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PERSPECTIVES IN VISUAL IMAGING FOR MARINE BIOLOGY AND ECOLOGY: FROM ACQUISITION TO UNDERSTANDING

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Abstract Marine visual imaging has become a major assessment tool in the science, policy and public understanding of our seas and oceans. The technology to acquire and process this imagery has significantly evolved in recent years through the development of new camera platforms, camera types, lighting systems and analytical software. These advances have led to new challenges in imaging, including storage and management of 'Big Data', enhancement of digital photos, and the extraction of biological and ecological data. The need to address these challenges, within and beyond the scientific community, is set to substantially increase in the near future, as imaging is increasingly used in the designation and evaluation of marine conservation areas, and for the assessment of environmental baselines and impact monitoring of various marine industries. We review the state of the theory, techniques and technologies associated with each of the steps of marine imaging for observation and research, and to provide an outlook on the future from the perspective of current active science and engineering developers and users.

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Introduction

Imaging has become one of the most important non-destructive tools to study the oceans and learn about their changing state. While acoustic imaging provides large-scale information about geological features of metre-scale and greater, visual imaging can answer scientific questions regarding biology and geology on a habitat scale of several square kilometres down to the millimetre-scale. As cameras are used on a range of platforms, from ships and underwater robots to SCUBA divers, and applied to defence, commercial or scientific endeavours, marine imagery is transforming our understanding of the oceans and ultimately our planet.

Undersea photography has long been a medium of documenting discovery and capturing the attention of the public. Marine photographers have become famous for making underwater environments accessible, melding adventure, exploration, art and science. Of these, Jacques Cousteau is perhaps the most famous for his passion for marine life, innovations to diving technology, breadth of marine exploration, and sheer volume of films made in the 20th century. His most famous film, *The Silent World*, won both an Academy Award for Best Documentary Feature, and the Palme d'Or at the Cannes Film Festival (Cousteau & Dumas 1953). His contemporary, Hans Hass, was an equally prolific filmmaker who also contributed to underwater diving and camera technologies, and was well-known for his books (e.g. Hass 1954) and television programmes. In the last 30 years, exploration filmmaking has begun to focus on the deep sea. The photographs of hydrothermal vents captured in the late 1970s (Lonsdale 1977) gave glimpses of a faunal community fuelled by chemosynthesis, a novel concept at the time. The discovery and filming of the RMS TITANIC in the deep Atlantic Ocean (Ballard & Archbold 1987) attracted considerable popular attention. More recently, filmmaker James Cameron's 2012 dive to the Challenger Deep in the Marianas Trench, demonstrated marine imaging at extreme depths (Gallo et al. 2015).

Underwater photography was pioneered in 1856 as portable cameras were being developed, and the first images were captured using a pole-mounted system (Vine 1975). Over the next century, camera and mount technologies improved, and marine colour photography and video were developed, the history of which is reviewed in Kocak & Caimi (2005). Imaging was quickly adopted as a method for collecting qualitative and quantitative data on the marine environment (reviewed in Solan et al. 2003), particularly the benthos (Fell 1967, Heezen & Hollister 1971, Owen et al. 1967, Vevers 1951, 1952). Over the last 30 years, the use of marine photography and video in scientific publications has increased by two orders of magnitude (Figure 1).

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Marine imaging has been used in several different biological applications, for example still images used for ecological surveys, while video is commonly used to observe animal behaviour. Large areas of the seabed can be captured in photographs for spatial analyses (e.g. Morris et al. 2014, Priede et al. 2013), while time-lapse photography has been used for temporal studies (e.g. Bett et al. 2001, Lampitt & Burnham 1983, Paul et al. 1978). For ecological applications, marine imaging is becoming increasingly favoured over traditional sampling techniques, such as trawls, since more taxa are represented in photographs, and the area or volume surveyed can be accurately determined (Gage & Bett 2005, Menzies et al. 1973, Rice et al. 1979, Rice et al. 1982). Additionally, as a non-destructive technique, it has minimal impact on habitats or marine life.

New technologies have improved the value and ease of obtaining visual imagery in biological and ecological studies. The application of photography and video to investigating biological and ecological questions typically involves several steps, including: survey design, image acquisition, post-processing the images to prepare them for data extraction, extraction of data from the images (typically referred to as ‘annotation’), and statistical analysis of the extracted data. The technology to acquire marine visual imagery has significantly evolved in recent years with the development of novel camera platforms (e.g. long-range autonomous underwater vehicles, remotely operated vehicles and cabled observatories), cameras (e.g. digital cameras), illumination (e.g. light emitting diodes), sensors and digital image storage. As a result of these developments in technology, a multitude of new data can be recorded. This poses new challenges in the remaining steps of image use, including storage and management of ‘Big Data’ at a terabyte scale; sharing images, image data and derived or accompanying meta-data; standardisation of annotation; and strategies for large-scale annotation, such as automated or crowd-sourced annotation. Computer-aided treatment of marine images includes image processing for a variety of factors (e.g. colour or illumination correction, removal of noise), software for still image and video annotation, and databases and data management applications (for imagery, metadata and annotation data). Technology has also added a new dimension to the long-standing challenge of identification of specimens and other features in images; the increased sharing of information over the internet has facilitated comparison of morphotypes among experts and the development of standardised classification schemes (Althaus et al. 2013). Manual image annotation has long been the standard, but computer vision approaches are becoming more capable, including habitat characterisations and morphotype identification. These are the first, but important, steps on the way to ‘automating’ identification (MacLeod et al. 2010).

The theory, techniques and technologies associated with each of the steps of marine imaging for biology and ecology (Figure 2) are reviewed. A look to the future is also provided, from both the scientific and engineering perspectives.

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Survey design

Photography can be employed to address a broad range of biological and ecological objectives in the marine environment. It may range from pure exploration to strict quantitative hypothesis testing, and may be carried out in either or both the space and time domains. Beyond the simplest serendipitous observations, some advanced planning including consideration of analytical approaches will always be useful. Almost all field operations are based on 'sampling' a much larger 'population', and can seldom, if ever, achieve complete coverage or a total census. Regardless of application, there are a number of basic choices to be made in any environmental survey. Below we consider some of the primary issues, drawing on a "statistical checklist" published by Jeffers (1979) that provides a useful framework for the systematic development of an effective field survey.

State the objectives

Researchers should attempt to clearly and explicitly state the objectives of the investigation, and the reasons for undertaking it. Those objectives should be converted into precise questions that a photographic assessment could be expected to answer. These questions will then guide the development of appropriate survey design and methodology. Explicit objectives help ensure the project will be effective and efficient, and to avoid wasting resources, time and money (Underwood & Chapman 2013).

Qualitative versus quantitative studies

The most basic decision when considering a survey is to determine whether the aim requires the collection of qualitative or quantitative data (Fell 1967).

Qualitative study of the environment is inherent to image-based investigations. Qualitative studies (or studies with a qualitative element) have been used to improve taxonomic knowledge (e.g. Rogacheva et al. 2013), inventory a fauna (Benfield et al. 2013, Desbruyères & Segonzac 1997, Lindsay et al. 2004), examine faunal traces (Przeslawski et al. 2012), catalogue habitats (Kostylev et al. 2001), observe organism-habitat interaction (Fell 1967, Morris et al. 2013), document behaviours (Bett & Rice 1993, Jones et al. 2013, Smith et al. 2005), and reveal life histories (Durden et al. 2015b, Solan et al. 2003). Image-based studies are also often used for semi-quantitative surveys, for example in categorical estimates of abundance (Hirai & Jones 2011) or seabed coverage (Bohnsack 1979).

