The use of Low-Cost ROV for Deep-Sea Mineral and Ore Prospecting

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Abstract
With the development of ever more powerful micro-computers, the cost and capabilities of robotic systems for environmental surveying using remotely control systems continues to decrease and improve. Historically, submarine exploration was restricted to companies or organisations with considerable finances and resources; however, the last decade has seen the advent of 'low cost' remotely operated vehicles (ROV). These cost anywhere from $400-$40,000 and provide an opportunity for wider participation in ocean exploration. However, with 60% of the world's seafloor lying at depths in excess of 1000m and current low cost ROVs typically depth limited to just 100m, there is presently an inability to "go deep" affordably. This review assesses the state of the art for deep ROV technologies and identifies the primary technological hurdles to overcome in order to facilitate proliferation of low cost ROVs for deep ocean exploration with an emphasis on their application to mineral and ore prospecting.

Highlights

- Scarcity of base metals and minerals on land driving a growing interest in deep ocean prospecting
- Estimated market value of metals in the seabed globally is over $2 trillion per annum
- The associated costs of technologies for prospecting ore can be significantly reduced

Keywords
Remotely Operated Vehicle (ROV); Seafloor Massive Sulfide (SMS); Deep-Sea; marine technology; Marine Mining

1. Introduction

Terrestrial mining has been a practice since the beginning of civilization; people have extracted stone, ceramics and, later, metals found close to the Earth's surface. The oldest known mine on archaeological record is the "Lion Cave" in Swaziland, which radiocarbon dating shows to be about 43,000 years old. (Williams, 1980). Fast forward to the 21st century, the mining industry, while still large, has undergone a significant size reduction especially in Europe. The European mining industry has seen a 35.99% decrease from 1984-2014 (Reichl *et al.*, 2016). Until the late 1960s, coal was the main source of energy produced in the UK, peaking at 228 million tonnes in 1952. Ninety-five per cent of this came from 1,334 deep-mines that were operational at the time, with the rest arising from around 92 surface mines. (GOV UK, 2014).

Globally, mining companies were 28% less efficient in digging and moving a ton of total material from 2004 to 2014 meaning mining productivity has declined 3.5 percent per year according to the MineLens Productivity Index. (Lala et al., 2015). The global exploration budget between 2012 and 2015 has seen a 60% decrease in early-stage exploration, between 2014 and 2015 exploration spend decreased globally. The largest budget decrease occurred in Africa with a 30%, or $500-million, decrease in exploration spend from the United States Geological Society (USGS).(Hancock, 2016). The smallest decreases occurred in the US, which lost 6%, or ~$44-million, in exploration spend. Latin America remained the region with the largest mineral exploration budget. (Hancock, 2016). However, Australia topped the list of active exploration sites, followed by Canada and Latin America. There were 1,930 active exploration sites in 2015 and about 24%, or 463, of the sites were in

Australia. (Hancock, 2016). The global trend is that terrestrial resources are getting harder to exploit, most of the 'easy' deposits have already been exploited and hence the costs of minerals and metals are continuing to rise. This leads to high value deposits in the ocean over the terrestrial high volume ones. Whilst terrestrial deposits tend to be vast they are of a relativity low economical value but due to quantity makes them economically viable, the deposits in the ocean are the opposite generally low quantity but high value.

2. New ventures: Untapped Treasures in the Deep-Sea

By 2020, 5% of the world's minerals, including cobalt, copper and zinc could come from the ocean floors. This could rise to 10% by 2030. Global annual turnover of marine mineral mining can be expected to grow from virtually nothing to ~$5 billion in the next 10 years and up to ~$10 billion by 2030 (EC, 2012). This quote outlines the requisite for ocean exploration, and justifies the growing technological activity aimed at contributing to our global oceanic exploration capability.

A small number of mining companies are working on overcoming the perceived challenges of submarine mining, and developing island nations, in particular, are watching with strategic interest particularly those with substantial economic exclusion zones (EEZs). As typically this is due to the stretch of their insular shelf, the shelf surrounding islands, that allows them to claim rights to a 200 nautical miles limit beyond the shelf giving them vast areas of sea floor for potential mining. The estimates of the total resources available in the world oceans are from the areas of international water which have been claimed, excluding the minerals lying within the EEZ of certain countries such as Papua New Guinea and New Zealand (Gleason, 2008), (Sharma, 2011). As the demand for base metals and minerals outgrows what terrestrial deposits are able to provide, new technological and technical developments are helping to drive forward this new sector of the mining industry (Deep Sea Mining summit, 2016).

