AUV Docking System for Sustainable Science Missions

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Abstract – *In this paper, we present a technological development of an Autonomous Underwater Vehicle (AUV) docking system motivated by science requirements. Twenty-seven case studies were drafted after having elaborate discussions with twelve senior marine scientists from a wide range of oceanographic fields including Physical Oceanography, Ocean Chemistry, Midwater Ecology, Bio-logical Oceanography, Molecular Biology, Marine Micro-biology, Geology, Evolutionary Biology, and Benthic Ecology. These science cases spread over coastal ocean, deep-ocean, mid-ocean ridge, and polar regions. All of these science missions can be significantly benefited from new and improved sets of data and samples that will be collected by using a docked AUV. The case studies are organized to address the science issue, significance of the problem, required data and measurements to address the scientific importance, a non-docked method for acquiring data, and the benefit of using a docked AUV. More than twenty science instruments (in addition to navigational sensors) are identified and evaluated for these science missions. Science payloads for the AUV and the docking system are discussed in detail. Functional requirements for a general purpose docking system are identified and pros & cons of various docking subsystems are explained. A Fuzzy Logic based solution approach for an autonomous docking system design and development is also proposed in this paper.*

I. INTRODUCTION

More than 70% of the earth's surface is covered with water. This vast watermass not only possesses a tremendous amount of resources, but it also influences the global climate and ecosystem enormously. The economic and social impacts reflect how natural marine, atmospheric, and coastal phenomena affect us. For example, industries affected by weather and climate account for nearly 30% of the gross domestic product (GDP) of the United States [1].

The need and desire to explore the vast oceanic environment for better understanding, extraction of resources, and preservation of global environment have provided a significant momentum in the deployment of advanced oceanographic systems. Conventional systems such as smart moorings, drifters, towed-instruments, ships, etc., and robotic systems such as gliders, remotely operated vehicles (ROV), human occupied vehicles (HOV), autonomous underwater vehicles (AUV), and underwater vehicle-manipulator systems (UVMS) are being developed and deployed to enable the exploration. The oceanic environment is unstructured, uncertain, and dynamic in nature. As a result, every system (robotic or non-robotic) encounters various limitations when deployed in this complex environment. These limitations include poor sensing capability, immobility, poor spatial and temporal resolutions, susceptibility to weather, hazards in frequent deployments and recoveries, incapability in long-term operation, poor event response, lack of flexibility and availability, and high operating costs, to mention some of them. Some science missions such as mid-ocean ridge observations, study of canyon dynamics, and episodic event responses require both continuous monitoring and prompt deployment. Thus, to enhance the capability of exploration of the large oceanic environment, there is a need for prolonged operations of robotic systems (such as AUV) that avoids frequent deployment and recovery and can respond to any episodic event promptly.

Another vital issue is the cost involved: for example, the daily operating cost of a ship for AUV operations ranges between $20K-$30K. The next question that comes into mind is – "whether the weather conditions, availability of operators and ships, etc. will allow for daily operation of an ROV or a non-docking AUV for an extended period of time". But, many of the important scientific data and samples must be collected in rough weather conditions and at odd working hours. Thus, a docked AUV appears to be the one of best feasible solutions to address most of the challenging problems that is faced by other platforms in oceanic environment. A wide range of the science missions can be significantly benefited from new and/or improved sets of data and samples that will be collected by using a docked AUV. Therefore, an AUV docking system that allows an AUV to home and transfer data and power, as required for long-term underwater operations, appears to be one of the most important platforms for various scientific missions.

In the past several years, various research groups have designed, developed and tested different types of underwater docking systems for AUVs [2-9]. These docking systems are: (1) WHOI-MIT-EDC-AOSN dock, (2) WHOI-REMUS dock, (3) NRaD-Flying Plug, (4) FAU-Morpheus dock, (5) EURODOCKER, (6) ALIVE dock, (7) KRISO-KORDI dock, and (8) Kawasaki docking system. Most of them are mainly intended for intervention missions. Not a single autonomous docking system, to the best of our knowledge, is currently available for sustainable science missions. In fact, hardly any literature is available where one can find a detailed discussion on the utilization of a docked AUV for science missions. In many instances, scientists cannot figure out the most suitable tool/platform for their research work; on the other hand, technologists find it difficult to justify the use of AUVs and/or docking systems. Therefore, in this paper we discuss in details the importance of a docked AUV for science missions as an effort to bridge the gap between the science requirement and technological development. This, in turn, provides us the real motivation for designing and developing a sustainable autonomous docking system to fulfill various mission objectives of marine scientists.