Visual imagery is now widely used for the quantitative study of patterns (Grassle et al. 1975) and processes (McClain et al. 2011) in marine communities and

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associated habitats, and to gather information about human impacts (Jones et al. 2007a, b, Pham et al. 2014, Schlining et al. 2013). Photographs have been used to quantify the communities of topographically complex features (De Leo et al. 2010, Durden et al. 2015a, Friedman et al. 2012, Rowden et al. 2010) where conventional sampling may be difficult or impossible (Williams et al. 2015).

Translate the objectives

Once the objectives have been established, they are translated into specific parameters of interest, either qualitative or quantitative. Translation involves determining what is to be measured as primary data (and to what precision). Even for purely qualitative studies, this translation could involve defining the location, area or volume to be surveyed and the particular assemblage or taxa of interest. For many biological or ecological studies, the primary data from imagery involve counts, dimensions and/or coverage in an image of species and/or habitats in a number of images drawn from some larger area or volume of interest.

In addition to the primary image data, secondary variables may be necessary or desirable to fulfil particular objectives, to aid interpretation, or to improve the primary parameter estimates. Many of these secondary variables may be measured or recorded as part of the imagery metadata (see Metadata), such as position, date and time, or depth. Others may be obtained from the imagery, such as substratum type, food availability or behavioural observations. Additional sensors may be employed to collect simultaneous physical, chemical, biological, topographical or geological data. The precision and resolution of such measurements should be considered in conjunction with the primary variables.

Survey planning

Many authors address survey design for ecological or biological studies in detail (Krebs 1999, Steel et al. 1997), providing approaches that may be applicable to marine photography. There are two key concepts that impact on survey design and the subsequent interpretation of survey data that may be of particular concern in photographic studies: (1) pseudoreplication (Hurlbert 1984), and (2) autocorrelation (Legendre 1993). Both concepts represent potential practical difficulties, and apply equally in space (transect photography) and time (time-lapse photography). In simple terms, pseudoreplication can be seen as the extrapolation of results (statistical inference) beyond the predefined sampling area, “the actual physical space over which samples are taken or measurements made being smaller or more restricted than the inference space implicit in the hypothesis being tested” (Hurlbert 1984). The problem of spatial autocorrelation is perhaps most briefly stated in the “First Law of Geography: everything is related to everything else, but near things are more related than distant things” (Tobler 1970). In statistical terms, observations that are structured in space (transect photographs) or time (time-lapse photographs)

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are not independent, a common underlying assumption of many statistical techniques.

The detailed means of tackling pseudoreplication and autocorrelation are beyond the scope of the present contribution, but continue to be the subject of research (Hamylton 2013, Millar & Anderson 2004). General good practice in survey design, as considered below, should nevertheless alleviate these problems. In terms of simple, direct general advice we consider two related opinions to be particularly valuable:

1) “Completely randomized designs should only be used in the very particular case of [known] spatial homogeneity at large scale” (Dutilleul 1993), and

2) "Stratified random sampling ... represents the single most powerful sampling design that ecologists can adopt in the field with relative ease. ... every ecologist should use it whenever possible." (Krebs 1999).

In many, if not most, cases our limited knowledge of variation in the physical and biological characteristics of the marine environment suggest that stratification of the survey area by known or suspected systematic variations is sensible (into ‘survey strata’ or treatments), and that formal randomisation within the resultant strata is necessary.

Assess existing information

Prior knowledge of the survey area or population should be reviewed in advance of designing the survey. In particular, knowledge that informs the practicalities of surveying, the logical partition of the area into sub-areas and the likely variance of survey parameter estimates, can be extremely useful. If prior information is not available, a pilot study may be a sensible precaution.

Practical information about the survey location, such as water depth, light availability, bathymetric features or water turbidity, could suggest an appropriate platform or camera setting. For example, avoiding collision of a towed camera platform with the seabed is difficult in areas of rough terrain (Jamieson et al. 2013), while periodic dredging or tidal movement may increase particulate matter in the water column that could obscure images.

Information about the biological population of interest could be gained from previous studies by another sampling method, or of a similar population in another location or time. Useful previously collected information would include life histories of the organisms of interest, along with information about spatial and temporal processes causing variation in the population (and scales of these processes), interactions within the population, and the response of the population to the environment (Underwood and Chapman 2013). Examples include the timing and depth of a plankton survey that would need to accommodate diel vertical migration

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(e.g. Itoh et al. 2014), a study comparing spatial variation in benthic faunal densities would need to consider seabed topography (e.g. Alt et al. 2013), and knowledge that the use of artificial lighting may influence the behaviour of some fauna (Smith & Rumohr 2013).

Location-specific environmental information, such as physical and chemical oceanographic data, and habitat-related data, may provide insight into heterogeneity or gradients that may influence the population of interest. The survey could then be designed to target the population accordingly, considering the occurrence of any variation and the magnitude of the variance, including determining the sample size, and defining the level of stratification required.

Define the sampling population

The sampling population to be surveyed must be explicitly constrained in terms of space and time, either of which may be implicit in the objective set. It may also require definition in biological or ecological terms, for example to include (or exclude) certain taxa, functional groups, or size classes of organisms. Other categorical constraints might also be imposed, for example limitations to certain habitats or environments. This sampling population encompasses the 'universe' from which samples will be selected within strata (Figure 3).

The level of detail involved may best be illustrated by example. If the aim is a quantitative assessment of megabenthic fauna on an abyssal plain, then practical definition of the sampling population might be: (1) a geographic region of a 40 km radius from a notional centre point (with fixed coordinates); (2) local topography, such as abyssal hills rising >100 m above the seabed being excluded for ecological reasons; (3) areas within 5 km of submarine cables being excluded for practical reasons; (4) accept only those images captured within an altitude range of 2-4 m above the seabed; (5) accept only those images where an areal extent of the seabed can be estimated; (6) image capture in a specific month to constrain seasonal influences; (7) all identifiable individuals having a linear dimension of >1 cm (sensu Grassle et al. 1975) to be counted. Defining such terms *a priori* will greatly assist in the design, planning, execution, analysis and interpretation of the survey.

Select sampling unit and sample size

Sampling units, typically defined by physical dimension and shape, of a given size are used to sample the population of interest (Figure 3). These two factors are linked and must be considered jointly; sample size considerations may feed back into the most effective choice of sampling unit. In marine ecology, sampling unit most often refers to the physical size (areal extent or volume) of an individual sample. The physical size and number of these units must be selected carefully to meet the objectives of the survey, considering both the statistical requirements and the practicalities of the sampling process. In physical sampling (e.g. sampling the seabed

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with corers), the investigator may have a very limited choice of sampling units; that limitation is largely removed in photographic studies and requires careful consideration in any survey design.

A complication in the determination of sample size in image-based studies is variability in the physical size represented by each image. In some approaches the physical size is fixed, for example in static time-lapse photography. In many others, particularly in many spatial surveys, the physical size changes as the camera-to-subject distance varies. Light absorption and scattering ultimately limit the physical size imaged, such that light availability, turbidity, and distance to subject are important factors. The minimum and maximum size of the organisms of interest will dictate the camera and illumination systems, platform types and the operational camera-subject distance. In applications with varying camera-subject distance, ensuring adequate resolution for identification can be critical, effectively defining a minimum object size that can be reliably identified throughout the survey (Jones et al. 2009). Conventional visual imagery generally confines studies to pelagic and epibenthic organisms >1 cm in diameter (Fell 1967, Grassle et al. 1975, Owen et al. 1967). In such cases, a single image of the seabed with biological resolution for large organisms represents a small area, generally on the order of 1-10 m^2 (Jones et al. 2009, Rice et al. 1979).

