Europe's Growing Fleet of Scientific Deepwater ROVs: Emerging Demands for Interchange, Workflow Enhancement and Training

V. Ratmeyer[1] and V. Rigaud[2]
[1] MARUM, Center for Marine Environmental Sciences, University of Bremen, 28359 Bremen, Germany
[2] IFREMER, L'Institut Francais de Recherche pour l'Exploitation de la Mer, 83507 La Seyne sur Mer, France

Abstract- **During the past 10 years, large developments and improvements on the technical possibilities and operational availability of full-size, Class III deep ocean work ROVs took place (> 3000 m). This is especially true for the marine science community. Where in the early 90's scientific ROVs for ultra-deep operations were a true technical challenge for technology leading institutions like IFREMER, MBARI, WHOI, and JAMSTEC, the sub-sea technology driving offshore oil and gas industry was orientated almost solely into developments for the shallow water production business. This relation changed dramatically with the achieved breakthroughs in ROV technology, some major of them developed by science institutions, and was adapted quickly into the 3000 m depth range increasingly provided by the underwater industry. However, ultra-deep, truly operational remote diving technology beyond 3000 m still remains a technical frontier both for industry and science. This paper addresses key issues emerging from such rapid developments for marine science, including inter-operability at different levels from vessel to payloads and procedures, at the same time cost and crew reducing/sharing demands, aspects of enhanced and effective training and testing, and new technical challenges to provide compatible scientific operations and data.**

I. Introduction

As a consequence of recent industrial developments, it was never easier for the marine science community to choose from a number of off-the-shelf heavy work-class ROV systems, in order to gain technology capable of deepwater scientific intervention and observation, and to obtain platforms for state of the art research campaigns. Today, a coherence between new, commercially based systems on one hand, and existing small-series / solitary developments by scientific expert groups on the other, appears in the worldwide marine science community (see Table I). A dominant increase of available platforms took place during the last 5 years: From 7 to over 10 dedicated heavy work-class, ultra deep diving (> 3000 m) systems are continuously operated solely for marine science today, 4 of them currently only in Europe, and with increasing tendency. Providing such seagoing research infrastructure and hosting capabilities for mobile, worldwide operated deepwater platforms opens a new dimension of accessibility in Europe. The research area "deep sea" gets closer, easier to access, and is increasingly confirmed to be a major driver for today's scientific key questions in marine research, such as climate change, gas hydrates and marine biodiversity.

TABLE I
TODAY'S LARGE SCIENCE ROVS (WORKCLASS, >= 3000M)

Vehicle	Depth (m)	Operating Institution	Builder	Industrial/ small series	Country
HOLLAND I	3000	MARINE INSTITUTE	SMD	industrial	Ireland
Dolphin 3K	3000	JAMSTEC	JAMSTEC	small series	Japan
Hyperdolphin	3000	JAMSTEC	ISE	industrial	Japan
TIBURON (retired)	4000	MBARI	MBARI	solitary	USA
DOC RICKETS	4000	MBARI	SMD	industrial	USA
QUEST 4000	4000	MARUM	SCHILLING ROBOTICS	industrial	Germany
ROPOS	5000	CSSF	ISE	industrial	Canada
KIEL 6000	6000	IFM-GEOMAR	SCHILLING ROBOTICS	industrial	Germany
VICTOR 6000	6000	IFREMER	IFREMER-ECA	solitary	France
JASON II	6500	WHOI	WHOI	small series	USA
ISIS	6500	NOC	WHOI	small series	UK
UROV 7K	7000	JAMSTEC	JAMSTEC	solitary	Japan
NEREUS	11000	WHOI	WHOI	solitary	USA

As an illustration, after 10 Years of operations the veteran of deep diving ROVs in Europe - VICTOR 6000 - has produced a mean number around 0,8-1,0 scientific publications per dive.

However, although institutional builds like VICTOR (France), TIBURON (USA) and JASON II / ISIS (USA, UK) are dedicated developments with specialized, partly prototyped technology made for scientific remote diving, recent installations relying on state-of-the-art industrial equipment such as i.e. the German QUEST 4000 provide a similar rate of usage efficiency today (see Table II).