II. SCIENCE MISSIONS

A wide range of marine scientists such as Physical Oceanographer, Biological Oceanographer, Molecular Biologist, Marine Microbiologist, Midwater Ecologist, Geologist, Ocean Chemist, Evolutionary Biologist, and Benthic Ecologist have been consulted to know how their science missions can be enhanced and fulfilled by using a docked AUV [10]. As a result, we have come up with twenty-seven strong cases where docked AUVs can significantly improve the quality and quantity of data and sample collection as compared to other oceanographic platforms such as mooring, ship, towed instrument, drifter, glider, and ROV. A sample data set (for the Case 1 type science mission) collected by MBARI's Dorado AUV is presented in Figure 1 below. Science missions can broadly be classified into two categories, based on the data collection methodology, namely: (1) *Data Collection* - in situ data collection such as temperature, salinity, depth, current, chlorophyll density, bioluminescence, etc., and (2) *Sample Collection* – collect samples quickly and then analyze the samples in a laboratory, process data and archive it; examples are microbial organisms, Harmful Algal Blooms (HABs), larvae, sediment, and rock sample collection. Here, we present the case studies that cover both the above mentioned categories excluding the force contact type data or sample collection.

CASE 1: Consequences of small to meso-scale upper ocean circulation phenomena in the coastal ocean.
CASE 2: Long-term observation of benthic creatures, mapping of vents, seeps, and clam beds.
CASE 3: Data and power transfer between Benthic Instrument Nodes (BINs) and Remote Instrument Nodes (RINs).

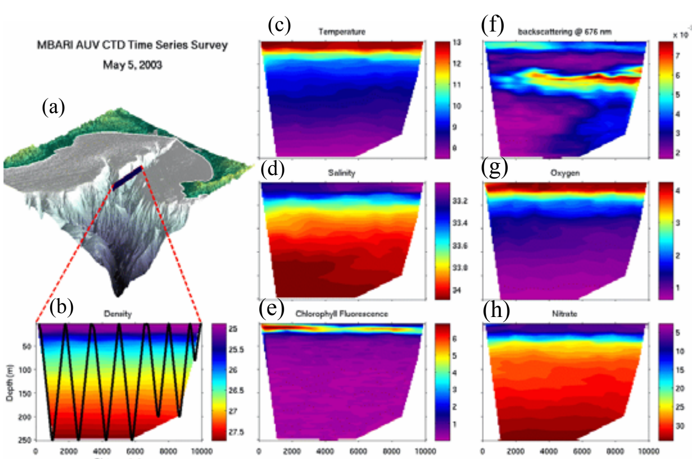

Figure 1: MBARI AUV CTD time series survey
(a) Monterey Bay & Canyon bathymetry, (b) water density, (c) temperature, (d) salinity, (e) chlorophyll fluorescence, (f) particle backscattering, (g) dissolved oxygen, and (h) nitrate.

CASE 4: Periodic and long-term monitoring of physical and biological processes in and around Monterey Bay Canyon System.
CASE 5: 3D time-series study of the California Current System (CCS).
CASE 6: High resolution 3D tracking of a particular volume of upwelling water in Monterey Bay (study of its dynamics, subduction at the edge of the California Current, impacts on ecosystem and climate).
CASE 7: Iron-fertilization experiment, its short-term and long-term effects on oceanic environment (physical, biological, and ecological) as well as effects on global climate (especially CO_2 budgeting).
CASE 8: Enhancement of California Cooperative Oceanic Fisheries Investigation (CalCOFI) time-series measurements.
CASE 9: High resolution spatial and temporal sample collection for monitoring and research of HABs.
CASE 10: Mapping and monitoring of bio-chemical agents in coastal water for developing a regional scale model for prediction of HABs.
CASE 11: High resolution (spatial and temporal) Eulerian survey and sample collection for microbial organisms (0.2-2.0 micron) in upwelling water in coastal area.
CASE 12: High resolution (spatial and temporal) Lagrangian survey and sample collection for microbial organisms (0.2-2.0 micron bacterioplankton/ picoplankton) in Monterey Bay.
CASE 13: Detection (event response) of submarine earthquake's epicenter, vent and eruption; and collection of microbial (0.2-2.0 micron) organism (archaea and bacteria) samples in the vicinity of the epicenter, vents, and eruption zones.
CASE 14: Bioluminescence measurement and sample collection in upper-water column (5m-50m) in coastal and offshore regions.
CASE 15: Bioluminescence measurement and sample collection in midwater column (500m-1500m).
CASE 16: Continuous and long-term observation of active mid-ocean ridge segment.
CASE 17: Continuous long-term observation and event response inside Monterey Canyon from a geological point of view.
CASE 18: Periodic and long-term survey and tracking of chlorophyll in the view of carbon export beyond the photic zone.
CASE 19: Periodic and long-term monitoring of ecosystem parameters in the oceanic environment.
CASE 20: Episodic event response and tracking and monitoring hydrothermal plume and associated organism spreading.
CASE 21: Mapping of seeps, vents and their habitats; and monitoring their behavioral pattern and migration, and evolution.
CASE 22: Integration of ESP with AUV for in-situ measurement of microbial organisms, HABs, and larvae.
CASE 23: Regular and long-term video transecting and low-light imaging in the midwater column.
CASE 24: Study the effects on midwater animals due to re-suspension of materials from turbid flow caused by the Monterey Canyon System.