In many applications, particularly in spatial studies, a single photograph will not represent an adequate sampling unit. This is most obviously the case where parameters such as species diversity and species composition are being estimated when faunal density is low. If the sampling unit contains only a few specimens, estimates of diversity and composition will be crude at best and frequently meaningless. Little definitive guidance is available on this subject. For example, McGill et al. (2007) suggest a threshold of hundreds to thousands of specimens per sampling unit. We can perhaps suggest that where the number of individuals per sampling unit drops below 100, the survey results must be interpreted with caution. In photographic applications, an adequate sampling unit may therefore be some aggregate of visual observations, such as pooled or mosaicked still images, segments of video, or images extracted from video at fixed intervals (Jones et al. 2009). How images are aggregated to produce an adequate sampling unit is also a significant consideration, and must be guided by the objectives of the survey. Images may be pooled sequentially in space or time, such as along a photographic transect or quadrat (Bohnsack 1979, Kershaw 1964), or may be drawn at random. The desired overlap between images must be considered when intending to mosaic images (Jamieson et al. 2013). Video footage may be analysed in native format, turned into still images for analysis by extracting frames at appropriate intervals and can also be mosaicked (Johnson-Roberson et al. 2010, Marcon et al. 2013, Pizarro & Singh 2003).

Having selected an appropriate sampling unit, the question of sample size can then be addressed. The sample size required to achieve a particular precision of

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estimate, or desired statistical power in hypothesis testing can be calculated given some prior knowledge. The scale at which differences between sampling units may be detected, and the precision of data should be considered, as should the variation in the population of interest including patchiness (Underwood & Chapman 2013). The effect-size must also be considered related to the factor of interest, to ensure that the sampling unit is sufficient to detect it. For example, Sokal & Rohlf (1995) give an equation to relate the coefficient of variation in a particular parameter, the significance level desired, the smallest true difference to detect, and the likely number of replicates required (Equation 1).

$$n \geq 2\left(\frac{CV\%}{\delta\%}\right)^2 \left\{t_{\alpha[v]} + t_{2(1-P)[v]}\right\}^2$$

Equation 1. Calculation of the number of samples required (n) from the coefficient of variation (CV%), smallest true difference to detect (δ%), significance level (α), degrees of freedom (v, a[n-1], where 'a' is the number of groups or strata), power of the test (P), and two-tailed t values (t) (Sokal & Rohlf 1995).

As an example, Equation 1 has been employed to produce a table showing the number of samples required to detect a difference (with significance of p = 0.05) between two survey groups or strata, for a range of coefficients of variation (Table 1). In order to detect a true difference of 56% in the mean value with 5% significance would only require two replicate samples per stratum where the coefficient of variation is 5%, but would require 10 samples per stratum if the coefficient of variation was 35%. This obviously has huge implications for the sampling necessary to detect differences of common versus rare taxa.

Knowledge of the anticipated CV%, even imprecisely, can thus have a major impact on the ultimate statistical value of the survey. Note that values for the coefficient of variation are parameter-specific, so faunal density, diversity and composition (for example) will each have its own CV%, thus different parameters of interest may require different sample sizes (Jeffers 1979). As an example, typical values of CV% have been calculated using data from a towed camera study of benthic invertebrate megabenthos of the Porcupine Abyssal Plain (Durden et al. 2015a). Density data from four photographic transects yielded a CV% of 5%. Across common diversity measures (Margalef, Pielou, Brillouin, Fisher, Hurlbert rarefaction, Shannon, Simpson; see Magurran 2013), the CV% ranges between 12 and 25%. Establishing a simple measure of variation in species composition is not straightforward, but using among-replicate sample faunal similarity as an approximation, the CV% in faunal composition is in the order of 40%. The values of CV% given here are only intended to be illustrative; the important point to note is that in surveys recording multiple parameters, it would be wise to base survey design on the worst case parameter (i.e. with the highest CV%).

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The physical size of the sampling unit has a direct impact on the precision of parameter estimates and the statistical power of hypothesis testing. This effect likely operates through two factors: (1) the number of specimens (or other observations) per sampling unit increasing with physical sample size, and (2) the influence of patch size/autocorrelation effects changing with physical sample size. Applying the sample size estimation method described above is relatively straightforward when using standard physical sampling devices (e.g. corers), but may be more complex in the case of photography, particularly with mobile cameras, where the physical size and shape of the sampling unit may not be fixed. This potential variation in the size of an image can generally be constrained to a particular range or tolerance, thus estimation of the sample size is still possible.

Systematic variation in CV% may be expected with change in the physical size of the sampling unit, an important consideration when pooling images. To illustrate the effect of sampling unit physical size (number of pooled images) on CV%, artificial samples of varying size were generated using a dataset from Durden et al. (2015a). Faunal density data from individual photographs of four replicate transects were combined, randomised, and re-sampled to generate sampling units of approximately doubling physical size from 25 to 400 photographs (the mean number of individuals per sampling unit similarly doubles through the range 38 to 535). Figure 4 illustrates the effect of varying sampling unit size (number of images per sampling unit) on the value and variability of species diversity and density measures. In all cases, a narrowing of the range in estimates with increasing physical sample size is apparent; the corresponding reductions in coefficient of variation are given in Table 2. Note also that the values of most of the diversity measures tested are also significantly correlated with physical sample size (Table 2).

A similar assessment of the effect of physical sample size on species composition estimates is also possible. The same re-sampled data were subjected to a common form of multivariate analysis: two-dimensional non-metric multidimensional scaling ordination of a Bray-Curtis similarity matrix, based on log(x+1)-transformed taxon density data. The resultant ordination (Figure 5) provides a clear indication of the increasing ‘precision’ in the description of species composition with physical sample size (i.e. reducing area of ordination space occupied by replicates). The result illustrated in Figure 5A is difficult to interpret in practical terms, as it does not indicate what level of ‘precision’ in the description of species composition is required to meet a given scientific objective/question. What is required is a comparator ‘outgroup’ against which to assess variation in species composition. To that end we generated matching outgroup samples from the same data simply by switching the identities of the rank 1 (*Iosactis vagabunda*) and rank 2 (*Amperima rosea*) species (Figure 5B). The distinctiveness of samples, comparing original to outgroup, in terms of species composition was measured as the difference between mean within-group and mean between-group similarity (i.e. the

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basis of ANOSIM- and PERMANOVA-type tests, Figure 5C; Anderson & Walsh 2013). Variability in distinctiveness by species composition was assessed as the coefficient of variation of between-group similarity. With increasing physical sample size (number of photographs pooled) distinctiveness in terms of species composition increased and variability declined (Table 3). These examples illustrate the value of prior knowledge of the population of interest in the design of effective surveys.

