. The vehicles, on the other hand, cannot work without seeing the object on which they are working.

Other aspects of diver work *vis-à-vis* vehicle work must be considered. Rigging tasks with vehicles are generally restricted to attaching a hook or grasping device. The diver cannot only do this, but he can also tie a knot. No manipulator system now in use is known to offer this capability unless the conditions are strictly controlled and favourable. Underwater welding is uniquely the diver's domain. No vehicle today can produce a weld that is in accordance with A.S.M.E. requirements; in fact, there is no reported incidence where vehicle operators offer welding services.

The diver is an incredibly versatile tool, and there seems little prospect of matching his performance with mechanical manipulators. Many of the jobs he does, particularly the scheduled tasks, might be performed through remote mechanical means by redesigning the structures so that they are amenable to mechanical manipulation, but the unscheduled tasks, where something breaks or loosens, will place demands far beyond the present capability of manned or remote-controlled vehicles if the diver is not available for work at 2 km. At this point the likelihood of ambient diving to 2 km should be considered.

The deepest working dive to date was performed by Comex at 309 m in 1975. At the time of writing (March 1977) Comex is scheduled to conduct a 460 m working dive in the Mediterranean. These are record working depths; the average is currently between 90 and 120 m. Undoubtedly 'routine' working dives will be deeper than 120 m, but how much deeper and what is the depth limit are extremely difficult to predict. Some indication of the foreseeable working depth can be gleaned from the diving companies themselves. A sampling of 11 major offshore companies shows a maximum operating depth of 460 m (Ocean Systems Inc., Samson Divers, Comex), the average being 325 m.

Another indication is obtainable from the U.S. Navy, specifically R. C. Bornmann of the Naval Medical Research Institute who projected that compression rate and breathing mixtures for saturation and saturation–excursion divers to 760 m could be available by 1990. Bornmann's estimate time is based on pursuing this goal in an orderly and reasonable manner. Similar estimates from the industrial diving community have not been made public. Various experiments indicate that depths in excess of 760 m are a possibility, but 2 km seems very remote, and personal communications with members of the industrial diving community reveal serious doubts concerning the likelihood of divers working at depths of 2 km. Compression/decompression tables and gas mixtures present just one obstacle on the way to 2 km; others include developing breathing apparatus and environmental protective equipment, determining allowable major contaminant concentrations and developing an ability to treat decompression sickness or any injury or illness that may reasonably occur at 2 km. These are but a few of the foreseeable major obstacles, other may reveal their presence as the depth increases.

It is futile to state categorically that the diver will not proceed safely beyond a particular depth. With the proper resources and no time limitations there is no present way of predicting just what, if any, depth will be an implacable barrier. However, if a time limitation of a decade hence (1987) is assumed, then it seems reasonable that the ambient diver will not have progressed much beyond 760 m. So, from 760 m to 2 km the major problems will arise in support for offshore oil and gas, because the present manned and unmanned vehicles cannot fully substitute for the ambient diver.

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Deep water: potential problems

The magnitude of the potential problems which will confront manned and remotely controlled vehicles at 2 km depth depends upon the tasks they pursue. For example, the problems confronting manned vehicles at greater depths in performing the tasks they now conduct in shallower depths will be small compared with the problems they face as lockout support vehicles at 760 m, and minuscule if they must substitute for the diver at any depth level. The RCVs face similar problems, with the obvious exclusion of diver support, for which they are not designed. For convenience, the following discussion of these problems is categorized thus: general (i.e. problems uniquely imparted by increased depth), diver support, and diver substitute. The problems within each category are not mutually exclusive; some overlapping is unavoidable.

One problem area not discussed below concerns work in the polar regions or under an ice cover. Submersible excursions under ice have been limited, the main reason being safety (i.e. retrieval of the vehicle if it is immobilized) and lack of power to reach areas of interest. While this is not a deep water problem as such, it will be a problem of tremendous magnitude in future attempts to retrieve polar oil and gas resources. Specifically, the major problems are power, navigation and reliability. There is no known project today that is addressing submersible under-ice operations in a concerted and adequately funded effort.