CASE 25: Midwater surveying and monitoring in ice-covered Arctic and Antarctic regions using Lagrangian and Eulerian platforms.
CASE 26: Continuous recording of plankton (LHPR/CPR type instrument) with an AUV.
CASE 27: Hand-off assignment to multiple vehicles for tracking and monitoring a particular animal.

The above studied cases cover a wide varieties of marine science missions where the application of a docked AUV very significant. Based on the operational zone of the AUV, the above mentioned science cases can be categorized into two ways: (1) *Oceanic region wise* – three oceanic regions, namely, coastal, offshore & polar, and (2) *Position in the water column* – three levels in water column, namely, upper water column, midwater & benthic. A zonal distribution of these science cases is shown in Table 1. It is interesting to notice that about 50% of the total operation of the AUV is confined to the upper water column and about other two quarters are in the midwater and the benthic layers. The upper water column appears to be more dynamic and drawing more attention from the oceanographic community. However, the major sink and some of the main sources of the upper water column dynamisms lie in the midwater and the benthic zones. Therefore, a methodical study of the entire water column is significantly important to understand the complex oceanic phenomena.

Table 1: Distribution of science missions

	Oceanic region	**Position in water column**		
	Coastal (C), Off Shore (OS), Polar Region (PR)	Upper water column (0-250m)	Midwater (250m from surface to 250m above seafloor)	Benthic (<250m from seafloor)
CASE 1	C	100%		
CASE 2	C, OS, PR			100%
CASE 3	OS, PR		20%	80%
CASE 4	C, OS		20%	80%
CASE 5	OS	50%	40%	10%
CASE 6	C, OS	90%	10%	
CASE 7	OS	80%	20%	
CASE 8	C, OS	60%	30%	10%
CASE 9	C	100%		
CASE 10	C, OS	90%	10%	
CASE 11	C	100%		
CASE 12	C, OS	90%	10%	
CASE 13	OS		25%	75%
CASE 14	C, OS	100%		
CASE 15	OS		100%	
CASE 16	OS, PR		20%	80%
CASE 17	C, OS			100%
CASE 18	C, OS	90%	10%	
CASE 19	C, OS	50%	25%	25%
CASE 20	OS, PR	10%	60%	30%
CASE 21	C, OS, PR			100%
CASE 22	C, OS	70%	20%	10%
CASE 23	OS, PR	25%	65%	10%
CASE 24	C, OS	10%	80%	10%
CASE 25	PR	40%	40%	20%
CASE 26	C, OS	50%	50%	
CASE 27	C, OS, PR	25%	50%	25%
	Zonal Total (%)	**46.3**	**26.6**	**27.1**

Table 2: Representative science missions

Science mission	**Science data required**	**Range and resolution**	**Science sensors required**
CASE 1: Consequences of small to meso-scale upper ocean circulation phenomena in the coastal ocean.	Temperature, salinity, chlorophyll fluorescence, optical backscatter, nitrate, ocean current velocity, and dissolved O_2.	*Range:* horizontal ~20-100km^2; vertical ~0-300m (or near-bottom on the shelf). *Resolution:* horizontal sub-kilometer; vertical sub-meter. *Others:* synopticity <1day, at least twice in a week in different seasons.	CTD, ADCP, fluorometer, BBD/ OBS, O_2 sensor, ISUS.
CASE 4: Periodic and long-term monitoring of physical and biological processes in and around Monterey Bay Canyon System.	Temperature, salinity, ocean current velocity, particle abundance, seafloor surveying, visual observation (digital images), and dissolved O_2.	*Range:* horizontal ~50-100km^2; vertical 3-5m above the seafloor for observation, and up to ~300-500m above seafloor for benthic boundary layer observation. *Resolution:* horizontal ≤100m (for survey), ≤250m (for observation); vertical ≤50m (for observation). *Others:* once/twice a week for 2-3 years.	CTD, ADCP, BBD/OBS, multibeam sonar, low-light imager, O_2 sensor, fluorometer.
CASE 9: High resolution spatial and temporal sample collection for monitoring and research of Harmful Algal Blooms (HABs).	Temperature, salinity, ocean current velocity, nutrients, phytoplankton, zooplankton, particle scattering, and water sample.	*Range:* horizontal ~10km x 10km; vertical ~0-200m. *Resolution:* horizontal ~0.5-1.0km; vertical few meters. *Others:* regular observation, once HAB is detected then daily sampling for several weeks.	CTD, ADCP, OBS/BBD, ESP, fluorometer, pH sensor, O_2 sensor.
CASE 16: Continuous and long-term observation of active mid-ocean ridge segment.	Temperature, salinity, ocean current, dissolved O_2, nutrients, microbial organisms, and water sample.	*Range & Resolution:* for regular/ continuous observation - horizontal ~10km x 20km; vertical ~50-200m off the seafloor (single lawn mowing pattern). After events - horizontal ~20km x 60km; vertical ~50-1000m off the seafloor (lawn mowing patterns at 250m, 500m, 750m and 1000m layers off the seafloor). *Others:* synop-ticity <1day, for 2-4week time series after events.	CTD, ADCP, BBD/OBS, ISUS, ESP, multibeam sonar, digiscanner, pH sensor, O_2 sensor.
CASE 25: Midwater surveying and monitoring in ice-covered Arctic or Antarctic regions using Lagrangian and Eulerian platforms.	Temperature, salinity, ocean current, dissolved O_2, ice-thickness, particle distribution, chemical agents, abundance and distribution of midwater animal.	*Range:* horizontal ~5km-10km circle; vertical ~entire water column. *Resolution:* horizontal <200m; vertical<50m. *Others:* twice/thrice per week throughout the year.	CTD, ADCP, dissolve O_2 sensor, BBD/ OBS, color digital camera, (or high-resolution low-light camera).