In the final assessment of sampling unit and sample size considerations, it is worth noting the potential trade-offs between the number of photographs pooled (sampling unit) and the number of replicates (sample size) analysed. In the simplistic case of a fixed resource of 1600 photograph, options would include (1) 200 photos x 4 replicates x 2 strata, and (2) 400 photos x 2 replicates x 2 strata. It is almost certain that option (1) will yield the best outcome. In the simplest terms, a non-parametric comparison (e.g. Mann-Whintey test) could yield a significant ($P < 0.05$) result for case (1) but not case (2), similarly a permutation-based test (e.g. ANOSIM) could yield a significant ($P < 0.05$) result for case (1) but not case (2). Balancing potential statistical power and precision/representativeness in individual species diversity and composition estimates requires some thought, and is a non-trivial matter in photographic surveys.

Randomisation

As noted above, Krebs (1999) advises the use of stratified random sampling whenever possible. The sampling design in an ecological study should use an explicit randomisation procedure to ensure that independent replicates are obtained (Jeffers 1979, Sokal & Rohlf 1995). Without explicit randomisation within strata, the investigator risks serious errors in the analysis and interpretation of the resultant data. Randomisation requires a formal process; haphazard sample selection should be avoided. Every member of the sampling population (within a stratum) must have an equal chance of selection. This is usually easy to achieve in most practical marine surveys, with random geographic coordinate selection often the simplest method. Regardless of the particular method employed, a formal statement of that method should be included in the description of the survey design. In cases where simple or stratified random sampling is not possible or practical, probabilistic design may be used (e.g. Hill et al. 2014).

Practical considerations

Consideration must be made for time, budgetary or equipment-related constraints, while not allowing them to compromise the collection of appropriate data for the scientific objectives. Significant cost and infrastructure (physical and human) is associated with the use of ships (the deployment platform for many image-capture methods), and particularly with the use of Autonomous Underwater Vehicles (AUVs) and Remotely Operated Vehicles (ROVs), which require control infrastructure and

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personnel. Some published ecological survey design schemes include stratified random design with specific considerations for the reduction of platform or ship time (Strindberg & Buckland 2004), with software available to implement such designs (Thomas et al. 2010).

Equipment requirements
The type of equipment needed will depend on the science objectives and the type of data required (see **Image acquisition**). Video is commonly used to collect data which may have both spatial and temporal variation. Images from stereo cameras may be appropriate for detailed identification and precise sizing of individual organisms (Dunlop et al. 2015). Images captured perpendicular to the seabed are commonly used for spatial benthic ecological studies of sessile or hemi-sessile organisms, and substratum or seabed composition (Clarke et al. 2009). Images captured at oblique angles are commonly used for motile fauna such as fish, because each image represents a larger area of seabed or larger volume of water. Some subjects may be more easily identified in oblique-view images rather than in plan-view images. These image types may be captured using stationary or mobile platforms (see **Image acquisition**). Temporal studies examining process rates (Bett 2003, Paul et al. 1978) are generally conducted using time-lapse imagery from tripod-mounted cameras, although video may be used. Examples include estimation of rates of phytodetrital flux and accumulation by Billett et al. (1983), and growth rates of xenophyophores Gooday et al. (1993). Time-lapse photography is used in combination with bait to examine foraging strategies of mobile fauna (Jamieson & Bagley 2005), with consideration that the sampled area extends as far as the bait plume, rather than the extent of the image.

Recording data and metadata
The detail of the data to be recorded from the images should be considered as part of the survey design (Jeffers 1979). This may include details of the attributes of the observations in the images, including a catalogue/list of morphotypes, species, or behaviours, and any abiotic parameters, such as habitat features or types. The data type to be recorded should be included, such as the count, measurement and dimension(s) of measurement, or coverage estimation. The required photographic metadata should be considered, such as the camera or image location, camera attributes, date, time, altitude, angle of acceptance, and the precision required of each. In addition, procedures and ancillary data required for converting data from images into a format desired for the results should be defined.

Auxiliary data may be collected to complement the imagery by other means. Acoustic imaging, *in situ* biological samples, physical and chemical parameters of the associated seawater or sediment are commonly used to maximise information (Fell 1967) on the sampling unit, by ground-truthing data obtained from images, or to add data not available directly from the images.

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Image acquisition

The acquisition of underwater images has been revolutionised in the last decade by improvements to digital camera technology. In fact, this is the area of marine imagery that has seen the most change. Camera improvements have led to higher resolution images and a reduction in the cost of image capture. Obtaining good underwater images in many situations no longer requires the use of custom-designed and purpose-built cameras and platforms, but can be done using commercially available cameras, housings and mounts. The advent of compact digital cameras with intrinsic features such as multiple exposures and episodic video, and the popularity of adventure sports-related photography means that shallow-water photography, including time-lapse work, can now be accomplished with off-the-shelf consumer products. The availability of a wide variety of high quality imaging equipment ensures that the appropriate equipment can be selected to meet the scientific goals.

Challenges of the marine environment

Optical challenges

The application of standard computer vision techniques to underwater imaging involves addressing the transmission properties of the medium (Funk et al. 1972). The optical properties of different water bodies depend on the interaction between light and the aquatic environment, with light penetration ranging from less than 10 m to more than 100 m (Smith & Rumohr 2013). This interaction includes two processes: absorption and scattering. Absorption is the process whereby light energy is converted to a different form of energy, principally heat, and light disappears from the image-forming process. Scattering is produced by change of direction of individual photons, mainly owing to the different sizes of the particles in the water, and the extent and form of scattering is nearly independent of the wavelength of the light. Scattering can be further divided into backscatter and forward scattering. Backscatter appears when the light is reflected in the direction of the imaging device. Backscattering can be caused by particles in the water column, such as marine snow (Carder & Costello 1994). Forward scattering is produced when the light reflected by an object suffers from small changes in its direction. This effect normally produces a blurring of the object when viewed from the camera (Prados et al. 2011). Backscattering is normally reduced by increasing the distance between the light source and the imaging sensor, and forward scattering can be reduced by decreasing the distance to the imaged object. More detailed descriptions of the propagation of light in the ocean, and optical challenges are given in Jaffe et al. (2001) and Ackleson (2003).

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Environmental challenges
In addition to optical challenges, environmental conditions add to the difficulties in marine image acquisition. In particular, high pressures, wide temperature ranges and the presence of salt in the water mean that designs and materials for equipment and housings must be selected carefully. The use of plastic or epoxy resin, anodised aluminium and titanium are common for external components, and small aspects of design such as seals and O-rings are vital to the success of the design. Examples of environmental challenges include working near deep-sea hydrothermal vents, where water temperatures can reach 300˚C and the water can be highly acidic, and the tideline in polar regions, where camera housings are exposed to repeated freeze and thaw cycles, sharp ice crystals can damage O-rings as they grow, and where freshwater ice can form and remain permanently frozen in front of the lens. Areas where there is rapid growth of encrusting organisms or algal films present their own set of challenges. A short description of major considerations is available in Smith & Rumohr (2013).

Fundamental options

Video and still images
Video and still images are used to capture different types of biological and ecological information. Video and time-lapse still images are used to observe behaviour, interaction between biota and habitat, and processes occurring over time, while individual images are used in spatial studies. Regardless, the resolution of still images is still generally greater than that of video (Jamieson et al. 2013), so both are often used in combination for studies where video is considered to be the optimal choice; quantitative work is done in still images, with video providing the context. Previously, video has primarily been used in midwater surveys (Heger et al. 2008), while still images and video have been used in benthic studies.