Recent projects such as i.e. the Russian-French Serpentine cruise, the European HERMES cruises and the German Mid-Atlantic-Ridge program and MAKRAN cruises have - among others - illustrated the growing interest of ROV usage for the exploration of new sites, thereby utilizing VICTOR 6000, QUEST 4000, ISIS and KIEL 6000 for joint projects on a number of European research ships.

TABLE II
SINGULAR DEVELOPMENT (VICTOR) VS ADAPTED INDUSTRIAL ROV (QUEST): COMPARISON OF USAGE RATES

Vehicle	years of operation (by 2009)	days of use	days of technical cruise	days on foreign ships
VICTOR 6000	10	964	198*	109
QUEST 4000	6	591	22	0

* Including valorized transit and overhaul dives

Scientific key issues concern the discovery of the deepest known active hydrothermal sites with identification of natural hydrogen seeps (Serpentine [1]), super-critical hydrothermal fluid temperatures at hot vents (SPP1144 Mid Atlantic Ridge Program [2]), or a new understanding of the evolution of methane seeps and gas hydrate related sites on an active continental margin (MAKRAN [3]), to name just a few.

On the other hand, a new emerging type of surveys with increasing percentage of underwater intervention action, i.e. the remote installation of "observatory type" structures, are more and more requested, bringing new skills and technologies into the scope of operations [4]. These include installation, maintenance and recovery of permanent instrumentations at the sea floor as stated with the ANTARES Neutrino Telescope system installation with VICTOR 6000, 4 years ago off Toulon in the Mediterranean Sea (Fig.1). Further attempts include the international large scale projects such as KM3, ESONET Demonstration Missions, MOMARETO, NEPTUNE Canada and NEPTUNE USA.

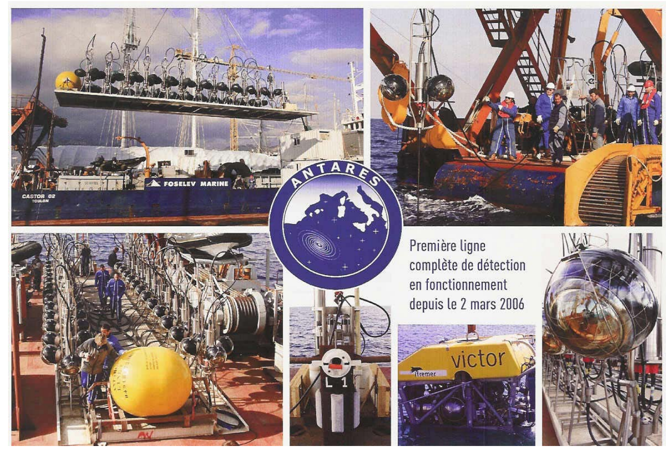

Figure 1. Deployment of ANTARES Neutrino Telescope and maintenance by VICTOR 6000 (Photo: CNRS-IN2P3/Ifremer).

II. INTEROPERABILITY: IMPLICATIONS FOR FUNDING AND OPERATIONAL EFFECTIVENESS

A. Costs

Despite their increasing number, full-size ROVs dedicated to high-quality observation, sampling and scientific deep-ocean intervention remain an expensive research tool, both in terms of investment as well as for the running costs of operation, maintenance and adaptation to ships. Comparable almost more to infrastructural investments than to scientific instrumentation, funding requirements for the scientific operation of these vehicles are rising significantly.

For example, it seems comparatively easy to get funding for investment, but way more complex over time to get the funding to operate and maintain systems and establish a sustainable operational structure.

In France, IFREMER and Genavir cooperate with integrated and complete teams, remaining on a central, global management of a wide scope of systems, from manned submersible to AUV. Interoperability of subsystems between vehicles and multidisciplinary, yet dedicated teams help in the modularization of investment, running costs and competences.

In Germany the management of underwater systems is decoupled from fleet management, and the global management of the fleet is distributed between different competences (i.e. Control Station R/V Meteor/ R/V Maria S. Merian (University of Hamburg), RV Sonne (PT Jülich), R/V Polarstern (AWI Polar Institute Bremerhaven)). Management of large underwater systems here is positioned at regional institutional levels - mainly due to a different history in this field compared to France and UK - namely MARUM and IFM-GEOMAR, providing less expensive operations with teams employed from technical and scientific staff, and allowing higher operational flexibility at lower rate of usage compared to equivalent systems operated i.e. in France or US.

