AUV'S -- THE MATURITY OF THE TECHNOLOGY

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Abstract

The development of autonomous underwater vehicles (AUVs), and their introduction into the military and offshore markets, has been a slow and costly process. This paper will provide an overview of those using and developing AUVs, discuss the state-of-the-art, and provide a projection on where the technology is heading and the hurdles it must overcome to reach maturity.

I. Introduction

AUV development began in the early 60's with vehicles such as Rebikoff's *SEA SPOOK*, and the Applied Physics Laboratory, University of Washington's *SPURV* (Self-Propelled Underwater Research Vehicle). They were soon followed by others such as *SKAT* at the Shirshov Institute of Oceanology (Russia); *OSR-V* (Japan); *EAVE West, RUMIC, UFSS* (U.S. Navy); *EAVE EAST* (University of New Hampshire, U.S.); and *EPAULARD* (France).

Unfortunately, most of these early AUVs were either large, inefficient, expensive, or a combination of all three. While the Remotely Operated Vehicles (ROVs) were beginning to gain in maturity in the early 1980's, AUV technology was essentially in its infancy. ROVs have the attributes of a brain (the human operator) attached via a long nervous system (the umbilical) and brawn (hydraulic power), which is provided by heavy duty electro-hydraulic power systems to thrusters, tools and manipulators. Conversely, AUVs are required to carry their brain and brawn with them, a requirement that, in the early 1980's, left them waiting for advances in computer technology and energy storage. The good news is that during the last twenty-odd years of continued development, the brains and brawn have begun to arrive. The following sections will discuss the state-of-the-art in AUV development, provide sources for obtaining additional information, and discuss the necessary steps for AUVs to become accepted and fielded.

II. Today's Status

Table 1 provides a comprehensive listing of international AUVs that are either planned, under development or operational along with directions to world wide web based sources for additional information on AUVs. Surface only or snorkeling vehicles (such as ISE's Dolphin) are not included. And the many historical AUVs that were instrumental in developing today's AUV technology base are not included (unless they're still operational). Such historical information is adequately documented in references 1 and 2. Also, the state of AUV system and subsystem technology will not be addressed in detail, reference 3 provides an excellent assessment of that topic. What will be discussed are the present trends, where they are leading, and an assessment of their adequacy in driving AUVs to their ultimate capability.

Today, at least 12 countries either have significant AUV developments ongoing (Table 1), or they are purchasing an initial capability. For example, China (Fig. 1) and Korea have purchased their AUVs from Russia's Institute of Marine Technology Problems (IMTP). In Europe, consortia such as MAST and NERC are underwriting the costs of AUVs like *SIRENE* and *AUTOSUB*. And in the U.S., the most significant developments have been undertaken by the military, where overall investments will reach hundreds of millions of dollars once the *NMRS* and *LMRS* reach operational status. Vehicles have been developed that range from *Robo-Lobster* and *Robo-Tuna* up to the mammoth DARPA (Defense Advanced Research Projects Agency, U.S.) UUVs. The offshore oil industry is looking at AUVs, such as the *Hugin* being used by Norway's Statoil, to lower the cost of operations in many areas. Japan is planning an AUV to reach the depths of the Mariana Trench and JPL (Jet Propulsion Laboratory, U.S.) is developing AUVs to bore through the ice and investigate the seas of other planets and moons.

With at least 66 different AUVs under development or operational, is there really a technology problem? The answer is both Yes and No. The technology to field AUVs is at hand. There are high-energy batteries, closed cycle diesel engines and fuel cells operational in today's AUVs. There are techniques to obtain adequate navigation fixes to complete a task. Depth is not a limitation, and depending on the launch platform and method, neither is size of the AUV. All of these have been demonstrated and as discussed in the next section, there are operational approaches to the problem that will allow orders of magnitude increases in today's use of AUVs.

On the "No" side, cost is the primary driver. The almighty bottom line rules. Even though we can build AUV systems, they are still costly. However, when placed into the context of the future of our planet, is the cost really that high? An understanding of the small and large scale processes taking place in the ocean are not only necessary to understand and predict the climate and future of our food supplies, they will be critical to the survival of the human race. Satellites are launched into space at an ever increasing pace at a cost that often reaches hundreds of millions of dollars each. Sputnik I was launched into orbit in 1957. When will the first "real" inner space satellite be launched? The world has gained a tremendous understanding of global processes through the use of outer space satellites flying high above the seas. What would our understanding be if an equal number of inner space satellites were exploring the oceans in situ?