Manned submersibles

General

The general problems associated with increased depth are the predictable consequences of increased pressure.

(*a*) *Pressure hull configuration*. Below about 760 m depth the shift to a spherical, rather than a cylindrical, pressure hull is now required to obtain the most weight-efficient geometry. The consequence is the least efficient configuration for interior arrangements and human factors.

(*b*) *Viewing*. All industrial vehicles manufactured in the 1970s have a plastic bow dome. The present domes for vehicles of 240 m depth are 914 mm diameter and 51 mm thick; in 1 km depth vehicles they are 762 mm diameter and 102 mm thick. At 2 km the diameter will be less; consequently, the capability for direct visual observations will decrease.

(*c*) *Batteries*. Vehicles of 730 m operating depth carry their batteries in pressure-resistant pods on roller trays; this allows for quick turn-around time in replacing spent batteries with charged ones. Greater depth requires stronger and therefore weightier pods. The generally exercised option is to put the batteries in a pressure-compensated fluid to save weight. The consequence is that the batteries must be charged in their containers and quick turn-around time is no longer achievable.

(*d*) *Electrical interference*. The multi-mission concept for submersibles requires extensive use of electronics, specifically sonar. In some operational modes a variety of equipment and components may be operating concurrently (e.g. propulsion motors; forward-scanning sonar; side-scan sonar; sub-bottom sonar; CO_2 scrubbers; cameras, lights; altitude/depth sonar and navigation systems). Few submersibles are provided with shielded conductors to avoid interference between these components.

The above problems are not particularly difficult to deal with, but they must be brought into the design for efficient 2 km operations.

Diver lockout support

(*a*) *Power*. The major problem in support of the ambient diver will be providing adequate power for heating (hot water and breathing gas) and for employing certain tools requiring electrical power. Studies of the Canadian submersible SDL-1 show that, if the entire energy of the battery supply (36 kWh) could be transferred to the microenvironment of the crew clothing suit with total efficiency, there would not be sufficient energy to provide thermal comfort for the crew of six for 6 h at 0 °C. Underwater welding requires about 25% more power than welding in air and increases with depth. The Royal Navy Diving Manual specifies a 70–75 V, 300–400 A (30 kW) d.c. generator for welding at about 60 m; only the 30 m long 'Auguste Piccard' can supply this quantity of power. The penalty for increased vehicle size and mass to provide the additional power is discussed below. The alternative of supplying power via a surface umbilical is attractive, but drag and potential entanglement are thereby introduced.

(*b*) *Breathing gases*. The amount of breathing gases for present lockout vehicles limits the actual working time to minutes. Increasing the diver's duration by increasing the amount of gas carried results in a greater vehicle mass. Converting to closed-circuit instead of open-circuit systems can result in a respectable gas saving. An option is possible here as with electrical power – a surface umbilical – but the disadvantages have been mentioned.

(*c*) *Mass and size*. The problems in this instance are introduced by virtue of gaining sufficient payload to supply adequate power and breathing gases to support the diver as discussed above. When vehicle mass (dry) is increased, the repercussions are evidenced in launch and retrieval. There is no doubt that a submersible can be built to supply the required power simply by acting as a battery supply platform, but this vehicle will be extraordinarily heavy and launch and retrieval will be restricted to very large support ships. The recently built Taurus is a 1977 attempt to supply an improved diver lockout and dry transfer vehicle; it weighs 26 t, almost twice the mass of currently operating vehicles. The handling system that must be available to launch and retrieve Taurus will be beyond anything presently in use. Indeed, at 26 t, the various classifying societies' minimal dynamic loading requirements may rule out conventional over-the-stern handling techniques.

Another operational repercussion is introduced by increased size: the potential for damaging the structure being worked upon or inspected. Quite simply, the larger the vehicle the more difficult it is to control. In present diver-supporting rôles the submersible stations itself as closely to the work site as possible; precision manoeuvring and control is a primary requirement. Since most present lockout support vehicles are relatively small, adequate control is obtainable. The large lockout vehicles of the future may not offer adequate control and impacting with the structure is a probability, expecially under fluctuating current conditions. While most impacting would probably damage the submersible more than the structure, the problem is one of safety; but where the structure might be a concrete-coated pipeline, both safety and damage to the coating is jeopardized. Further, placing a large vehicle in the desired proximity for working on a structure may be precluded or severely restricted simply by its bulk.