Some of the representative science missions are presented in Table 2. These missions cover all the three oceanic regions namely: (1) the coastal regions – Case 1, 4 & 9, (2) the offshore regions – Case 4 & 16, and (3) the polar regions – Case 25. It is noticed that several sensors are common. This commonality will help us to accommodate more sensors on the AUV which in turn will widen the window for the science missions. The type of data collection, range and resolution of measurement vary significantly for different science missions. However, the parameters such as temperature, salinity and depth appear to be common for all the cases. On the other hand, parameters like CH_4, pH, imaging, etc. are mission dependent. The range of AUV operations may vary from a few kilometers to hundreds of kilometers). The spatial and temporal resolutions also vary widely depending on the mission. Additionally, the deployment duration of the docking system depends significantly on the science missions; it may range from a few weeks to months to years. There are some science missions, such as Case 8 (CalCOFI time-series), where multiple docking systems may be required. On the other hand, multiple AUVs will be required to pursue the science mission as mentioned in Case 27.

III. SCIENCE PAYLOADS

We have identified twenty-one different types of science sensors that are required to cover the above mentioned twenty seven cases. It does not include the sensors required for the AUV's navigation, guidance and control. A detailed list of these science sensors is provided in Table 3. The size, shape, weight, data collection and power consumption of these sensors vary significantly. The operating depth of these sensors ranges from 200m to 7000m. Therefore, one should be careful to select a suitable sensor suite for a docked AUV which may travel in deeper water for some other science missions. Some of the sensors such as a multibeam sonar, low-light imager, and a digital color camera not only draw enormous amounts of power but also accumulate huge amounts of data. They are significantly bulky. One of the main bottlenecks in technology is the high-density rechargeable energy storage for the AUV. As a matter of fact, the multibeam sonar array is quite expensive and dedicated for some special deployments, thus, it will not be considered for science payload analysis in this work (see cases numbering 2, 4, 16, 20 & 21). Since ESP (gen-2), BiOSA, Splat screen, and Multibeam sonar are in final development phase, some data for these sensors are approximated.

Table 3: Science sensors

Science sensor	Size (mm)	Volume (cc)	Weight in air (kg)	Weight in water (kg)	Power consumption (W)	Average data/km @3kt (MB)	Average data/hour (MB)	Max. depth rating (m)
CTD (SBE 37)	67.3x526.5	1872	4	2.4	3.5	0.083	0.456	7000
ADCP-DVL unit (RDI)	225.3x218	8687	11.6	6.7	8	0.92	5.051	6000
OBS (Chlorophyll fluorescence and particle backscattering-HS2)	117x230	2472	4	1.5	1	0.648	3.558	4000
Transmissometer (Particle size distribution, backscattering; C-Star)	93x64x490	2916	2.2	0.9	0.5	0.173	0.950	6000
ECO-BBD (Optical backscattering)	63x170	530	1.3	0.75	0.5	0.079	0.434	6000
LISST (Particle size distribution)	125.7x955	11845	16.3	9	2	0.201	1.103	5000
FRR Fluorometer (Phytoplankton photo-efficiency)	160x990	19895	23	15	9.1	0.154	0.845	500
Dissolved O_2 sensor (SBE 43)	52x295	626	1.5	0.7	1.4	0.083	0.456	7000
ISUS (Nitrite, Nitrate, Bi-sulphide, Bromide, Dissolved Carbon)*	127x508	6432	8.3	1.5	8	0.331	1.817	4000
BiOSA sensor package (O_2, pCO_2, pH, Fluorescence)*	70x500	1923	10	5	10	0.066	0.362	4000
pH sensor (SBE 18)	48x294	532	1.5	0.7	0.2	0.083	0.456	1200
CH_4 sensor	50x162	318	1.5	0.5	9	0.036	0.198	2000
pCO_2 sensor	127x635	8040	8.3	2	10	0.331	1.817	4000
MBBP (Bioluminescence)	102x165x305	5133	3.5	1	6	0.291	1.598	500
Splat screen (Bioluminescence)*	225x650	25831	19	10	145	182	999.18	4000
B&W Low-light Imager	220x650	24696	18.5	10	145	182	999.18	4000
Color digital Imager	220x650	24696	19.5	10	155	183	1004.67	4000
Multibeam sonar system*	533x1829	407885	317.5	-1.4	240	600	3294.00	6000
ESP sampler (Phytoplankton species, HABs, microbials, larvae)*	300x1000	70650	25	8	8	0.91	4.996	4000
LHPR/ASP (Plankton recorder)	140x235x291	9574	12.75	4	45	0.75	4.118	200
Water sampler (>2500m on request)	146x623	10425	8	0	0.5	0.3	1.647	2500