Digital and film photography
Nearly all underwater still imagery has moved to digital technology, with film cameras generally only in use as back-up systems. Digital storage and file formats have thus become an important aspect of image acquisition (see also **Data management**). Saving information in RAW format, which retains all of the information recorded on the sensor, is generally preferable to saving information in a compressed format, such as JPEG, because it increases the available dynamic range and post-processing possibilities. This comes at a cost, in terms of storage space, as RAW images are typically 2–6 times larger than corresponding JPEGs, although with the declining cost of digital memory, this is becoming less of a concern. A complication of RAW format is that it is not a single format, with several proprietary file-structures in use. Nevertheless, (free) software is available to deal with multiple RAW formats (e.g. IrfanView; Skiljan 2015), and there are moves to establish a common archival format for RAW files (e.g. Adobe's Digital Negative, DNG).

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Many video cameras used for scientific purposes are ‘High Definition’ (HD), with an image size of 1080 (H) X 1920 (W) square pixels for HDTV cameras or 1080 (H) X 1440 (W) rectangular pixels for cheaper HDV cameras. The resolution of frame grabs from HD-video is often as useful as in still images.

Monocular, stereo and omnidirectional photography
Single cameras are most commonly used, and capture video or images successively in a wide variety of marine biological and ecological applications. The use of parallel-mounted matched stereo cameras (Boyce 1964) or stereo video (Smith & Rumohr 2013) has been popular in fisheries for the determination of fish size and abundance (Moore et al. 2010, Santana-Garcon et al. 2014), but has also been used to examine benthic fauna (Shortis et al. 2008) and their behaviour (Ohta 1984), and has recently been applied to the sizing of both planktonic (Lindsay et al. 2013) and benthic invertebrates (Dunlop et al. 2015). Omnidirectional cameras have also recently been applied in the marine environment (Yamashita et al. 2011).

Colour and monochrome photography
The choice of image colour is dependent on the image use, and the appropriate camera should be selected for its spectral response. Monochrome images may provide better resolution than full colour, but natural colouring may be necessary for the study’s objectives, such as for taxonomic identification (Smith & Rumohr 2013). Greyscale images may be used to reduce the effect of light scattering in turbid conditions, or in low-light conditions, such as imaging from 10 m or more above the seabed.

Non-conventional photography
Multispectral fluorescence imaging is used to observe bioluminescence in a variety of deep-sea animals, and fluorescence in corals (Mazel 2005, Mazel et al. 2003). Fluorescence imaging is reviewed by Kocak & Caimi (2005).

Most imaging applications have concentrated on two dimensions, but 3-dimensional laser holography (Graham & Nimmo Smith 2010) has been used to quantify plankton (Hobson et al. 2000, Hobson & Watson 2002, Karp-Boss et al. 2007), identify the plankton (Hermand et al. 2013), measure their geometry (Tan et al. 2014), and to assess their locomotion *in situ* (Jericho et al. 2006). Shadowgraph illumination and line scan camera systems such as the In Situ Ichthyoplankton Imaging System (McClatchie et al. 2012), and systems using darkfield illumination with highly sensitive greyscale digital cameras such as the Underwater Vision Profiler 5 (Picheral et al. 2010) have also been used to image plankton and other particles in quantitative assessments. Light-field cameras enable the focus of captured images to be changed after the imaging event and their application in the underwater environment will allow both the seafloor and objects above it to be successfully imaged simultaneously.

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Camera orientation and image scaling

The camera is oriented either perpendicular to (with a vertical or horizontally-mounted camera) or oblique to the object, area or volume of interest (Figure 6A). The calibration of the camera orientation is discussed in **Image acquisition**. The conversion of measurements from an image, such as the size of an object in the image or the area represented by the image, to real-world units using trigonometry can be accomplished simply in benthic photography by accounting for the altitude of the camera above the seabed, and using the vertical and horizontal acceptance angles of the camera (Jones et al. 2009). These computations are straightforward for instances where the camera is, or is assumed to be, perpendicular to the seabed, and only slightly complicated when an oblique angle is involved. Wakefield & Genin (1987) provide a method for the construction of a perspective grid useful in such cases. Note that there is a minor error in their computations, referring to Figure 6B for example. The latter authors overestimate the distance of the camera to the top and bottom of the image, by employing dimension JH to estimate dimension DC, and thereby derive seabed scaling, rather than the more appropriate dimension JM (i.e. distance to the subject plane).

Another simple approach is to place an item of known size in the field of view during image capture. In video surveys this is often an item suspended at a known distance beneath the camera. A common approach is to mount two or three lasers at a known separation, so that their beams may be seen in the field of view (Barker et al. 2001). Both of these approaches assume a flat and normal imaging plane, but may also be done for oblique images (e.g. Dias et al. 2015). Stereo imaging can be used in midwater, or on steep or complex terrain, where it is very rare for multiple lasers to correctly indicate scale for any given object (Shortis et al. 2008). If lasers and stereo cameras are unavailable, but detailed position and altitude data (e.g. location, altitude and rotational parameters of the camera with respect to the field of view) can be captured (see **Metadata**), then 3-axis rotations may be successfully used to scale flat surfaces (Morris et al. 2014).

Photographic components

Despite their price, many commercial underwater camera systems are based on comparatively low cost consumer compact digital cameras, with relatively poor lenses, small sensors, limited control and low dynamic range. When selecting cameras, care should be taken to fully assess the technical specifications of the camera. Many systems with quoted high resolutions (big ‘Megapixel’ number) will perform worse than lower-resolution systems with better optics, electronics and software. For example, increased pixel count on a fixed sensor size reduces the amount of light per pixel, which in turn can negatively impact the sensitivity and dynamic range of the camera.

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Lenses

Wide-angle lenses are often used for their increased field of view, but the short focal length may increase distortion at the edge of the image, making quantification near the edge difficult (Smith & Rumohr 2013).

The design of the housing port for the lens is important in terms of material, shape and distance from the lens. Light is diffracted at both the external water-port interface, and at the internal port-air interface, potentially impacting optical performance (effective focal length and resolution). A flat port reduces the angle of view and may distort the image edges including chromatic distortion, so that the entire image may not be useable. However, corrective domed ports are more expensive and harder to produce (Smith & Rumohr 2013). The material of the port (e.g. glass or Plexiglas) must be durable, scratch-resistant, and produce consistent diffraction.

Artificial illumination

Since light dissipates in water, flashes or strobes are often used to supplement the ambient light or provide light to illuminate objects in an image. The type of flash used is adjusted to the ambient light conditions, with consideration for the impact of light on the subject. For example, habitats may not be altered by the temporary addition of light, but an animal's behaviour may change in response to it (Patrick et al. 1985, Wiebe et al. 2004). The use of flashes in turbid environments may increase the scattering of light and thus the visibility of objects in the image. The type of flash used will be dictated by the desired spectrum and the energy available for powering it. A review of the common types of flashes and their practical application, including halogen, HID, HMI and LEDs, is provided in Smith & Rumohr (2013). The orientation of the flash to the camera and field of view dictates the area illuminated and image clarity, as well as illumination of objects, and also the creation of shadows from features. These shadows are often useful in the identification of objects in the image, but larger shadows reduce the illumination uniformity across the image (Jamieson et al. 2013). The timing of the flash in relation to the shutter in still images is also to be carefully considered. The use of a flash or strobe may increase the range of the image, but may introduce other problems, such as low contrast and non-uniform illumination.