Deep-sea mining is not a new concept. In the mid-1960s the prospect of deep-sea mining was first highlighted by the publication of J. L. Mero's Mineral Resources of the Sea. (Mero, 1965), (Glasby, 2000). The book presented the idea of relatively limitless supplies of cobalt, nickel and other metals that could be found throughout the planet's oceans as shallow sea floor deposits. From the 1960s to 1984 an estimated $650-million had been spent on deep sea mining globally, with little or no return for nearly 50 years (Glasby, 2000). Deep-sea mining has remained a high-risk, expensive and experimental industrial activity focusing on exploiting one of the most fragile, unexplored areas of our planet.

Currently the 'working class' ROV is used as the standard to prospect and identify potential areas of minerals and ore. For example, between 2009-2010, a working class ROV (Perry Slingsby built T200), was used by Nautilus Minerals Inc. to test for sea floor massive sulphide (SMS) deposits in the Bismarck Sea, Papua New Guinea (PNG) identifying and sampling from five new SMS systems (Solwara 12, 13, 14, 16 and 18). Another such project supported by the Research Council of Norway from 2008 to 2010, led to the discovery of the first black smoker vent field at the AMOR Arctic Mid-Ocean Ridge. The vent field was located and sampled using a Bathysaurus XL ROV system provided by Argus Remote Systems. The technology for effective and efficient extraction on an industrial scale is still under development but at the moment prospecting is a bottle.

2.1 Deep-Sea Mining Operations

The discovery of submarine hydrothermal vents at the Galapagos Rift in 1977 triggered a period of intensive seafloor exploration that continues today. Within five years of finding the first black smokers at 21°N East Pacific Rise, more than 50 sites of hydrothermal venting and seafloor massive sulfide deposits had been identified on the mid-ocean ridges. By the early 1990s more than 150 sites had been discovered (Rona and Scott, 1993). Although most of the deposits have been found on the mid-ocean ridges (65%), many also occur along volcanic arcs (12%) and at backarc spreading centres (22%). (Hannington *et al. 2011*). There are three types of potentially economically viable mineral resources: sea-floor massive sulphides (SMS), cobalt-rich ferromanganese crusts, and polymetallic (manganese) nodules.

Since the discovery of hydrothermal smokers, more than 300 sites of high-temperature hydrothermal venting have been identified, but significant massive sulphide accumulations have only been found at 165 of these sites (figure 3), including at least 25 sites with active high-temperature black-smoker venting and associated mineral deposits. In addition, many polymetallic sulphide deposits are found at sites that are no longer volcanically active. (Ascension Holdings, 2016). Plume studies and deposit occurrence models suggest that anywhere from 500 to 5000 vent fields and associated mineral deposits may exist globally. (Hannington *et al. 2011*).

Seafloor Massive Sulfide (SMS) deposits have been found over a wide range of water depths, ranging from less than 1000 m to more than 4000 m. They accumulate in areas where new ocean crust is forming, such as seafloor spreading centres like the mid-Atlantic ridge. The generation of hydrothermal fluids heated by the molten rock (magma) beneath the crust, has been observed to form 'black smokers', which escape the seafloor at temperatures up to 400° Celsius and pH2. The prior migration of these hot acidic fluids through the oceanic crust, leaches metals from felsic minerals, and interactions with other hot fluids rising from magma bodies. Upon venting into the cold oceanic waters, the rapid cooling & dilution causes immediate precipitation of metals from the fluid to form dense plumes of particles referred to as smokers. Principally these metals are precipitated as sulphide minerals, including galena (lead), sphalerite (zinc) and chalcopyrite (copper), silver and gold, barium, nickel and other trace metals (Baker and German, 2009). That settle locally from suspension to form an accumulation of sulphide material on the seafloor. Over long periods significant deposits of these minerals can accumulate; referred to as a sea floor massive sulphide (SMS) deposits. SMS deposits commonly carry high concentrations of copper (chalcopyrite) and zinc (sphalerite) in addition to gold and silver (Ascension Holdings, 2016) & (Nautilus Minerals, 2016). They are the modern-day equivalents of ancient 'land-based' Volcanogenic Massive Sulphide (VMS) deposits which are prized for their grade and economic worth. (Nautilus Minerals, 2016).