At the end the cost analysis is complicated due to the different scenarios and setups. In US the additional cost of the scientific services get by underwater system is clearly defined for each cruise. The request of a permanent core team, with additional non permanent staffs as student or trained scientist is a way to optimize the rising costs at sea of underwater systems and instrumentations. However, all these systems require more and more education of technical skills and operational training due to a rapid increase in number and complexity of such platforms requested by science.

As a general indication, the cost of possession of heavy tools such as deep sea ROVs for a scientific institution relies on:

- The initial investment cost which varies from 2 to 10 M€
- The personnel running cost, depending on the structure and use of teams (i.e. permanent technical staff vs. freelance teams or trained scientists), and quoted by the number of days of operations per year
- The internal or external cost for maintenance, adaptations, upgrade, and logistics of the systems , with a typical "cycle of life" of technical upgrading each 3 to 5 years and big overhaul each 10 years, based on a proposed duration of life less than 20 years (including personal and subcontracting costs)

Figure 2. QUEST 4000 aboard R/V Meteor (Photo: V. Diekamp, Marum).

Figure 3. Mobilizing VICTOR 6000 on R/V Sarmiento De Gamboa (Photo: A. Massol, Ifremer).

If one estimates the property amortisation and the exploitation means, a typical rate of usage around 100 days of operation (excl. transport/logistics) per year appears reasonable.

In the great majority the owners have a core team for the operation and the first level maintenance of the systems, but relying on industrial vendors for further evolutions and heavy maintenance. However, the increasing number of systems adapted from the industry rather than developed in-house, allow to a higher degree than before the use of modular spare part packages and exchangeable units - sometimes called "LRUs" (lowest replaceable unit), thus avoiding costs of small series spare-part production and integration as often needed on singular systems. The QUEST 4000 ROV built by Schilling Robotics (USA) was the first vehicle successfully utilizing this concept within routine scientific operations in Germany, followed by the MARUM MeBo remote drill-rig, the IFM-GEOMAR KIEL 6000 ROV as well as DOC RICKETS at MBARI in the US and HOLLAND I at the Irish Marine Institute, both built by SMD in UK.

Mean agencies as IFREMER successfully optimized the cost of their systems (if singular or in-house developments) by the use of multidisciplinary operators and operational crews operating a large scope of systems (ROV-AUVs, Manned Submersibles and instrumentations).

At this stage nobody is utilizing an industrial leasing solution - although widely accepted in the offshore industry - with fully subcontracted services. This is mainly due to the high specifications of the scientific requests and a high flexibility required both in the adaptation and operation of new science tools and specialized sensors, most of them never used in the standard offshore business (i.e. CH4 Sensors, Autoclave samplers, Mass Spectrometers). On the other hand, an illustration of a unique and possible convergence between offshore industry and scientific users is the SERPENT project in UK, which aims to offer industrial offshore work-class ROV technology for scientific operations through cooperation between industry partners and the DEEPSEAS group hosted at NOCS [5].

B. Vessel Adaptations

At least in Europe, national and international scientific proposals pay increasing attention towards the recently extended availability of deep water ROV technology, resulting already in higher exchange between requested systems and ships of opportunity (i.e., OFWG Report 10, [6]). This even includes the request and use of US and Canada based systems (JASON II and ROPOS) on European ships (R/V Maria S. Merian, R/V Sonne, R/V L'Atalante).

Besides the resulting gain of technical routine, this is leading to a more open and realistic discussion of day rates and operational costs which will hopefully result in a transparent model for the evaluation of costs in the proposal phase. As a first outcome, due to the growing complimentary usage of full ocean ROVs in Europe, adaptations of such systems to ships of opportunity are now becoming a routine work-task (see Table III and Figs. 2, 3).