Sensors

The vast majority of cameras use semiconductor charge-coupled devices (CCD sensors), which are most sensitive at the red end of the spectrum, the portion of the visible spectrum that is most rapidly absorbed by seawater. Low-light or intensified CCD sensors are used in environments without daylight. Super-HARP (High-gain Avalanche Rushing Photo-conductor) sensors, most sensitive at the blue end of the spectrum, have been employed in both standard and high-definition video cameras for deep-sea research because they have greater effective range (Lindsay 2003). The majority of cameras in use for biological and ecological studies use one of these

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three types of sensor. More detail on these sensors and others is provided by Smith & Rumohr (2013).

Filters
Polarising filters have been used to reduce scattering in underwater scenes by imaging the same scene twice with the filter rotated by 90 degrees for the second photograph (Kocak & Caimi 2005). Other types of filters are used to enhance contrast or emphasise certain colours or wavelengths, such as the use of yellow filters for fluorescence. Many of these traditional filters have now been replaced by digital post-processing techniques.

Photographic techniques and devices

Shutter speed
Successful photography relies on a suitable amount of light being able to reach the camera sensor. The exact amount of light that is needed or used to record an image is known as the exposure. In ambient light photography, the amount of light entering the camera is controlled with the aperture and the shutter speed. In flash photography, the power, distance to subject, and duration of the flash become additional key factors.

The shutter speed controls the amount of time the camera sensor is exposed to light. The faster the shutter speed the less time the light entering the lens has to strike the digital sensor. The result is a sharper picture (Edge 2006). Shutter speeds are expressed in fractions of a second (e.g. 1/30, 1/60, 1/125). The denominator of the fraction doubles between one speed and the next indicating that the shutter is remaining open half as long. Note that digital cameras may or may not have a mechanical shutter, and may use both mechanical and electronic exposure time controls.

Selecting the appropriate shutter speed can be complicated. In many, if not most, underwater field applications the camera and/or subject are in relative motion and a short exposure is required to acceptably 'freeze' that relative motion. Control of that exposure time can become a complex matter in sophisticated digital imagery systems, potentially involving variations in aperture, mechanical shutter, electronic shutter, flash power, flash duration, background illumination, and subject distance. It may be necessary to consider the nature of the shutter mechanism itself. In older conventional film cameras a choice could be made between mechanical diaphragm and blind shutters. Today the choice is more likely to be between electronic rolling shutter and frame (global) shutters. The rolling shutter (e.g. CMOS sensors) reads image data line by line, resulting in a slight time offset between the capture of each line of the recorded image. This may be significant in terms of 'freezing' relative motion and the flash intensity recorded across the image. The frame shutter (e.g. some CCD sensors) effectively reads all image data simultaneously avoiding these

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potential problems with relative motion and flash exposure. In the completely dark conditions of much deep-sea photography using strobes, the shutter speed is effectively redundant and is set by the flash duration. Many conventional film low light or deep-sea cameras have no shutter (which simplifies design and improves reliability), relying entirely on aperture and flash characteristics to control exposure. With the advent of video in low light situations, continuous lighting and shutter control became necessary. Where laser illumination is used to provide physical scaling (see **Fundamental photographic options**), it becomes necessary to expose correctly for both the scene of interest and the bright spots or lines of the laser scaling system. Given the potential complexities of exposure control the best advice may be to test and experiment with the system in appropriate conditions (e.g. ambient light, using any/all sources of illumination, with the camera/subject in motion, in seawater) prior to field data collection.

Aperture
The aperture is the size of the opening through which light must pass to reach the imaging sensor. It regulates both the amount of light reaching the sensor and the degree of collimation of that light. The amount of light influences the exposure, and the degree of collimation influences the quality of image focus. It is usually measured as an *f*-stop number: $N=f/D$, where f is the focal length and D is the diameter of the effective aperture. An increase of one *f*-stop unit allows half as much light into the camera, so for example *f*/5.6 lets half as much light into the camera as *f*/4 (Edge 2006). In practice, modern digital cameras are likely to operate at 1/8 *f*-stop intervals, with the value reported to the nearest 1/3 *f*-stop. Small apertures (high *f*-stop number) increase the collimation of light entering the camera, giving a greater range of acceptable focus, referred to as the depth of field (see below). However, the smallest apertures may also result in a loss of focus through diffraction effects. In practice, a mid-range aperture (e.g. *f*/4-*f*/8) is likely to offer the best compromise; some photographers suggest avoiding two *f*-stops from either end of the camera system's available range.

Depth of field
The depth of field is the distance between the nearest and farthest objects in a scene that appear acceptably sharp in an image, and is controlled by the aperture, the focused distance and the focal length of the lens. In most underwater applications, it is usually advantageous to maximise the depth of field, without resorting to the minimum aperture. A wide depth of field is important in seabed imagery when using platforms that vary in altitude and hence camera-to-subject distance. Sufficient lighting to correctly expose the image at a small aperture is therefore important. Note that stopping down below *f*/8 (i.e. *f*/11 or higher) may become counter-productive for overall image sharpness.

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Focus

Successful photography depends on the images being in focus. Most cameras have automatic or manual focus. Automatic focus often uses a beam of infrared light to determine distance between the camera and the subject (Hedgecoe 2009). Infrared light is very rapidly attenuated in water and thus autofocus may be limited to subjects close to the camera. Passive autofocus systems can operate successfully underwater provided continuous illumination of the scene is provided. However, they may have difficulty with low contrast or highly reflective subjects, and the lag time to achieving autofocus may become unworkable when there is relative motion between camera and subject. While autofocus may be desirable in situations where there is time to compose and hold the shot (e.g. ROV missions), it can quickly become a liability on both fixed and mobile camera platforms. In many applications a preset fixed focus may be the best option, easily determined in the case of a fixed platform, and readily estimated for a mobile platform that targets a particular camera-subject distance, for example altitude in off-bottom towed camera and AUV missions. Figure 7 illustrates the effect of aperture and focusing distance on the acceptable range of focus for a common, commercially available deep-water camera system. This example is based on a consumer-grade compact digital camera at the heart of the system, having a comparatively small sensor size and correspondingly short focal length lens. For larger sensor format and longer lens, this type of assessment will be more critical. A practical example is illustrated for a towed camera system targeting 2.5 m altitude above the seabed, with a hope for reasonable imagery in the 1.5-3.5 m range (e.g. dealing with 2 m swell motion on the platform). Two significant practical aspects are apparent in the diagram: (1) the preset fixed focus setting is not particularly critical, and (2) setting the focus somewhat closer than the target distance may be advantageous, since images taken at greater distances may have insufficient illumination to be useful, even if in focus.

Light sensitivity

Digital cameras allow the user to adjust the sensitivity to light of the image sensor. This is measured using the International Standards Organisation (ISO) scale for film speed. A high sensitivity (high ISO, e.g. 800) allows correct exposure of photographs at lower light levels. Unfortunately, as the film speed increases, so does the amount of image noise. An ISO of 200 is commonly used to obtain good quality images in deep-sea settings. Larger-sized image sensors have lower noise levels than smaller sensors. For this reason it is important to consider image sensor type and size, and not simply rely on the ‘Megapixel’ count when assessing the potential quality of a camera system.