Cobalt-rich ferromanganese crusts are hard, solid layers up to 25 centimetres thick that form when manganese and iron precipitate out of cold seawater. These crusts are firmly adhered to the surfaces of sea mounts, ridges and plateaus at water depths of 400-7,000 metres. They mainly contain cobalt, nickel, as well as other traces of rare earth elements and have the potential to provide 20% of the global cobalt demand (Ramirez-Llodra *el at.* 2010). Initial licences issued by the International Seabed Authority are targeted at the flat tops of seamounts (guyots) in the western Pacific Ocean where thick cobalt crusts have been formed. (ISA, 2013a; b).

In addition to SMS deposits and Cobalt-rich ferromanganese crusts, the world's undersea reserves are estimated to include 10 billion tonnes of polymetallic nodules. These are rocky lumps that vary from between five and ten centimetres in size. They form from iron and manganese hydroxides at depths between 4,000 and 6,500 meters. The metals within – including nickel, copper, and lithium, among others – hold commercial value for many technological applications. The most significant known concentration of these deposits can be found in the Clarion Clipperton Zone of the equatorial Pacific. (UNEP, 2014).

It is this substantial & valuable untapped resource that has recently attracted the interest of the international mining industry and several countries, including China, Japan, Korea, Russia, France, and Germany. (Hannington et al. 2011). The International Seabed Authority has already issued 26 licenses to explore 1.5 million square kilometers of the Pacific Ocean floor, as well as additional swathes of the Atlantic and Indian Oceans, and the Red Sea. Additional areas are being opened to exploration on a regular basis. (Earthworks, 2015).

Whilst many are keen to prospect for valuable ore deposits, currently there are few with the ability to actually capitalise on them. One such company, the afore mentioned Nautilus Minerals Niugini Limited (Nautilus) is advancing a proposal to develop the “Solwara 1 Project” (Figure 5) and has been awarded the world’s first licence (20-years issued in January 2011) to operate a deep-sea mine. This project involves the recovery of high-grade polymetallic SMS deposits that are located at water depth of approximately 1,600 m on the floor of the Bismarck Sea, New Ireland Province, Papua New Guinea (PNG), ~ 50 km north of Rabaul: Latitude 3°47’25.06”S, Longitude 152°05’41.65”E. (Nautilus Minerals Inc. 2010). The company estimates that Solwara 1 exploitation is likely to cost ~$407-million, excluding the vessel hire, and is scheduled to commence in 2018. Based on the current resource estimates, the Project has a mine life of approximately 30 months, with a minimum extraction of 5,900 tonnes per day. However, this could extend to five years if additional mineralisation is discovered at the site (Nautilus Minerals, 2008). The copper ore from the site alone is expected to net over ~$44 billion over the course of the mine’s life.

On average, the most promising of these deposits (SMS) will break down to about 30% manganese, 1.5% nickel, 1.5% copper, and 0.3% cobalt. In short, the ocean floor is home to a staggering quantity of useful minerals - and these deposits also contain smaller traces of rare earth elements. The estimated value of all metals from all the deposits in the seabed globally is worth $2 trillion per annum and has the potential to significant profits for any mining company able to support and minimize the up front and operation costs profit providing the operation costs can be minimized. (Lodge, 2015).

2.2 Environmental/Social/Political concerns

The project, Solwara 1, is not without opposition due to the vastly unexplored nature of the earth’s sea floor. The science community especially environmentalists believe that resources needed for independent scientific assessment at those depths are essentially non-existent. Hence, there is controversy as to the impact of mining to the benthic flora and fauna as well as the fisheries because so little environmental research has been completed. Our ability to anticipate the impacts of mining is limited by the lack of knowledge about deep sea biodiversity, ecosystem complexity, and the extent of environmental and social impacts from mining operations. Ecologically speaking, Solwara 1 is a huge environmental, financial and technological experiment. Many of the marine organisms that could be affected are yet to be discovered, let alone studied. (Earthworks, 2015). It is also important that there are policies in place guiding mineral extraction, rooted into adaptive management – allowing for the integration of new scientific data alongside advances in technology. Current governance mechanisms for international waters and seabed policy need to be strengthened. The precautionary approach should be used to avoid repeating instances of well-known destructive practices associated with conventional mining.(UNEP, 2014).

The Nautilus minerals group have already expressed that there is an important need to understand the biology and potential impacts of mining on the hydrothermal vent communities and the surrounding seafloor, where knowledge of the dynamics of recruitment, growth, diversity and geographic interrelationships is still under development. (Nautilus Minerals, 2008).