Awareness of this evolution could already be successfully implemented in new ship's construction, as i.e. for the R/V Pourquois Pas, the R/V Celtic Explorer, the R/V Maria S. Merian, the R/V James Cook, and the R/V Sarmiento de Gamboa, which was designed from the beginning in cooperation between CSIC and IFREMER to welcome Victor 6000 using standardized interfaces (Fig. 3)

C. Shared Use

When understanding scientific deep-sea operations as a true European capability in an international context, the differing national structures, funding strategies and ways of fleet management as described above, make a concurrent use of existing platforms not an easy task, both in terms of funding as well as operation and scheduling. Where facilities such as IFREMER (FR), or NOC (GB), labeled as a National Mean agency in France and UK with identified budged, represent

TABLE III
EXISTING LARGE ROV ADAPTATIONS TO EUROPEAN RESEARCH VESSELS

Vehicle	**Research Vessel**	**Country**	**Year** of first Installation
VICTOR 6000	RV Thalassa	France	1997
	RV L'Atalante	France	2000
	RV Pourquois Pas	France	2005
	RV Polarstern	Germany	1999
	MV Castor 2	Industrial, France	2003
	RV Sarmiento de Gamboa	Spain	2008
QUEST 4000	RV Meteor	Germany	2003
	RV Polarstern	Germany	2007
	RV Sonne	Germany	2008
	RV Maria S. Merian	Germany	2009
KIEL 6000	RV Sonne	Germany	2007
	RV L'Atalante	France	2008
	RV Maria S. Merian	Germany	2009
	RV Meteor	Germany	2009
ISIS	RV James Clark Ross	UK	2007
HOLLAND I	RV Celtic Explorer	Ireland	2009
ROPOS	RV Sonne	Germany	1997
JASON II	RV Maria S. Merian	Germany	2007

clear national interests and have to perform to a certain extend services for their national scientific (and technical) communities, other institutions like universities or high-level nationally funded research centers such as i.e. MARUM or IFM-GEOMAR in Germany, have to deal with a sensitive balance between internal and external services on project and expedition level, but with limited resources and personnel capabilities.

This has direct implications for scientific proposals placed at EU level, being dependent on the availability of special platforms to fulfill the promised tasks - the higher the need for special operations such as observatory installations or dedicated sensor deployments, the higher the probability of using more than a single platform (ROV, AUV, research vessel) throughout a joint project duration period. Regarding underwater vehicle platforms, both technical availability on certain vessels, as well as schedule of crew and technical staff has to be investigated more carefully prior to proposal delivery than this is currently the case.

As an example, a mean of 3 expeditions per year for a true mobile worldwide operating system such as the MARUM QUEST 4000m becomes a limiting factor. Based on a standard mission of 4 weeks at sea, accompanied by 4 weeks transport of the system each way, a total of 9 months per year leaves 3 months for maintenance – ideally one month after each cruise. This is barely enough when mission objectives and ships change between cruises, not to mention recovery from technical failures or damages possibly happened during a mission. One approach to overcome such time limits and the connected crew planning limitations could be to facilitate a resource and operations-personal sharing. When saying this, it is necessary to emphasize the real limitations of such ideas – one of them being the individuality of systems regardless of their similarity. Full Ocean ROV Systems are extremely complex, and individual by definition, and even in industry almost none is equal to another. This has major implications on expertise sharing and team exchange. However, it has become experienced that team sharing in the dimension of 1 or 2 persons per mission may be a realistic number (within a total team of 8-10), providing a strong knowledge base from the original team, but still being substantially supported by “externals” from another group. With these numbers in mind, knowledge transfer may go conform to team member exchange in a healthy way.

As a consequence, enhancing the compatibility of systems and operational resources is a key task to ensure the future of international scientific underwater work capabilities within the EU and clearly has to be further developed to ensure the success of state of the art, top-level research projects in the deep sea. Such development is to be requested in different ways, and will include both - the funding for crew exchange and training, and the costs for hardware compatibility at platform/vehicle/sensor and at platform/vehicle/vessel adaptation levels.

First attempts have been undertaken in different initiatives to address an evaluation of interoperability on a wider basis, some of them already for those systems available in European institutions. OFWG, OFEG, ESONET NoE and the proposed EUROFLEETS program already define different tasks and work packages dealing with the expressed need for such interoperability among heavy ocean equipment. One important aspect to be solved in the near future may be the sharing of payloads, which will also include a wider international community, not only Europe’s platforms. New online tools like web-based information databases are helpful and should be further developed, yet today they often lack more information than they can provide. Workshops like the TSM2007 or others (i.e. Deep Submergence Payload Meeting Bremen, May 2007; ESONET Best Practises Workshop Bremen, January 2008) provide a necessary platform to identify and discuss the key parameters which will lead to a better understanding and a concise definition of a realistic level of compatibility. ESONET may provide an outreach platform to collect and distribute the necessary detailed information to identify interfaces and trends in payload development. The process of definition becomes increasingly important and may well be an initial key task for a “living” interoperability, ultimately giving the scientific community a well known pool of technical solutions and hence, comparative approaches and results. Standards have to be evolved, yet they are difficult to be defined and shared within the dynamic real world scientific business.