Diver substitute

Re-examining table 4, which tabulates the capabilities divers now provide to offshore oil and gas, it is seen that a great number (two-thirds) of the tasks a diver performs are also performed by manned submersibles. The table, however, is somewhat misleading and the dis-

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cussion attending it explains why. In essence, the manned submersible, as an underwater constructor, maintainer or repairer, is extremely limited in where it can work and what work it can do. As a substitute for the diver, the vehicle lacks his agility and manoeuvrability, and its manipulators lack his dexterity and sense of feel. Perhaps the greatest problem is that the submersible itself cannot manoeuvre and hold itself into and around structures where the diver routinely works. Contemporary manned submersibles can support and augment the diver's capabilities, but they cannot substitute for him.

Remotely controlled vehicles

The problems facing RCVs at great depths are somewhat different from their manned counterparts. By taking the human aspect and battery power factors out of the underwater equation, safety is not jeopardized and power is not a limitation. However, the cable which now carries the power and transmits control and data brings with it a new set of problems. The surface ship or platform from which power and control is provided also introduces problems unique to the tethered RCV. The following discussion treats three problematical aspects of the RCV: the support craft; the cable, and the vehicle itself.

The support platform

(*a*) *Station keeping*. In certain applications, such as long transect bottom surveys or pipeline/cable inspections, the support ship is required to maintain a position directly over the RCV while both are underway. In other applications, e.g. site surveys or hardware inspection, the support ship may be required to maintain position within a limited radius over the RCV. The solution is provided by a support ship with a dynamic position-holding capability, such as bow thrusters and/or laterally trainable stern propulsion. Such ships are available, but they are not often attainable and their cost is high. Furthermore, as witnessed by the recent F-14 search/recovery off Scapa Flow, where deteriorating weather forced the 'Constructor' to abandon the search, they are sea-state limited. Without a dynamic positioning system the support ship may be repeatedly – and literally – blown off station. A conventional two- or three-point static mooring system would solve some station-keeping problems but at the expense of time and a potential for entanglement.

(*b*) *Launch and retrieval*. The small RCVs are not significantly hampered by launch and retrieval problems, but the larger and more specialized vehicles can and have confronted launch and retrieval problems equal to those of manned submersibles. During sea trials with the M.M.S., described earlier, major repairs were required to the device when its handling system failed and it was dropped on the deck. Calculations for the Hydrotech unmanned pipeline repair system show that launch and retrieval in sea-state 3 is possible; this would equate to a wave height of about 1 m, an extremely calm day in the North Sea and a rarity in the Gulf of Alaska.

The two vehicles mentioned above are quite large; most present RCVs are much smaller. The concept of a multi-purpose RCV requires multi-equipment, increased structural framework strength, greater propulsion and buoyancy: the result must be a heavier, larger vehicle. The operational consequences are for more sophisticated and stronger launch-and-retrieval devices and larger support ships. Several advantages of RCVs, such as use from virtually any ship of opportunity, and ease of transportation, will dwindle as the RCV's size and mass increase.

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The cable

(*a*) *Drag.* Hydrodynamic drag on the RCV cable can be provided by vehicle/support ship lateral motion or by water currents, and in some cases by both. The obvious consequences of drag is to reduce vehicle speed; this reduction is acceptable in most operations because high speed is not a primary requirement. The effect of drag on 2 km of cable can be serious if both the support ship and vehicle are attempting to operate while underway, on a pipeline or cable inspection for example. In this application the cable drag could be sufficient to produce a catenary that will pull the vehicle away from the object it is trying to inspect.