CTD – Conductivity Temperature Depth
ADCP – Acoustic Doppler Current Profiler
DVL – Doppler Velocity Logger
ECO – Environmental Characteristic Optics
BBD – Bio-optical Backscattering (Deep)
OBS – Optical Backscattering Sensor
LISST – Laser In Situ Scattering and Transmissometer
FRR – Fast Rate Repetition
BiOSA – Biophysical Oceanographic Sensor Array
MBBP – Multipurpose Bioluminescence BathyPhotometer
ESP – Environmental Sample Processor
LHPR – Longhurst Hardy Plankton Recorder
ASP – Autonomous Plankton Recorder
* Sensors being developed at MBARI (www.mbari.org)

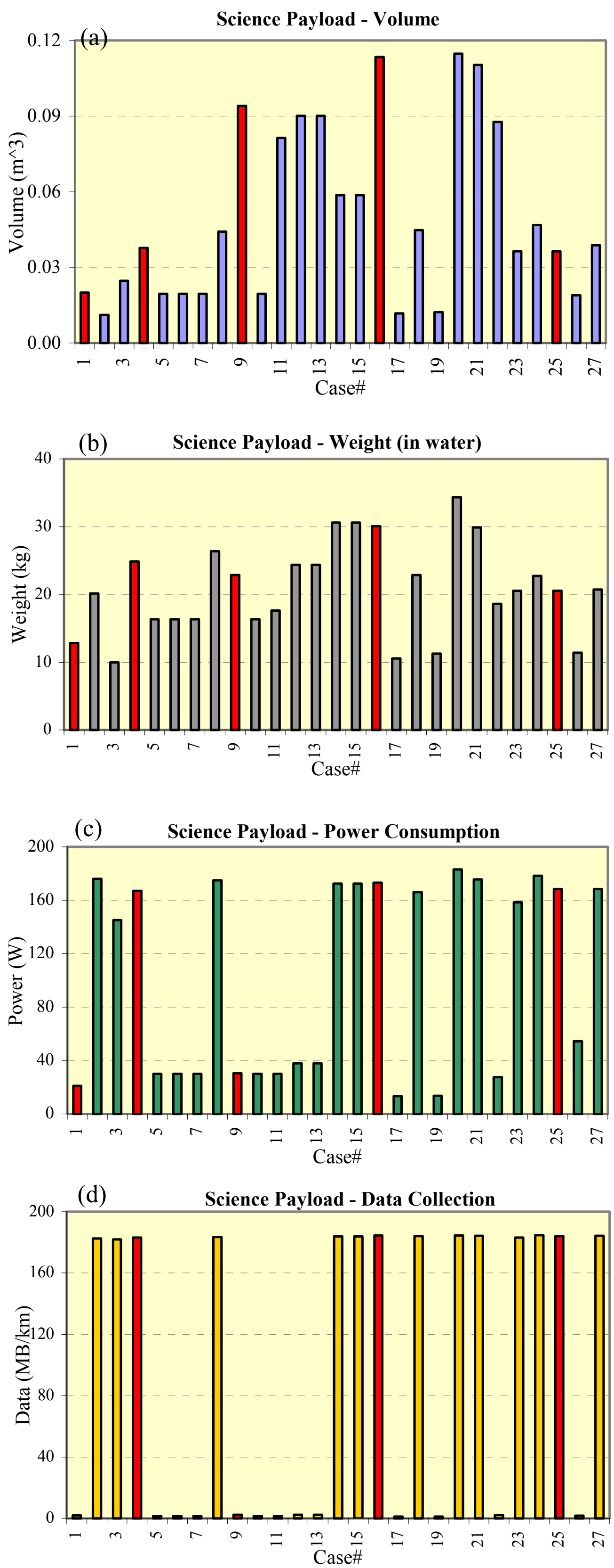

Figure 2: Science payloads for docked AUV

Note: The bars in RED color indicate the five representative science cases (Case #1, 4, 9, 16 & 25). Here, the multibeam sonar has been excluded.

The major issues regarding the science payloads are the total sensor suite's volume, weight (in water), data collection, and power consumption. Bar charts of the science payloads are provided in Figure 2(a)-(d) (excluding the multibeam sonar). From these plots it is noticed that each case-wise sensor suite's volume varies from $0.011m^3$ to $0.11m^3$, weight (in water) varies from 10kg to 34.35kg, power consumption ranges from 13.4W to 183W and average data collection ranges from 1.16MB/km to 184.59MB/km. The size of data collection may vary significantly depending on the mission plan of the scientist. Furthermore, additional space will be required for sensor mounting arrangements. However, it may not be possible to accommodate all the sensors into a single AUV. Thus, it is evident that a significant amount of trade off studies is required to decide how many different science sensors would be most suitable to be on an AUV. It will depend upon the importance of the science missions in a particular oceanic region and which scientists are involved. A detailed case wise science payload has been presented in Table 4 (including the multibeam sonar, see Appendix).