The facilities needed for the environmental research are provided by the same oceanographic vessel and ROV seafloor sampling equipment as needed for mineral exploration of the seafloor. Once the vessel and ROV facilities are mobilised for exploration, Nautilus has allocated time for research to be conducted on the necessary environmental studies, by independent institutions to name a few; University of Toronto, Scripps Institution of Oceanography, College of William and Mary, Duke University and Rabaul Volcano Observatory. (Nautilus Minerals, 2008).

Within Papua New Guinea, the local coastal communities have expressed serious concern for the quality of the marine environments and protection of the reefs and thus the fisheries upon which they depend, as well as protecting the megafauna that frequent these areas such as whales, sharks and turtles. There is also opposition within the wider community as US based consultancy firm Earth Economics (EE), which Nautilus commissioned to conduct an Environmental and Social Benchmarking Analysis (ESBA) has been criticized for the valuing the ecosystem goods and services provided by the Solwara deep sea and ecosystem at zero (Earthworks, 2015).

The maintenance of the health of the marine ecosystem is something that the project must adhere to protecting under the guidelines of the Environmental Impact Assessment (EIA). Therefore the project must demonstrate that shallow water animals are not exposed to the mineralised materials of the seafloor which would be detrimental to their health. Nautilus have devised a way to minimize these impacts, proposing to discharge the water from dewatering (and some entrained sediment) close to its point of original extraction at depths 25 to 50 m above the seafloor, and not at shallow or mid-water depths. (Nautilus Minerals, 2008). Figure 4 shows other sources of potential impact from offshore mining operations. ROVs could potentially be used as a monitor for mine activity before, during and after the mines operation life time, helping to give real time data to the effects and allow for practical and responsive mitigation of any potential impacts.

Potential impacts to surface marine pelagic animals are therefore only from the presence of the surface vessels and their normal operations, including lighting, underwater noise and routine discharges in compliance with MARPOL (The International Convention for the Prevention of Pollution from Ships). These impacts are then similar to shipping generally and to the exploration surveys already completed, and therefor extensively studied and understood such that the most extreme impacts can be mitigated. (O'Brien, 2009., Talley, 2003., Boehlert & Gill, 2010.).

2.3 Financial Accessibly

The use of low cost and open source ROV looks set to significantly the reduce substantial cost of industry standard working class ROVs and allow much wider participation in deep ocean exploration. For financially impaired countries, such technology will enable them to survey and evaluate their own seabed resources, thus preventing companies from unfairly exploiting them. As well as any reduction in costs for mining companies will help to minimise operational costs and maximize profits. Nautilus are already in talks for supplying 1.1 million tonnes of unrefined copper ore from Solwara 1 with a current value of ~$4.3-billion to Tongling, Nonferrous Metals Group Holdings Company Limited. (Jamasmie, 2015).

The value of the ecosystem services should also be considered when discussing the economics of the sea bed. Ecosystem services are hard to quantify in terms of currency value; the sea floor has much to offer besides minerals; for example biogeochemical cycling and undiscovered species including viruses, microbes and unique higher lifeforms that may have future value for pharmaceuticals, cosmetics and domestic products. Every expedition to the depths results in new species being found. (HADES, 2014). Such as the domain Archaea, an ancient lifeform related to the first life on Earth and all this with only 1% of the deep ocean floor so far explored. (WWF, 2016). The specialized adaptations of deep-sea organisms can also give science an understanding of their biochemistry that could also lead to biochemical, medical and in biomimetic advances. For example, Bioluminescence is being used to advance research on the progression of diseases like cancer and Alzheimer's, by taking bioluminescent traits from organisms and placing the genes responsible to non-luminescent model organisms. (Luker & Luker, 2010). The deep sea is increasingly being targeted by commercial fisheries, both in national waters and international. With overfishing having depleted many epipelagic and coastal fisheries, as many as 40% of the world's fishing grounds are now in waters deeper than 200m. (WWF, 2016). If the effects of extensive deep-sea mining turn out to be detrimental to these fisheries, substantial seafloor shortages could disrupt complex food webs.

3 Existing ROV technology

A current typical low-cost vehicle usually comprises a central air-sealed unit containing a camera for visuals and the main control electronics. Outside of this central unit are 3 or 5 (vectored thrust) propellers for propulsion & maneuvering. The operator controls the device on the surface by a tether - a set of cables that convey video and data signals between the operator and the vehicle (Marine Technology Society, 2012). A number of these cheap ROV have adaptations added to allow the vehicle to undertake scientific surveys or tasks using manipulators and/or sensor suites.