(*b*) *Entanglement.* When working around and within a structure the potential for cable entanglement is high; two remotely controlled vehicles have been lost by this means. In one instance the cable fouled in its support ship's propeller and was severed: the vehicle was never found. In another instance the cable fouled in a structure and the emergency cable cutting device was activated. The vehicle apparently surfaced, but it had no surface flashing light or radio beacon and was never located. Twice during an operation in the Santa Barbara Channel a remotely controlled vehicle fouled its cable in the structure it was inspecting; in both instances a manned submersible was launched to recover the vehicle.

(*c*) *Electrical interference.* The problems associated with electrical interference in present RCVs are few because the signal-transmission requirements are relatively simple. However, when consideration is given to the multi-purpose RCV the potential interference problems within the cable can be considerable. The U.S. Navy, during development of Ruws (a 6 km RCV), was forced to develop a cable which employed time-division frequency-division multiplexing techniques for signal and power transmission. The total cost of the cable exceeded $1 M, the production run cost $320000 for 7315 m of cable. The Ruws itself is still undergoing sea trials; although the electrical interference problems seem to be overcome, final judgement is being reserved until field tests are completed.

The vehicle

In their present rôle as inspection and t.v. photo documentation platforms, an increase in depth should not generate problems which contemporary vehicles find limiting. However, if they are deployed to substitute for the diver, they – like their manned counterparts – cannot provide the manipulative work capability required. In many respects remotely controlled vehicles have the same limitations as manned vehicles: lack of manipulative dexterity and a sense of feel, and a requirement to 'see' the object upon which they are working. Significantly, they demonstrate manoeuvrability which can exceed the diver himself.

Technological breakthroughs

Many of the problems identified with increased depth do not require technological breakthroughs *per se*; instead, they might find solution through a change in design philosophy. However, the loss of the diver's manipulative capabilities is one problem for which no practical substitute or alternative seems to be immediately forthcoming.

A potentially viable alternative to the ambient-pressure diver is the one-atmosphere diving suit called Jim, but for many of the tasks the diver performs the present Jim is too cumbersome and lacks the diver's sophisticated manipulation. Therefore the major technological breakthrough required to meet the needs of offshore oil and gas at 2 km depth is the development of a manipulator with the dexterity and tactile senses equal to the human hand. This surrogate hand must also be capable of memory and the entire system cannot be much larger in dimension than the human body if it is to find across-the-board application. The task is formidable, and if the solution is required within a decade or less, then alternatives must be considered.

The most readily available alternatives are arbitrarily placed into two areas: operational techniques and design philosophy. The former requires combining present manned and remotely controlled vehicles and one-atmosphere diving suits into a transport/support/work system; the latter requires designing undersea structures and hardware for inspection, maintenance and repair by mechanical manipulators.

Operational techniques

The diver lockout submersible has provided a measure of experience in combining and deploying varied capabilities; the problem remaining is to remove the factor of the ambient pressure diver from the submersible and introduce the RCV and/or the one-atmosphere JIM-type suit. In this combination the three components could work in the following manner:

Manned submersible: transportation of capabilities to work site; provide power and tool/instrument storage.

RCV: perform inspection/documentation and simple manipulative tasks around and within structures where the manned submersible cannot effectively or safely manoeuvre.

JIM-type suit: performs complex manipulative work tasks in confined areas.

The most critical obstacle to obtaining this solution is electrical power. The manned submersible could receive its power from a surface umbilical, but this solution is not altogether satisfactory for it introduces the problems already discussed for the RCV umbilical. Furthermore, it is not a viable alternative to under-ice operations. The pressing need therefore is for an independent power source, such as fuel cells or closed-cycle diesel generators. Other problems can be cited that will result from combining these three capabilities, but if an adequate, self contained power source were available the remaining problems could be readily solved.

To the author's knowledge, there is no government or industrial activity at present which is attempting to combine the three capabilities, therefore the potential problems which would be confronted are pure speculation. The entire spectrum of problems can only be identified by actually combining the manned and remotely controlled vehicle and the one-atmosphere suit and then deploying this system in the field.

Some consideration has been given to the potential of remotely controlled, untethered or robot vehicles in underwater work. Prototypes of these vehicles have been developed and used in the United States and Japan; their capabilities to support offshore oil and gas are meagre. Problems in real-time control, signal transmission, manipulation and power are too overwhelming to consider them practical alternatives to the systems already discussed.