Especially the combination of future observatories and ROV based intervention capabilities will become increasingly important, simply because the possibilities become easier available to deploy, control and maintain moored long-term measurement devices without the need for frequent surface recovery and re-deployment. Since it will remain a steady uncertainty if such devices will be maintained by the same platform after a given measurement period, standardization becomes a necessary issue in this context from the beginning of the design phase of observatories and sub-sea maintainable instruments.

D. *Standards and Workflow Enhancement*

Standards will either have to be developed – or defined among a variety of existing ones - for technical interfaces as well as for operational procedures, networked data protocols and final post-mission or post-deployment data access routines. Platforms exist which could provide data access during missions (i.e. Mimosa Mission Planning tool - IFREMER) or after cruises in a consecutive way (i.e. SeaDataNet, EurOcean - EU; WDC Mare, Pangaea - MARUM/AWI). On the hardware side, a whole range of technical standard definitions dedicated to different applications are available from the offshore oil and gas industry, and attempts were already undertaken to evaluate the benefits of these established but strictly industry related norms (investigation by IFREMER, 2007; ESONET first all regions workshop Barcelona - [7]). As a major difference to industry, it may well become a challenge itself to find a usable compromise between the highly variable demands of scientific methodology and a stable standard which can technically be used on different platforms and installations.

Emerging from all these exciting developments, both technical experts as well as scientists and ship's crews are now requested to follow this path, each in their dedicated field of expertise. This is of course a challenge itself, and appears even enforced by the directives of national and European funding agencies for enhanced cooperation and interoperability. Both the technical and the scientific experts are asked to come together in a much more concise way than even 5 years ago, to ensure that ambiguous programs such as international sampling and measurement or high resolution mapping campaigns, or installation and maintenance of seafloor or deep ocean observatories, will be successfully performed. This includes also the growing technical skills for both, pilot crews as well as scientists, to keep up with exploding velocity of technology developments and their potential for scientific application (i.e. HDTV, Lasers, Imaging Sonars, Control and Telemetry, etc.)

E. *Training and Testing*

Ways to solve these demands include straight definition of technical standards and common operational procedures on one hand, as well as emphasizing the needs and establishing the capabilities for training and testing both technician's and scientist's approaches of use. Establishing workflow optimization through payload exchange, pilot and procedure training and interoperability through adaptation to changing host ships, are some of these new tasks. Needs are now evolving for facilities, which can setup dedicated training and testing environments, including tools like vehicle simulators and dedicated hardware installations such as hydraulic test stands or water tanks capable of hosting large vehicles and systems for underwater testing.

Training becomes a relevant issue to address the procedural component of using different systems among similar environments and deep sea installations.

Both IFREMER and MARUM are currently developing a virtual mission training center, with different detailed objectives but with the overall common goal to gain highest possible mission efficiency and preparation quality. Attempts are currently being evaluated for both training setups - in situ object manipulation training as well as procedural training in virtual environments, rather than utilizing valuable scientific dive time while at sea. Proposed setups may include both approaches and allow the definition of scenarios with all physical constraints implemented, including vehicle dynamics, ocean environment dynamics (including weather, currents and real bathymetry), and object creation versus virtual manipulation up to a very high level of detail. Among commercial systems some exist which already fit to existing platforms, minimizing the need to develop the virtual vehicle base before being ready to use in a training or test mission.

In a final stage, such a training facility could be designed as a full virtual tele-operations control environment available for virtually testing and training several kinds of platforms, deployments, vehicle interactions, object intervention, mission planning and GIS based post processing. In the European context, access could be organized for regular training courses and mission testing and would be available for operational crews and - increasingly important - to scientists, an issue often overlooked when proposing the use of highly complex technologies such as ROVs. As a consequence, both the student and graduate education as well as the public outreach projects are further applicants for such a facility, offering i.e. possibilities for an interdisciplinary study course design among marine geosciences and engineering studies at the University of Bremen.