IV. AUV DOCKING SYSTEM

One of the main obstacles for the exploration of the vast oceanic environment is the shortcoming of the present technology, i.e., non-availability of affordable and suitable platforms that can be deployed for various science missions. For the last several decades marine scientists are using different platforms such as ships, towed instrument packages, and buoys. With the advancement of technology, some advanced platforms such as drifters, gliders, ROVs and most recently AUVs have been developed to enhance the capability of underwater exploration and data collection. Still we need to have a kind of affordable platform from which the scientists will be able to perform high resolution (both temporal and spatial) survey and data collection for a prolonged period of time at any oceanic conditions. This drives us toward the development of AUV docking systems which can be deployed for extended times ranging from months to years, data can be uploaded, instructions can be downloaded and the battery can be recharged.

In the past decade, several different types of AUV docking systems have been designed, developed and tested by researchers [2-9]. However, none of the docking systems was deployed/tested for prolonged operation. A very few of them have been tested for all the capabilities such as data/instruction transfer and battery charging. Hardly any of these docks has been tested for reliability, survival in harsh oceanic environments, or prolonged science missions. Maximum docking success rate of one of these docks has been reported as 85%, which is far from the expectation for sustainable science missions in an autonomous/unattended manner (or with minimum supervision from lab/shore).

The docking system consists of several subsystems, namely: (1) the AUV, (2) the homing & terminal guidance system, (3) a mechanical structure, (4) the capturing & latching arrangement, (5) the data & instruction transferring system, (6) a battery recharging system, (7) dock control module, and (8) surface expressions/cable for communication to shore/lab. The relative merits and demerits of the important subsystems are discussed below.

Mechanical System/Structure

a) Unidirectional: cone/funnel/cage type (REMUS Dock/ NRaD-Flying Plug/ EURODOCKER/ KRISO dock)

Pros: Good protection for a docked AUV, easy to make connections for data & power transfer.

Cons: Single direction of entry, needs a priori knowledge of dock orientation, big size, heavy, requires fairly accurate AUV approach, problem with AUV approaching cross-current, weathervaning may result in cable wind-up, bio-fouling, may be a natural home for marine creatures, big structure may change the flow pattern around the dock which changes the added-mass of the AUV and drag on the AUV resulting in control problems.

b) Multi-directional: pyramid type (FAU-Morpheus dock)

Pros: Four directions of entry, small size, light-weight.

Cons: Seafloor mounting, problem with marine growth on dock-gate, nose-diving of AUV, poor protection of docked AUV, breaking of stinger, possibility of damaging dock & AUV.

c) Omni-directional: pole & latch type (WHOI/MIT-AOSN Dock)

Pros: Omni-directional entry, AUV can be oriented in the direction of the current, not a natural home for marine creatures, hardly any winding up problem.

Cons: Imposes bulky hardware on the AUV, increases weight and drag, difficult to make connections for data and power transfer, needs to put homing beacon quite apart (top/ bottom) from the docking target, binding on the pole, may change the flow pattern around the dock & AUV which changes the added-mass and drag on the AUV, does not provide very good protection for the docked AUV.

d) Hook & wire type (Kawasaki docking system)

Pros: Simple, light weight, less bio-fouling.

Cons: Directional entry, susceptible to cross current, requires cross-thruster, seafloor mounting, proximity to seafloor may cause some sensing problems.

Homing and Terminal Guidance

a) Electromagnetic Inductive

Pros: High update rates, very robust under most all oceanic conditions, provides more precise control of AUV in the final stage of homing, convenient for a fixed entrance dock.

Cons: Large size, heavy, susceptible to magnetic anomalies and sharp salinity gradient.

b) Optical (Beacon Following)

Pros: Simple, robust, high accuracy, high update rate, does not fail if a good set up is provided.

Cons: Short range, visibility restricts the bounds of operation, susceptible to line of sight, fouling and presence of other light sources may create problems.

c) Optical (Video Image)

Pros: Good in clear water, moderate update rate.

Cons: Short range, visibility restricts the bounds of operation, susceptible to line of sight, fouling and presence of other light sources may create problem.

d) Acoustic (USBL)

Pros: Long range, quite accurate in short range.

Cons: Low update rate, susceptible to ocean surface, bottom or presence of other acoustic reflector, poor response very close to dock, in shallow-mid water applications – may have ambiguity problem multi-path).

Data Transfer

a) Inductive

Pros: Given a proper alignment transfer rate is good.

Cons: Susceptible to core alignment, puts bulky hardware on the AUV.

b) Optical

Pros: Physical alignment tolerances are not critical, high transfer rate.

Cons: Susceptible to fouling, poor visibility and presence of other sources of light, require power to drive laser/LED.

c) Direct/Conductive

Pros: Fast, easy, put less hardware on AUV, can use 100base-T ethernet.