On the "Yes" side, there is one area where technological advancements are necessary—the incorporation of advanced, miniaturized sensors. The ability to understand the ocean will be driven by the sensors that are placed into the environment by the AUVs. Dumb vehicles will provide nothing—intelligent vehicles will provide increased understanding. Some of the greatest strides in sensor exploitation can come from the space program, where the requirement exists to continually miniaturize sensors and systems, as they are driven toward smaller, lower cost satellites and space hardware. Technology transfer from outer space to inner space must be pursued.

With the existence of such potential, why aren't AUVs running rampant in the ocean? The desire is there. The need is there. The missions are there. The vehicles are there. And, considering the level of research that could be accomplished in the ocean today…the technology is there. What isn't there is a commitment to go forward.

III. Tomorrow's Requirements

As documented in studies on AUVs over the past thirty years, the technology limitations remain the same. AUVs have always had high-energy storage requirements, needed more computational power than technology could provide, and required the ability to accurately navigate, especially for long duration missions.

Luckily, the limitations in computational capability and data storage capacity are going the way of the vacuum tube. Today's high-speed computers and multi-gigabyte memory devices are virtually eliminating the problem. That assumes, however, that software developers will change their direction more towards efficiency in programming and stop using up the memory as fast as it is increased. In fact, the state-of-the-art in computers, control systems and data storage devices is moving so fast, it is becoming hard to keep pace with what is available. This rapid growth is making some newly developed computer systems obsolete they can be fielded.

Regarding energy storage, do we really need to make energy storage devices so compact that they reach the potency of a bomb? And, is it really necessary to incorporate high cost navigation systems that will deliver high accuracy position data long into the mission. In many cases, yes. However, the predominate number of potential missions do not necessarily need these features. Thus, what may be required is a more realistic look at the operational approach to any given mission. To do this, we must make two assumptions: the intelligence of the AUV will continue to increase along with computer technology, and the reliability of the systems will approach that being achieved by their older cousins—the ROVs (reference 4).

These two assumptions will be realized, leaving power and navigation the leading issues. Both can be solved by the approach taken to the mission planning problem. With brains and reliability in hand, one can solve the navigation problem, at a minimum, in one of three ways: don't go beyond the AUV's ability to return to a waypoint to allow a position fix; surface and use GPS; or deploy an inverse GPS system, i.e. acoustically communicate with a set of buoys on the surface that act as underwater satellites, providing accurate position to the AUV as it goes about its job. Now, none of these are unique ideas, and all three are being discussed or applied in various forms in on-going AUV programs.

The problem of onboard energy storage is definitely mission related. However, in those cases where the mission is confined to a given area, and not a long one-way ocean transit, then the ability to provide a stationary energy supply where the AUV can dock and recharge its batteries becomes an option. The ability to autonomously dock an AUV with a remote station has been proven in various fashions, using acoustics, optics and magnetics in programs funded by the U.S. Office of Naval Research. And, remembering our assumption, that we now have highly reliable vehicles, we will not worry (too much) about their remaining behind for long periods of time. Such a concept has been proposed by the Woods Hole Oceanographic Institution (WHOI) using their *ABE* vehicle.

With all of the above at our disposal—computers, data storage, navigation, energy—what will prevent the large-scale use of AUVs in ocean exploration and other missions? One primary answer is human nature: the inability to "cut the apron strings" and let the AUV leave home. And, as discussed earlier, such actions are cost driven. Thus, the cost of AUVs must be driven low enough to be considered expendable.

This cost is different depending on your perspective. Academic institutions are driving the cost down since they can't necessarily afford to lose their investment, or if they do, the vehicle's loss won't devastate their program. Consortiums provide the financial backing of larger groups, which allows the complexity and capability to increase, along with the cost. The military, with a mindset of multi-million dollar torpedoes and cruise missiles, drives the cost up due to the requirements of reliability and mission complexity.