There are numerous technical issues associated with adapting these simple vehicles for the deep-sea: crushing pressures, communicating over long distances, and temperatures near freezing. These present a major challenge to designing and manufacturing a low-cost ROV.

3.1 Pressure

The primary issue associated with current ROV systems is that as water depth increases the pressure exerted on an air-filled volume increases linearly (Every 10m = 1 atmosphere [14.5 Psi]). At 1000m the pressure is equivalent to 101.972 kg/cm2. With increasing pressure, an increasing stress is placed upon any component subjected to it. This is the most significant technical factor to overcome when designing a deep ROV; a housing that can withstand the immense 'crush' force that will be applied to it. The weakest part of the structure inevitably, will be the sealing joints and feedthroughs where cables need to pass out from the main command unit. Accordingly, there is an opportunity and challenge associated with developing. This may possibly be addressed in the near future by novel 3D printing techniques using high density polymers or metals, Metal Additive Manufacturing (AM) and Direct Metal Laser Sintering (DMLS), (3T RPD, 2017) to produce high pressure feedthroughs at low cost to allow cables (Power/data) to pass through whilst withstanding the pressure.

3.2 Temperature

The temperature reduction at depth will create an additional technical issue, especially in the case of batteries powered devices as generally all batteries and electrical components have an optimal operating temperature of around 20^{o}C; this will cause the batteries to reduce significantly in efficiency when operating at 2-5 ^{o}C. However, the circuit whilst in operation will produce heat as byproduct so should keep its self warm enough to operate, the batteries can also be insulated to reduce heat loss. The ROV's power management needs to be efficient enough to provide power to get an ROV down to survey depth, which depending on the target may take several hours. Power needs top be supplied on board because sending power down an umbilical is unfeasible over large distances due to energy loses from the cables.

3.3 Light

With the total lack of ambient light at depth, the ROV used for exploration will have to have a powerful LED matrix in order to illuminate features & objects on the sea floor. This is easily accomplished by adding powerful a LED circuit but heat and power management become critical considerations. LEDs are inefficient in terms of their ability to convert power to light heat is generated as a byproduct, the power powerful the LEDs the more heat generated so a heat sink needs to be added to take the heat away from the circuit. The use of flashing or strobing can help to conserve energy on the batteries whilst also providing the necessary light.

3.4 Salinity

As with any sea going robot, the components are subjected to salinity (35parts per thousand) this has a large impact on the density of the water, surface seawater ranges from about 1020 to 1029 kg/m^3. In deep oceanic waters under high pressure, seawater can reach a density of 1050 kg/m3 or higher. (Garrison, 2007). This will affect the buoyancy of the device, for example a standard 100kg ROV would require an extra 3.5kg weight in seawater than in freshwater. Buoyancy will also change with depth. The salinity also affects the conductivity of the water in a linear fashion, as increasing dissolved salt increases conductivity. This promotes an elevated risk of corrosion on submerged metal components and hence expensive corrosion resistant metals e.g. titanium or 316 stainless steel must be used in construction. Due care and protection must also be taken on the motors' copper windings as, if unshielded, these will also corrode over time. These can be protected using water repellants (hydrophobic oil based lubricants) or using motor housings.

3.5 Data Transmission

Another issue with dealing with significant water depths is the data transmission for the ROV's video, telemetry data and control commands to be sent and received from the device. The gold standard cable for data transission (CAT 7) can trasmit data only about 700m to 1000m (Kralicek, 2016), but at such lengths this type of cable is both weighty and provides significant drag, hindering ROV maneuverability and adding a greater thrust requirement for the motors and hence greater demand for any on-board power supply.

Some of the latest low cost opensource technology has sought to achieve long but low cost cable tethers by converting from an ethernet to 2 wire transmission at one end and then converting back again to ethernet at the surface - this is known as a transparent bridge. This uses a forwarding database to send frames across network segments. The forwarding database is initially empty and entries in the database are built as the bridge receives frames. In the context of a two-port bridge, the forwarding database can be thought of as a filtering database. A bridge reads a frame's destination address and decides to either forward or filter. If the bridge determines that the destination node is on another segment on the network, it forwards (retransmits) the frame to that segment. (Technopedia, 2016). This system has a limited range of 400-500m but also the speed associated with these lengths will also cause a delay in data transmission back and forward to the device. The way to overcome this limitation is to use a more powerful bandwidth by switching to another transmission method i.e. fibre optic communication. Optical fibres are used to transmit light pulses between the two ends of the fibre, permitting near-instantaneous data transmission over longer distances and at significantly higher bandwidths (data rates) and with lesser amounts of signal loss. The highest purity copper cables can only transmit information up to 2850m/2.85km due to power loss, whereas fiber cables can travel up to 4,000m/4km (Keiser, 2003). In addition, fibres are also immune to electromagnetic interference, a problem from which metal wires suffer excessively. (Senior et al. 2009).