Dynamic range

Maximising the dynamic range of an image increases the resolution of the image data recorded per pixel, and so increases the scope for post-processing (enhancing) the image. The dynamic range of a digital camera is the ratio of maximum light

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intensity measurable (at pixel saturation), to minimum light intensity measurable (above read-out noise). It can vary significantly between imagers. Even if a digital camera could capture a vast dynamic range, the precision at which light measurements are translated into digital values may limit usable dynamic range. Continuous light measurements from the sensor pixels are translated by the camera into discrete numerical values by an analogue-to-digital (A/D) converter. The precision of the A/D converter controls the amount of information contained in images. However, in practice, dynamic range in typical cameras with A/D converters of 12 or 14-bit precision is usually limited by the levels of noise. Noise can be reduced by increasing sensor size. The use of high dynamic range cameras allows for a corrected image to be constructed despite artefacts in the image from illumination and light attenuation (see **Image enhancement**).

Colour reproduction and white balance
Different sources of illumination have different colour spectra, referred to as ‘colour temperatures’, which affect how colours are recorded in a photograph. Digital cameras often allow the user to set the white balance, adjusting the red, green and blue channels of the signal. Most cameras have an automatic white balance setting, which is often measured directly from the imaging sensor, which can be problematic in underwater applications. The effective colour of light underwater has different characteristics from light in air (see **Image acquisition**) so it is important to set the white balance appropriately. Automatic white balance tends to give underwater images a blue colour as a result of higher attenuation of longer wavelengths of light in water (red light is attenuated more than blue light). As most underwater photographs are shot with flash illumination, white balance setting for ‘flash’ is preferable. It is usually possible and recommended to pre-set a custom white balance by taking test shots of a grey card underwater, for example in a test tank. If in doubt, recording digital images in an uncompressed ‘RAW’ format may be the safest option. Images shot in RAW mode enable the white balance to be corrected after the image has been obtained. This is particularly important in the recording of objects near the edge of the illuminated volume, dark-coloured objects, or near-transparent objects such as jellyfish, for which good colour resolution is needed at the ‘black’ end of the luminance-colour spectrum.

Photographic platforms

Platforms bearing image acquisition technologies are extremely diverse, from hand-held units used by SCUBA divers to highly engineered autonomous robots (Figure 8). Each platform has its own strengths and weaknesses, so the choice of platform should be determined by the proposed end use for the images. In shallow waters, for example, a SCUBA diver with a camera can be towed along a pre-planned survey grid behind a small craft with a GPS-positioning system to make high-resolution image maps of the seafloor. That same SCUBA diver could also be sent down to regions of interest on the seafloor to do macro-photography or be sent into a school

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of fish with a stereo camera to gain images useful for calculating the size composition of the fish in the school. Advantages of using diver-held cameras are their freedom of movement, immediate feedback of image quality, flexibility to adjust field of view, positioning and lighting, and ability to respond to current water clarity conditions (Smith & Rumohr 2013). Disadvantages include depth and time restrictions. A review of diver-operated video for transects appears in Mallet & Pelletier (2014). In addition to humans, marine mammals have also been used as camera platforms (Boult 2000).

Stationary and free-fall camera platforms
Stationary platforms are the simplest platform for underwater camera equipment. They include both free-fall 'landers' and wire-deployed instruments, such as drop cameras, camera tripods, and profiling cameras. Drop cameras are often used to collect images of the seafloor at a point location, and consist of a frame providing protection for the camera and sensors as it is lowered through the water column onto the seabed. Drop camera platforms may be fitted with a still or video camera, which is mounted a known distance from the base of the frame to ensure a consistent camera altitude above the seabed and thus a consistent field of view. A tilting motor may be used to allow the field of view to be adjusted. A tail fin can orient the frame during deployment, and retrieval may be achieved using a tether or an acoustic release. They are often used for ground-truthing benthic habitats imaged by acoustic methods, or to determine benthic cover, for example by seagrass, kelp, algae or coral, and as such are commonly used in habitat mapping (e.g. Grasmueck et al. 2006, van Rein et al. 2011).

Tripods or benthic landers (Table 4) are used as stationary platforms, particularly for long-term deployments such as those capturing time-lapse imagery. Time-lapse imagery is generally used for two applications: to capture phenomena that are slow in rate, or to capture rare or unpredictable events. Two routinely-used tripod designs are 'Bathysnap', operated at the Porcupine Abyssal Plain Sustained Observatory in the north-east Atlantic (Bett 2003), and the camera tripod used at Station M time-series site in the north-east Pacific (Sherman & Smith 2009). Both systems are deployed from a ship for multi-month periods, with an acoustic release to retrieve them. Still photographs are generally captured at oblique angles rather than perpendicular to the seabed in benthic applications, and thus the conversion of measurements from images requires the use of the perspective grid (e.g. Wakefield & Genin 1987), see **Camera orientation**. Details of varied lander operations are given in Jamieson et al. (2013). Stationary camera platforms are also used to study bait-attending species (Bailey et al. 2007). Cappo et al. (2006) and Mallet & Pelletier (2014) review the use of baited underwater cameras for studies of fish, including discussion of advantages and limitations. Time-lapse camera systems have also been used to give insight into bioturbation and the interaction of infauna with the

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sediment by allowing photography of a sediment profile (Germano et al. 2011, Rhoads & Cande 1971).

Simple mobile platforms
Photographic or video transects are often captured using cameras towed by a ship (Table 5). These camera platforms and camera sleds may be towed in midwater to study macroplankton and nekton, or at an altitude above the seabed, or along it, for benthic studies. Control of the platform is maintained through a cable to the ship, and live data may be provided by video transmission through that connection. Towed camera platforms are commonly used in deep-sea research, and reviews of their practical applications are provided in Jones et al. (2009), Wernli (1999), Jamieson et al. (2013), Smith & Rumohr (2013), and Mallet & Pelletier (2014). Cameras have also been attached to benthic sampling equipment (Jamieson et al. 2013) such as epibenthic sledges (Rice et al. 1979), trawls (Menzies et al. 1973), and coring systems (Sherlock et al. 2014). They have also been used with plankton nets for simultaneous sample collection and photography, or to assess the quantitative success of the sampling. Sediment profile imagers have also been deployed as part of towed systems (Cutter & Diaz 1998).

Underwater vehicles
Underwater vehicles can be classified into manned and unmanned vehicles. Manned vehicles (Human-Operated Vehicles, HOVs, Table 6) present similar advantages to the use of SCUBA in terms of interaction with and response to the environment, while avoiding some of the limitations, such as depth rate or diving time. Submersibles normally carry a pilot, often a co-pilot, and one or more scientists. These submersibles are able to survey at low altitude above the seafloor, capturing images of target areas and objects. HOVs are flexible in operation, but have the limitation of restricted diving time (e.g. battery life, air reserve). Ten large manned submersibles used by scientific institutions are listed by Smith & Rumohr (2013). Advantages to using manned submersibles include the ability for the scientist or pilot to adjust the vehicle and mounted equipment in real-time, without the limitation of a surface tether, but short bottom times and low power availability are significant limitations, in addition to potential human safety concerns.

Unmanned underwater vehicles can be further classified into Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs). ROVs are connected to a surface vessel through an umbilical/tether that provides control signals, power, and live video feedback. ROVs (Table 7) have navigation and imaging sensors, and may have equipment for capturing ancillary data and samples (e.g. manipulators, tools, and scientific samplers such as physio-chemical sensors, suction samplers, core tubes and water bottles). Significant design and maintenance infrastructure is required for the operation of large ROVs, including investments in technology and personnel (Jamieson et al. 2013). The size of ROVs ranges from small to very large, and they are used at depths of 30-6500 m. ROVs are commonly used in commercial and industrial applications, particularly in the offshore oil and gas industries, in addition to scientific research. Details of large scientific ROVs in use are provided by Smith & Rumohr (2013) and Wernli (1999). The flexibility of ROVs means that the desire to investigate interesting features is often tempered by strict adherence to the sampling plan to ensure successful quantitative use (Jamieson et al. 2013), and may involve the constant recording of camera and vehicle orientation (including zoom, tilt angles, altitude and location) to the objects of interest, or the absence of adjustment of these factors during the survey. Indeed, breaking a transect into smaller segments to stop and investigate features of interest can degrade the navigation data that are later used to calculate quantitative parameters.