Accordingly, the majority of AUV investments are driving the cost in a direction that leads away from what would be considered expendable. U.S. military programs, with high levels of financial backing, are forcing the technology toward multi-million dollar AUVs. Unfortunately, this makes them Non-expendable. Unlike systems such as torpedoes that have been around and have become accepted as expendable, the military has not been able to accept the loss of an AUV. They are being built to be recovered by the launch platform, such as the LMRS is by its host submarine. This results in added complexity, decreased reliability, and absorbs critical space that is limited on most platforms, especially submarines.

Is there an answer? Again—yes and no. The military will continue to build high cost systems because the desire to build the best system technologically possible is hard to overcome. But AUVs will not reach a level of integration within military missions that will provide a significant leap forward until they can become expendable. To do this, the cost must come down, which also means the number being built must go up. A vicious circle to say the least, but one that can be entered at any point. The military also has the requirement to understand the world's oceans, and that understanding will not come through the fielding of a few high cost AUVs.

What about offshore oil? AUV technology is sitting on the cusp of the curve where ROV technology was positioned at the beginning of the 1980's, prior to its acceptance into the oil patch. The acceptance of ROVs into the offshore arena provided the impetus for them to become highly reliable. Now they are an everyday fact of life off shore. And, while many of the technological breakthroughs were made through government or military laboratories, it was industry that made them reliable—and cost effective. Sources have indicated that within the next few years the financial barrier against AUVs for oil field work should begin to come down, but at this time, the barrier remains. Industry must also embrace AUV technology.

On a brighter side, there are some cost breakthroughs. FAU (Florida Atlantic University, U.S.) is pursuing nonmetallic pressure hulls that can be cast, allowing inexpensive AUV hulls that can be increased in size depending on the mission payload. WHOI has developed the reasonably priced *REMUS* vehicle (less than $70K U.S.), which is allowing various forms of autonomous missions. Approximately 12 have been delivered to different organizations to date. These are steps in the right direction. In many cases, there is underlying financial support by the government or military. But it is still not enough.

To adequately field AUVs, a change in attitude is required. This will happen when governments, preferably in a cooperative fashion akin to the international space station program, divert an adequate level of funding to produce a fleet of cost effective AUVs. Not high cost or perfect AUVs, but AUVs that can perform their given mission "well enough," and be considered expendable if necessary. Then AUVs will reach maturity. Until then, high cost and the related fear of losing the vehicle will overshadow their vast potential. This will result in only a limited number of vehicles operated by a limited number or organizations.

IV. The Future

The future for AUVs is wide open. The pockets of technology exist in many countries to develop cost effective, reliable, autonomous vehicles that can perform a multitude of relevant missions. When, and to what level, these "centers of excellence" are able to advance the technology and field cost effective AUVs is driven by funding. AUV technology can advance rapidly if increased government funding is provided to build something other than a handful of multi-million dollar systems. We can continue in this fashion—slowly with minimal advancement up the curve. Or, we can get serious about fielding the technology that presently exists, and investing into those AUV technologies that are truly critical. For the cost of launching one space satellite, hundreds of AUVs could be launched into the oceans on limited duration missions today.

The future can realize vast undersea networks of AUVs. Ocean networks of "innerspace satellites" can exist that will provide the data necessary to explore the oceans properly, predict the weather, provide a defense capability when required, and just possibly save the ecology of the world. Whether this capability is achieved within the next 20 years, or the next 100, will be determined by funding. Increased funding provided in an atmosphere of synthesis, where academia, industry and the government can leverage each other's attributes to reach an achievable goal. Now is the time to lose some AUVs.