Cons: Difficult to insulate, require excellent rotational alignment, susceptible to fouling and corrosion.

d) Acoustic: Acoustic modem can also be used for data transfer and communication.

Battery Charging

a) Inductive

Pros: No exposed connector in seawater, effective under proper core alignment.

Cons: Susceptible to alignment of the core, puts bulky hardware on the AUV, relatively less efficient, may create problems when power and data transfer are done simultaneously.

b) Direct/Conductive

Pros: Fast, efficient, simple and reliable.

Cons: Difficult to insulate, susceptible to fouling and corrosion.

Now, we are ready to identify the main functional requirements for an AUV docking system for science missions.

Functional Requirements of an AUV Docking System

The dock -

- Shall be capable of capturing and releasing both hovering and non-hovering AUVs
- Shall be capable of downloading data and uploading instructions reliably
- Shall be capable of supplying power to the AUV
- May assist an AUV in locating the dock and help in terminal navigation to capture mechanism
- Shall be capable of responding to nearby events promptly
- Shall be capable of being deployed in both shallow and deep water (up to about 4500m depth)
- Shall be capable of about 52 dockings per year
- Shall be maintainable on the same schedule as its host
- Shall be deployable from relatively smaller vessels
- Shall be capable of surviving in harsh oceanic environments

The docked AUV -

- Shall be capable of navigating and homing accurately to the docking position
- Shall be capable of capturing and latching with the dock
- Shall make reliable connections with the dock for data and power transfer
- Shall be capable of receiving instructions from the dock
- Shall be capable of transferring data to the dock
- Shall be capable of operating in deep water (~4500m)

- Shall be capable of covering a long range (>100km for round trip)
- Shall have high navigational accuracy
- Shall be able to accommodate both navigational and science sensors
- Shall be capable of charging batteries efficiently and safely
- Shall be capable of responding to nearby events promptly
- Shall be capable of reliable operations for at least one year
- Shall be deployable from relatively smaller vessels
- Shall be relocateable for at least seven days if not attached to the dock

V. CHALLENGES

Underwater exploration efforts are heavily constrained by many technological, environmental and other issues. Some of the technological issues are: limited sensor capabilities (range, update, accuracy, availability) because of poor signal to noise ratio, dense medium (water), continuous change in physical parameters (temperature, conductivity, pressure, visibility, current, drag), and slow progress in sensor development. The environmental problems are: marine growth, living creatures, corrosion, salinity, high sea-state, dynamism and uncertainty. Some of the other compelling issues are: insufficient funding, lack of public awareness, sharing/ conflicting deployment areas with fisheries and entertainment agencies. Therefore, with the limited technological methods/ tools, it is highly challenging to design and develop a general purpose docking system that can serve the purpose of a broader range of marine scientists.

VI. SOLUTION APPROACHES

There is no analytical or straight forward solution to this complicated problem. However, in-depth analysis and careful tradeoff studies along with incremental technological advancement can help us in designing and developing a sustainable docking system. In the foregoing discussion, we have observed various facets of the science, technology and environment regarding the development of a state-of-the-art docking system for science missions in the vast and unstructured oceanic environment. These aspects are posing a daunting task to decide which zone is the most suitable to mount the dock, how reliably the AUV can be docked, how data and power can be transferred, and what are the most appropriate subsystems required to satisfy numerous requirements of the scientific community considering the technology, the harsh oceanic environment and other challenges. Unfortunately, there is no clear-cut or rule based solution to this critical problem. Therefore, it seems better to pursue a sort of *fuzzy approach* that might be able to produce a prudent solution which converges to a suitable decision quickly [11].

VII. CONCLUSIONS

In this paper, we have discussed various marine science missions that can be accomplished and enhanced using a docked AUV system. An effort has been made to project how the science requirements motivate the technological development for a daunting task like AUV docking system development. A list of science sensors and case wise detailed analysis of science payloads are presented for the science missions which in turn help us in driving functional requirements for the docking system. A brief discussion on available docking systems and various subsystems have been included. We have also highlighted the technological, environmental and other challenges. Finally, we pointed out possible solution approaches.