Design philosophy

The 'breakthroughs' of this category are more philosophical than technological. In the early days of offshore oil and gas – because the water depths were shallow – the diver was called in to perform any underwater tasks. Consequently, the hardware used underwater was generally the same as that used on the surface. Bolts, nuts, shackles and rigging techniques were used that were designed for manual manipulation. The location of critical components was often in areas on the structure which were only accessible to the human. This approach is still evident in the design of much contemporary hardware, and it imposes severe limitations on the performance of present manipulators. The performance of present and future vehicles and their manipulation systems can be greatly increased if the designer is aware of their capabilities and limitations, and designs his structure within these constraints. Exxon's M.M.S. is a step in this direction; further assistance towards improved performance of non-diver inspection, maintenance or repair tasks can be provided by considering the factors listed below into the overall design philosophy.

Design components for mechanical manipulation.

Locate critical components in areas accessible to a manned vehicle or an RCV.

Include tracks or rails for guidance and stabilization for the manned or remotely controlled vehicle.

Structures should be as 'clean' as possible to reduce the potential for entanglement.

Legs, braces and other strength members could be visually coded to assist in identification and navigation. Magnetic compasses are all but useless in the proximity of a steel structure.

Quite frequently the fact that a structure is 'unclean' or inaccessible to other than a diver is revealed after installation. Revelations of this nature could prove traumatic if the structure is in 2 km of water. In such instances the design review policy, rather than lack of technology, may be the limiting factor. If, before the design is frozen, it is subjected to an operational analysis review by an operator of a manned or remotely controlled vehicle, it is probable that undesirable aspects of the design would come to light. Such analyses should not only concentrate on installation, but post-installation inspection and testing (visual and non-destructive), maintenance and repair as well. Such a review policy might also serve to identify inadequacies in the undersea vehicles before – not after – they are called upon to assist and would provide an adequate time period to make modifications.

To cope successfully with scheduled and non-scheduled work tasks at 2 km depth requires a cooperative approach. Technological breakthroughs in manipulation and power will greatly increase the performance of manned and remotely controlled vehicles, but these breakthroughs alone will not provide the ultimate answer unless they are accompanied by a closer working relationship between the designer of undersea structures and those who will service them.

Discussion

C. Kuo (*Department of Shipbuilding and Naval Architecture, University of Strathclyde, Glasgow G*1 1*XH*). I should like to take this opportunity to raise two points.

First, with regard to the rate in which we can close the gap between human and mechanical devices, I agree that this is affected by the rate with which we can develop the technology for manipulation by mechanical devices, but I believe there are other points which must be taken into consideration because they are just as important:

(*a*) We must devise better methods of handling submersibles and large masses through the air–sea interface. At present we are so restricted in mass and size of submersibles that they can only operate up to sea-state 5. However, if a major breakthrough can occur, then the opportunity for taking additional equipment under the sea would open up new opportunities to different approaches to the design and application of mechanical devices.

(*b*) At present the machine tools used are not completely standardized and if we can apply some form of standardization this would reduce the need for the human hand to perform some of the tasks: instead the mechanical devices can take on a more demanding load.

(*c*) The economic implication of trying to copy the human being would be so costly that alternative treatments must be devised.

Secondly, our research tends to throw grave doubts on the wisdom of developing equipment which can produce manipulative dexterity of the mechanical device equal to that of a diver. Our main reasons are as follows:

(i) The more degrees of freedom a device has, the more likely it is to go wrong, and for this reason we should avoid being too sophisticated and limit the methods to fewer degrees of freedom;

(ii) by adopting such forms of standardization it may be possible to relieve a lot of the tasks which need the human hand;

(iii) human divers have limitations and manipulative skill is not necessarily their strongest asset.

I know that Mr Busby is an outstanding diver but I should like to hear his views on these two points.

R. F. Busby. Professor Kuo has raised points with which, on the whole, I agree. There are, however, a few thoughts of his upon which I should comment.