III. Future Trends

From the technology standpoint, it becomes obvious that the difference between typical ROV and typical AUV developments becomes less dominant. A spectacular new approach is WHOI's HROV "NEREUS" [8], becoming the first of its kind being able to dive the true "full ocean" depth of 11000 m. Although JAMSTEC's KAIKO was previously capable of the same depth range, the new approach takes advantage of a combination of autonomous and remotely controlled technologies hosted within the same device. Previous approaches include industries prototypes (i.e. ISE, Canada) and collaborative science-industry projects (i.e. SWIMMER -

Cybernetix with IFREMER and others [4]). As a consequence, to a certain extent larger spatial envelopes become available for remotely controlled equipment. It has to be proven that scientific applications will take advantage of this new type of concept also for other, less deep ocean areas.

A decrease of system weight and size seems to become another trend, especially with the installation of new, commercially based ROV vehicles such as the QUEST systems operated by MARUM and IFM-GEOMAR. The advantages are an easier mobilisation and less requirements on vessel capabilities compared to larger systems in their original setup (which is about to change). Adaptation to new ships seem to come down to only few days, mainly because a major part of technology improvements during the last years allows higher propulsion power through given or less wire diameters, thus lighter winches, compacter buoyancy, new digital telemetries, and more compact or efficient data and video distribution and networked display systems. However, planned overhauls for large systems will take advantage of parts of these developments, probably resulting in a similar decrease of complexity and system size. All together, the possibility of usage of deep ocean ROVs on ships of opportunity currently increases.

Subsystems and science-related technical developments will include new kinds of exchangeable, dedicated tool-skids, mapping and observation devices, intervention technology (probably to be migrated from offshore oil and gas industry), and increased use of high definition video capabilities. Since not all of these and others to come can be installed at every institution hosting the appropriate platforms, it appears feasible to focus special expertise and develop above the proposed sharing policy among institutes also for special and very expensive tooling.

The combined use of AUVs and ROVs is a way to optimize the time at sea which is mainly dimensioned by the cost of the support ships. For survey tasks, AUVs are doing the job faster than ROVs. The tendency for ROVs to run long dives to avoid loss of ship time during Launch and Recovery and transit to depths is also a key issue in the optimization of cruises. It is today clearly envisaged to propose as a natural couple to use survey AUVs and ROVs in a complementary way, with feasibility demonstrated to use both systems at the same time. The AUVs data can be used as preliminary charts to prepare the ROV deployment or additional data to complete the ROV works. This kind of hybrid views are productive and safe (the ROV can cope with AUV failure and recovery) [4, 9].

A new field of developments could grow from the idea of the simultaneous deployment of ROVs and AUVs on given sites, proposing an instant access to spatial coverage by the AUV and immediate close inspection by the ROV.

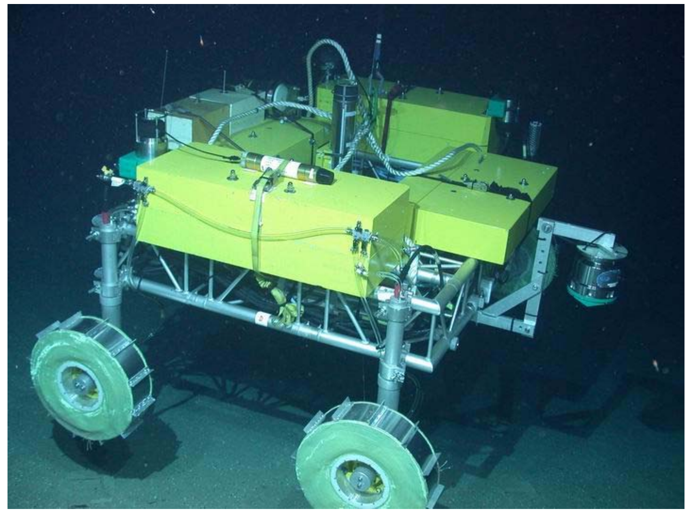

Figure 4. AUV MOVE maintained by ROV QUEST 4000 at 2045 m depth (Photo: Marum)

Initial experiences already exist, i.e. the maintenance and recovery of the crawler AUV MOVE with ROV QUEST 4000 at 2045 m depth in the Mediterranean Sea (Fig. 4). Operational setups like this will need enhanced communication possibilities between both types of vehicles at depth, as well as highly reliable, maybe guided, half-autonomous navigation and implementation of artificial intelligence [9].

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