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APPENDIX

Table 4: Science payload for docked AUV

	Science sensors	Volume (m^3)	Weight in air (kg)	Weight in water (kg)	Power consump-tion (W)	Average data/km @3kt (MB)	Average data/h (MB)
CASE 1	CTD, ADCP, fluorometer, BBD/OBS, O_2 sensor, ISUS	0.0200	29.20	12.85	21.00	2.06	11.31
CASE 2	CTD, BBD/OBS, ISUS, multibeam sonar, low-light imager, pH sensor, O_2 sensor, CH_4 sensor [BiOSA]	0.4437	361.12	18.79	416.00	782.60	4296.8
CASE 3	Digital imager [Optional - CTD, BBD/OBS, O2 sensor, fluorometer]	0.0247	18.50	10.00	145.00	182.00	999.2
CASE 4	CTD, ADCP, BBD/OBS, multibeam sonar, low-light imager, O_2 sensor, fluorometer [BiOSA]	0.4456	362.92	23.49	407.00	783.15	4299.5
CASE 5	CTD, ADCP, BBD/OBS, ISUS, fluorometer, pH sensor, O_2 sensor [BiOSA]	0.0194	35.20	16.35	30.00	1.48	8.12
CASE 6	CTD, ADCP, BBD/OBS, ISUS, fluorometer, pH sensor, pCO_2 sensor, O_2 sensor [BiOSA]	0.0194	35.20	16.35	30.00	1.48	8.12
CASE 7	CTD, ADCP, BBD/OBS, ISUS fluorometer, pCO_2 sensor, pH sensor, O_2 sensor [BiOSA]	0.0194	35.20	16.35	30.00	1.48	8.12
CASE 8	CTD, ADCP, BBD/OBS, ISUS, low-light imager, fluorometer, pH sensor, pCO_2 sensor, O_2 sensor [BiOSA]	0.0441	53.70	26.35	175.00	183.48	1007.3
CASE 9	CTD, ADCP, transmissometer (or OBS/BBD), ESP, water sampler, fluorometer, pH sensor, O_2 sensor [BiOSA]	0.0941	59.90	22.85	30.50	2.36	12.95
CASE 10	CTD, ADCP, OBS/BBD, ISUS, fluorometer, pH sensor, O_2 sensor, [BiOSA]	0.0194	35.20	16.35	30.00	1.48	8.12
CASE 11	CTD, BBD/ OBS, ISUS, ESP, fluorometer, pH sensor, O_2 sensor [BiOSA]	0.0814	48.60	17.65	30.00	1.47	8.06
CASE 12	CTD, ADCP, OBS/BBD, ISUS, ESP, fluorometer, pH sensor, O_2 sensor [BiOSA]	0.0901	60.20	24.35	38.00	2.39	13.12
CASE 13	CTD, ADCP, BBD/ OBS ISUS, ESP, pH sensor, O_2 sensor, pCO_2 sensor [BiOSA]	0.0901	60.20	24.35	38.00	2.39	13.12
CASE 14	CTD, ADCP, MBBP, LISST, low light imager, ISUS	0.0587	62.20	30.60	172.50	183.83	1009.2
CASE 15	CTD, ADCP, MBBP, LISST, low light imager, ISUS	0.0587	62.20	30.60	172.50	183.83	1009.2
CASE 16	CTD, ADCP, BBD/OBS, ISUS, ESP, multibeam sonar, digiscanner, pH sensor, O_2 sensor	0.5213	387.72	28.69	413.20	784.41	4306.3
CASE 17	CTD, ADCP, OBS/ BBD (or transmissometer), multibeam sonar, O_2 sensor.	0.4196	335.92	9.19	253.40	601.17	3300.4
CASE 18	CTD, ADCP, fluorometer, BBD/ transmissometer, and BiOSA/ ISUS, structured light imaging (low-light)	0.0447	47.70	22.85	166.00	184.06	1010.5
CASE 19	CTD, ADCP, BBD/ OBS, O_2 sensor, and pH sensor	0.0122	19.90	11.25	13.60	1.25	6.85
CASE 20	CTD, ADCP, ISUS, dissolve O_2 sensor, CH_4 sensor, pH sensor, ESP, multibeam sonar, BBD/ transmissometer and digiscanner (low-light imaging)	0.5227	396.22	32.99	423.00	784.39	4306.3
CASE 21	CTD, ADCP, multibeam sonar, transmissometer, digiscanner, ESP, dissolve O_2 sensor, pH sensor, and CH_4 sensor	0.5182	383.32	28.54	415.60	784.29	4305.7
CASE 22	CTD, ADCP and ISUS along with the ESP	0.0876	48.90	18.60	27.50	2.24	12.32
CASE 23	CTD, ADCP, dissolve O_2 sensor, BBD/ transmissometer, high-resolution color camera, (or low-light camera)	0.0364	36.90	20.55	158.40	183.17	1005.6
CASE 24	CTD, ADCP, dissolve O_2 sensor, transmissometer, pCO_2 sensor, color digital camera (or low-light camera)	0.0468	47.10	22.70	178.40	184.59	1013.4
CASE 25	CTD, ADCP, dissolve O_2 sensor, BBD/ transmissometer, sonar array, color digital camera, (or low-light camera)	0.0364	37.90	20.55	168.40	184.17	1011.1
CASE 26	LHPR type instrument along with CTD, ADCP, and O_2 sensor	0.0189	25.85	11.40	54.40	1.75	9.62
CASE 27	CTD, ADCP, transmissometer, sonar array, O_2 sensor, color digital camera, (or high-resolution low-light camera)	0.0388	38.80	20.70	168.40	184.26	1011.6

Note: BiOSA sensor package has been included instead of Fluorometer, O_2, pCO_2, pH sensors and multibeam sonar has been included during computation in Table 4. Sensor data are taken from Table 3. BBD is considered where appeared as an option for OBS or transmissometer.