References

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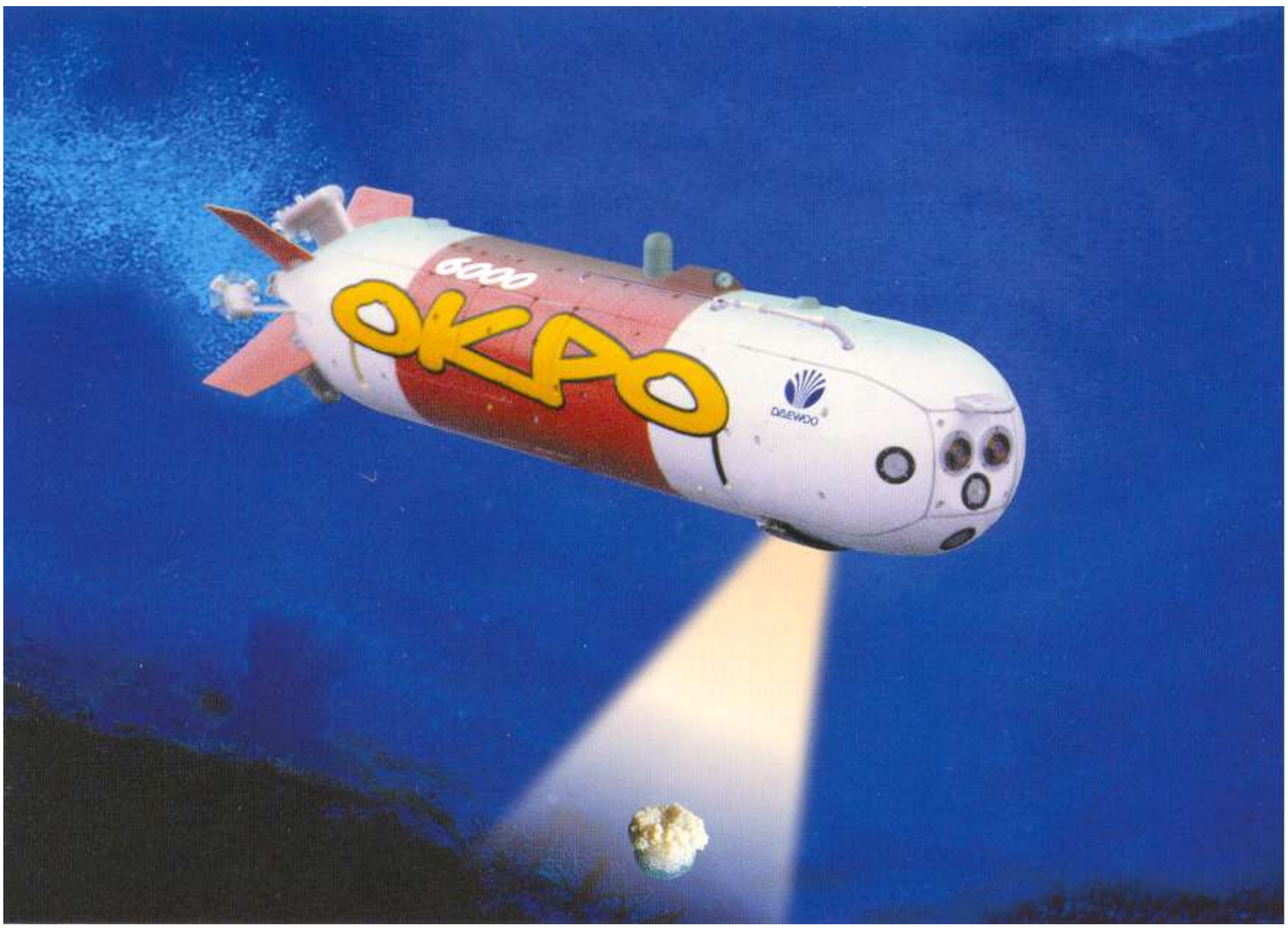

Fig 1. Daewoo Heavy Industry's OKPO AUV
(Courtesy Daewoo Heavy Industries Ltd.)