Better methods for handling submersibles through the air–sea interface are definitely required. At present the North Sea operators, Vickers Oceanics specifically maintain that they can and have operated in state 7 seas, not state 5 as Professor Kuo reports. While Vickers's performance is a significant achievement, it does not imply that the optimum system for launch and retrieval has been found. It is my belief that the all-weather launch and retrieval system is a large, long-duration support submarine which can deploy a smaller submersible, diver or remotely controlled vehicle while submerged. I think that state 7 is about the limit that one can practically and economically carry out over-the-side launch and retrieval.

In the final analysis, at state 7 and higher the old adage of 'one hand for the owner and one hand for yourself' is a fact of life, and launching and retrieving an object weighing 12 or 15 t is both difficult and perilous. Further improvements will, in my opinion, be best achieved by going beneath the surface rather than staying upon it.

The undersea servicing firms respond to a variety of customers. If they desired to standardize tooling, to which of the many customers would they respond? In virtually every instance the vehicle operator must tool-up to accomodate a particular task and/or a particular piece of hardware. In many instances the task or tool may never be required again. If, as I have suggested, the designers of undersea structures designed components that could be worked on by mechanical manipulation, then it is possible that standard tools could evolve. Until a specific task or tool sees repeated performance or use, standardization is not practical.

Professor Kuo is quite correct in remarking that the economic implication of trying to copy the human hand would be costly. I have not recommended that this be a design goal. My intent was simply to point out that the lack of this capability will severely limit deep-water support of oil and gas in the forthcoming decade. Co-operation on the part of the undersea structures designer, as I have mentioned previously, could reduce the technical capabilities requirements of a manipulator system. As an example, one can, with perseverance, proper tools and adequate lighting, open a knobless door, but a latch or knob certainly reduces the time and effort.

M. W. Thring (*Queen Mary College, University of London, Mile End Road, London E1 4NS*). Mr Busby referred to the need for mechanical hands which can have sufficient sensory feedback to tie a knot and also to have the memory of a human being. Such hands can be provided by the technology of telechirics (hands at a distance). These have already been developed for work inside nuclear reactors with all the movements of the human arm and at least one grasping movement, together with sufficient force of sensory feedback.

I am already working on the possibility of using telechirics so that a miner can use all his skill down a mine while remaining on the surface. In this case he will also need feedback of binocular vision, so that he can use his hands exactly as he would if he could see the work he was doing, and feeling it with all his trained skill.

It would certainly be possible to develop telechiric hands for work at and depth under the sea within 5 years if we really put our minds to it. These hands could be operated either by a man inside a submersible or attached to a suitable vehicle operated by cable from a ship. In this case the cable could also carry the power supply. Visual feedback can be by binocular t.v. cameras and a very powerful light source movable very close to where the hands are working, or by sonar, but in any case the tactile and force feedback would so so good that the man could do the job by touch if necessary.

R. F. Busby. The concept of transferring nuclear manipulative or telechiric techniques to undersea work is not new. In the early 1960s few discussions of manipulative capabilities were completed without questioning why the nuclear techniques were not employed on submersibles. I cannot argue Professor Thring's thesis that telechiric hands for work at any depth could be developed within five years if we really put our minds to it. But there are other technical and deployment considerations which are not readily apparent. Each finger of the human hand has not only sensory perception but memory as well. Technological memory is the domain of the computer. Further, the human is deployed by a 'platform' with outstanding characteristics for manoeuvrability and obtaining stability in close spaces. While I do agree that the human hand can be duplicated in the laboratory to a remarkable degree, I do not believe that five years is enough time to develop the techniques for its deployment within the space, manoeuvring and power constraints of contemporary manned and remote controlled vehicles.

To duplicate the human hand the telechiric system must at times operate in waters of zero visibility. Granted that acoustic imaging has made great strides in recent years, but as a replacement for the human hand's sense and memory it is a long way off the mark.

In view of these technological and operating constraints I cannot see complete duplication of the diver's manipulative dexterity by 1982, and still see this as the single major technological obstacle to providing deep water oil and gas support.