3.6 Positioning

A major operational issue for exploration lies in understanding the precise position of the ROVs. As GPS does not work underwater so another method is required there are a few ways to achieve this. The typical approach is to have an acoustic positioning system, with a network of transponders on known points (buoys or vessels) and on the ROV whereby the two communicate and from this a relative position can achieved by using the time taken for an acoustic ping to reach the ROV from the known point. This is complicated by; firstly, by needing to know the salinity/density profile of the water and secondly, acoustic reflections off the sea bed. Another way to achieve positioning is to have a 'smart' tether that has GPS at the surface and IMUs at known intervals down the cable that record angle and depth. From this the ROV position can be established from the known surface point of where the cable is. Both are very expensive methods - smart tether costing ~$15,000 per 100m (based on KCF smart tether) and the positioning system with smart buoys from ~$20,000 (based on South Star system) with the issue that these buoys need to be placed on the sea floor to begin with. Positioning remains a significant challenge for all submarine craft, though with the development of quantum devices for dead reckoning this issue may be solved and at low cost over the coming decade. (Orús *et al.,*2009).

3.7 Sensors

ROVs can be fitted with suites of sensors, that allow it to obtain useful data from basic optics (Camera) to more advanced data such as conductivity temperature depth (CTD) and manometry profiles which help to characterize the environment. As with the factors limiting the ROV, the sensors are also subjected to the stress and challenges and so design factors heavily on their cost &viability. A high resolution high sensitivity camera with 3,000 meter rated pressure housing costs upward of $5,000 (based on Tritech Typhoon) and sensors such as a 2D Multibeam Imaging & Sonar for bathymetry surveys can range from $27,000 (based on BlueView M900 Series). Sensor suites for ROV are a valuable asset to obtaining data but currently carry heavy price tags due to many of the same engineering requirements for ROV to go deep.

3.7 Operational Costs

The compounding factors detailed mean that the financial implication of going to depth remains significant, as the technology required is expensive and this is reflected by the current ROV market. A typical 'working class' ROV capable of deep water can be extremely expensive, for example, MBARI's Tiburon vehicle cost $6 million to develop and is used primarily for midwater and hydrothermal research on the West Coast of the US. This is a very specialized system custom built with a whole suite of sensors. This represents a very high end ROV and certainly at the top end of the market. The table below outlines some of the current ROV systems capable of reaching 1000+ m and the cost of the system. Standard working class can range from $600,000 - $4 million+.

It should also be considered that the larger 'working' class ROV must launch off a ship that typically costs >$50m or ~$60-70k/day. A qualified ROV pilot is also required to operate the craft adding a further significant operational cost for exploration.

4 Summary

It is clear that a significant opportunity exists for mass participation in Deep Ocean surveying but only if technical hurdles can be overcome at increasingly lower cost.

Whilst the international market for ROVs has seen a significant expansion in the number of vendors at the lower end of the market, these 'low cost' ROV do not facilitate deep (>100m) exploration. These devices are currently limited in terms of deep-sea operation by the pressure the vessel structure can withstand and the ability to control them via tether other such large distances. The fact that cables must feedthrough from an air-filled unit into seawater causes a localized weakness in the structure which, at pressure, water will seek to exploit. A critical bottleneck lies in the need to develop low cost 'feedthroughs' for data & power transmission. A problem which applies to the main ROV unit and any sensor packages it may carry.

A significant financial opportunity therefore currently exists for inventors to make this happen affordably. This is further incentivized by international competitions such as the Shell Ocean Discovery X prize. (Shell, 2017).

In summary, the next decade is likely to witness the proliferation of ever more affordable ROVs for ocean exploration. This will drive a new frontier of science, exploration and knowledge into the deep ocean realm. The key question remains whether deep ocean mining will also become environmentally as well as financially viable within the same period. Indeed, as deep sea exploration proliferates the role of ROVs will continue to take center stage. In a world of increased pressure for sustainability and responsible interaction with our ever fragile environment, perhaps the greatest impact deep sea ROVs will have is in the long term policing and monitoring of the industrial activities that they themselves allowed us to access.

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