Table 1. International AUVs

COUNTRY/VEHICLE	STATUS	FUNDING	COST	ORGANIZATION	CONTACT
UNITED STATES					
AUSS	STANDBY	GOV'T	HIGH	SSC SAN DIEGO	http://www.nosc.mil/robots/
FREESWIMMER	INACTIVE	GOV'T	LOW	SSC SAN DIEGO	"
LDUUV	OPERATION	GOV'T	HIGH	NUWC	http://www.npt.nuwc.navy.mil/
21UUV	OPERATION	GOV'T	HIGH	NUWC	"
MANTA	CONCEPT	GOV'T	VHIGH	NUWC	"
STDV	DEVELOP	GOV'T	HIGH	NUWC	"
NMRS	OPERATION	GOV'T	HIGH	NAVSEA/NG	http://www.onr.navy.mil/sci_tech/ocean/jcm/nmrs.htm
LMRS	DEVELOP	GOV'T	HIGH	NAVSEA	http://www.contracts.hq.navsea.navy.mil/pms403/
MK30 MOD 1	OPERATION	GOV'T	MED	RAYTHEON	
DARPA UUVs	STANDBY	GOV'T	VHIGH	NAVO	ingramc@navo.navy.mil
COTS AUV	DEVELOP	GOV'T/ACA	HIGH	NAVO/PENN STATE	"
LSV	OPERATION	GOV'T	VHIGH	NSWC	http://www.dt.navy.mil/sites/bayview.html
MUST	OPERATION	COM	HIGH	LOCKHEED-MARTIN	http://www.perrytech.com/mustlab2.html
XP-21	INACTIVE	COM	MED	RAYTHEON	
PHOENIX	R&D	GOV'T	LOW	NPS	www.cs.nps.navy.mil/research/auv/
OCEAN VOYAGER II	OPERATION	ACA	MED	FAU	www.fau.edu/AMS/auv.html
OCEAN EXPLORER	OPERATION	ACA	LOW	FAU	"
MINI-AUV	DEVELOP	ACA	LOW	FAU	"
ODYSSEY IIB	OPERATION	ACA/GOV'T	LOW	MIT SEA GRANT	http://auvserv.mit.edu/
CETUS	DEVELOP	COM/ACA	LOW	LOCKHEED-MARTIN/MIT	"
ALTEX	DEVELOP	ACA/GOV'T	MED	MIT SEA GRANT LEAD	http://auvserv.mit.edu/Miscellaneous/altex98.htm
ROBOTUNA	R&D	ACA/GOV'T	LOW	MIT SEA GRANT	http://web.mit.edu/afs/athena/org/t/towtank/www/tuna
ABE	OPERATION	ACA	LOW	WHOI	http://www.marine.whoi.edu/ships/auvs/auvs.htm
REMUS	OPERATION	ACA	LOW	WHOI	http://adcp.whoi.edu/REMUS/
EAVE-III	R&D	ACA/COM	LOW	AUSI/MSEL	http://cdps.umcs.maine.deu/MSEL/
LRAUV	DEVELOP	ACA/COM	UNK	AUSI/MSEL	http://cdps.umcs.maine.deu/MSEL/
Solar AUV	DEVELOP	ACA/COM	MED	AUSI/MSEL	http://cdps.umcs.maine.deu/MSEL/
VIMSS	DEVELOP	ACA/GOV'T	L/M	APL UW	www.apl.washington.edu
6.25" UUV	R&D	ACA/GOV'T	L/M	ARL PENN STATE	http://www.arl.psu.edu/core/usvs/usvs.html
26.5" UUV	R&D	ACA/GOV'T	HIGH	ARL PENN STATE	"
SLOCUM	DEVELOP	COM/GOV'T	L/M	WEB RESEARCH CORP.	http://www.vsa.cape.com/~dwebb/slocum.htm
OTTER	R&D	ACA/COM	LOW	MBARI/STANFORD UNIV.	www.mbari.org/projects/
DORADO	DEVELOP	COM	UNK	MBARI	"
FETCH	OPERATION	COM	LOW	SIAS/PATTERSON INC.	
CRYROBOT	DEVELOP	GOV'T	UNK	JPL	http://www.jpl.nasa.gov/ice_fire//europao.htm
HYDROBOT	DEVELOP	GOV'T	UNK	JPL	"
DARTS	R&D	COM/GOV'T	LOW	IS ROBOTICS	www.isr.com
ODIN	R&D	ACA	LOW	UNIVERSITY OF HAWAII	www.eng.hawaii.edu/~asl/

ABBREVIATIONS: DEVELOP (Developmental), R&D (Research & Development), OPERATION (Operational)
ACA (Academic), COM (Commercial), GOV'T (Government)
L/M (Low to Medium), VHIGH (Very High), MED (Medium), UNK (Unknown)
NOTE: Costs are estimates for relative comparison only.

Table 1. International AUVs (continued)

COUNTRY/VEHICLE	STATUS	FUNDING	COST	ORGANIZATION	CONTACT
UK					
AUTOSUB-1	OPERATION	COM/GOV'T	HIGH	SOC/NERC	www.soc.soton.ac.uk/autosub
ODAS	OPERATION	COM	HIGH	GEC-MARCONI	http://itri.loyola.edu/subsea/e_mus.htm
MARLIN	DEVELOP	COM/GOV'T	HIGH	GEC-MARCONI/DERA	http://www.gec-marconi.com/prod_ser/a-z/a-z.htm
RAUVER	R&D	ACA	LOW	HERIOT-WATT UNIV.	http://www.cee.hw.ac.uk/oceans/
SINKA	R&D	ACA	VLOW	HERIOT-WATT UNIV.	"
NORWAY					
HUGIN	OPERATION	COM/GOV'T	HIGH	CONSORTIUM	http://www.nui.no/hugin2.html
FRANCE					
SIRENE	OPERATION	COM/GOV'T	MED	IFREMER/MAST	www.ifremer.fr
MAUVE	OPERATION	COM/GOV'T	UNK	IFREMER/MAST	www.ifremer.fr
TAIPAN	R&D	ACA/GOV'T	LOW	LIRMM	www.lirmm.fr/~vaganay/taipan/index.html
REDERMOR	R&D	GOV'T	HIGH	GESMA	www.gesma.fr
DENMARK					
MARIUS	INACTIVE	COM	MED	MARIDAN	www.maridan.dk
MARTIN 200 & 1000	OPERATION	COM	MED	MARIDAN	www.maridan.dk
JAPAN					
R-1	OPERATION	ACA	HIGH	UNIV OF TOKYO	htttp://kerama.iis.u-tokyo.ac.jp
TWIN BURGER	R&D	ACA	MED	UNIV OF TOKYO	htttp://kerama.iis.u-tokyo.ac.jp
MANTA-CERESIA	R&D	ACA	LOW	UNIV OF TOKYO	htttp://kerama.iis.u-tokyo.ac.jp
PTEROA 150	R&D	ACA	LOW	UNIV OF TOKYO	htttp://kerama.iis.u-tokyo.ac.jp
ALBAC	R&D	ACA	LOW	UNIV OF TOKYO	htttp://kerama.iis.u-tokyo.ac.jp
AQUA EXPLORER	R&D	ACA	LOW	TOKAI UNIVERSITY	http://mdesign.os.u-tokai.ac.jp/katolab/
LONGRANGE AUV	PLANNED	COM	UNK	JAMSTEC	www.jamstec.go.jp
10,000 METER UROV	PLANNED	COM	HIGH	JAMSTEC	www.jamstec.go.jp
CANADA					
ARCS	OPERATION	COM	HIGH	ISE	www.ise.bc.ca
THESEUS	OPERATION	COM/GOV'T	HIGH	ISE	"
AURORA	DEVELOP	COM	MED	ISE	"
PURL I & II	R&D/OPER	ACA	LOW	SIMON FRASER UNIV.	www.ensc.sfu.ca/research
RUSSIA					
TYPHLONUS	OPERATION	GOV'T	MED	IMTP	http://www.itri.loyola.edu/subseafe/c2_imtp.htm
SEA LION (MT-88)	OPERATION	GOV'T	MED	IMTP	"
TUNNEL SEA LION	DEVELOP	COM/GOV'T	MED	IMTP	"

Table 1. International AUVs (continued)

COUNTRY/VEHICLE	STATUS	FUNDING	COST	ORGANIZATION	CONTACT
ITALY					
SARA	DEVELOP	COM/GOV'T	UNK	Tecnomare/ENEA	
SAM	CONCEPT	GOV''T	UNK	National Research Program	
GERMANY					
C-CAT	DEVELOP	GOV'T	UNK	STN ATLAS Elektronik GmbH	
CHINA					
CR-01A	OPERATION	GOV'T	HIGH	Chinese Academy of Sciences	http://www.qdio.ac.cn/
KOREA					
OKPA	OPERATION	COM	HIGH	Daewoo Heavy Ind.	jswoo@daewoo.dhi.co.kr