The diving time of AUVs (Table 8) is typically limited by the endurance of the on-board batteries; 24-hour operation is now common, with much longer durations becoming possible (Griffiths & McPhail 2011). Some AUVs employ acoustic communication with a surface ship to monitor and update navigation and to activate command sequences (e.g. abort mission). AUVs are commonly used in the water column for bathymetric mapping (Wynn et al. 2014), side-scan sonar imaging, and other geophysical sensing (e.g. sub-bottom profiling, magnetometry). Many AUVs require to be in continuous motion (typically at 1.5 to 3 knots) to maintain trim, and this type has been very successful in obtaining hundreds of thousands of images with precise navigational information over large areas (Morris et al. 2014). Some AUVs are able to move at very low speeds and to hover (i.e. remaining in one place while keeping constant altitude), and to capture images at low altitudes (e.g. <2 metres; Pizarro et al. 2013). AUVs commonly accommodate instruments for navigation, and detection of physical and chemical parameters, in addition to the camera system. Advantages include their ability to work in remote environments, stability in the water column, and long deployment times (Jamieson et al. 2013, Morris et al. 2014).

Bottom-crawling ROVs and AUVs offer another mode of camera operation. The “Benthic Rover” is an autonomous seabed-transiting vehicle designed and operated by the Monterey Bay Aquarium Research Institute (MBARI) at the Station M deep-sea time series site in the north-east Pacific (Sherman & Smith 2009). It captures images and measures sediment oxygen consumption rates over deployments of up to one year.

Fixed point observatories

Both stationary and mobile imaging platforms are now being integrated into fixed point observatories, in combination with other scientific equipment (Vardaro et al. 2013). These observatories (Table 9) are intended for long-term multidisciplinary study of the water column and seabed. In some cases, live video feed can be accessed from a land-based control station, and mobile equipment can be controlled remotely. In contrast to deployable/retrievable lander systems, fixed stations are difficult to maintain, with ROV or submersible intervention often required for maintenance. Details of existing observatories are provided in Favali et al. (2015).

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Metadata

Metadata is information that may be used to process the images or information therein. It includes information on the position and orientation of the camera, and camera settings used in capturing the images. For example, in order to relate the images (and observations therein) to a geographic coordinate system, it is necessary to know the camera position and orientation. To correct for colours and intensities, photometric properties such as camera sensitivity, lights used and water properties are needed. Although it is often theoretically possible to recover all those parameters from the data themselves (‘self-calibration’), it is advisable to obtain parameters by calibration whenever possible as this is more robust and reliable. Data on the environmental conditions at the image capture location are often collected in tandem with the imagery using sensors and sample capture devices.

Underwater navigation

To geo-reference an image (and the objects within it), the position and orientation of the camera at the time of image capture is required. In many towed camera platforms, the position of the camera may be estimated from the ship or platform’s position in calm or low-current situations (a combination of the ship’s position, the platform position relative to the ship and the camera position on the platform). Vehicles often have integral systems of collecting position data. The Global Positioning System (GPS) and derivatives of it (DGPS, RTK-GPS) have greatly improved navigation on land and at sea and in routine use, but do not work underwater. Applying one or several methods for locating an ROV, AUV or towed camera system underwater is developing into a standard procedure. Several different methods exist for tracking the location of underwater vehicles: inertial navigation systems and acoustic systems, such as Long Base Line (LBL), Ultra or Super Short Base Line (USBL, SSBL) navigation, and Doppler Velocity Log (DVL) measurements (Bingham 2009).

Inertial Navigation Systems (INS) record position changes in a relative coordinate system by combining accelerometers with gyroscopic sensors and navigational processing routines (Woodman 2007). INS do not rely on external sensors, but at least one reference point is needed to locate the vehicle in a generally accepted geographic coordinate system (e.g. WGS84, UTM) to obtain absolute positions. This can be done in real-time or post-processing. Inertial navigation sensors use accelerometers to determine the path of vessel motion; they are often used simultaneously as motion sensors or motion reference units of the vehicle (roll, pitch, yaw, heave).

LBL systems are composed of a group of transponders deployed in a known formation at the seafloor. Based on sound velocity, they determine slant range between the vehicle and each transponder in the network. LBL systems use low frequencies (5 to 20 kHz) to achieve a good working range (Stanway 2012). They

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have the advantage over USBL navigation in being independent of the water depth with regards to accuracy. Depending on the distance of the vehicle to the transponders, position update rates with a good accuracy (± 0.1 - 10 m) typically vary between 1 - 20 seconds. For obtaining sub-centimetre position accuracy, high-frequency (typically 300 kHz or greater) LBL systems can be used with an update rate of up to 10 Hz (Kinsey et al. 2003).

USBL systems that are fixed to the ship are geo-referenced via GPS systems and thus do not drift over time. USBL systems measure the travel time and phase difference of the reply signal after interrogating the vehicle transducer, which when combined with the GPS position, heading information of the vessel and static offsets between the GPS antenna and the USBL system fixed to the ship, allow the absolute positions to be calculated in real time. USBL systems need to account for the ship's attitude and often have in-built high quality motion reference units. The accuracy of USBL systems decreases with depth and slant range.

DVL systems, which in their basic concept are Acoustic Doppler Current Profilers (ADCP), are installed on the vehicle and measure the position change of the vehicle relative to the seafloor (bottom-lock). As for INS, DVL systems provide data on relative changes of position with great accuracy, but not on absolute positions. They further suffer from drift as a result of bias and offset in heading as well as possible uncorrected attitude information. Similar to INS they have the advantage of delivering position information close to the seafloor regardless of water depth and even allow improved dead-reckoning in the water column (Stanway 2010).

Underwater navigation systems in mobile vehicles often combine multiple location systems. A joint processing workflow uses the high accuracy of accelerometers and DVL for short time periods, and performs a drift correction using USBL and LBL systems.

Simultaneous Localisation and Mapping (SLAM) is a suite of tools that uses existing knowledge about a location to register the camera location in a spatial framework. This can include both acoustic and imaging settings. For example, some mosaic tools will use SLAM feedback to navigate the vehicle to achieve full overlap, where machine vision recognises features from one image to the next and judges navigational and image capture (Mallios et al. 2010).

Camera position and orientation

The position of the camera (i.e. the centre point of the sensor) may be acquired as latitude/longitude or UTM easting/northing, and depth value or altitude above the seabed. The orientation of the camera specifies the viewing direction and attitude of the camera. While information such as 'facing forward' or 'downward' are useful in some cases, very often more detailed information is required (such as 42° from vertical), particularly where absolute measurement is desired.

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The absolute position and orientation of the camera is typically not measured directly, but may be computed from relative dimensions. The orientation of a rigid body in 3-dimensional space can be described by several different representations. In robotics this is typically a rotation matrix or quaternion. Euler angles are used to represent the orientation of ships, AUVs or ROVs, as these platforms cannot tilt to 90° and thus avoid the gimbal lock problem otherwise inherent in Euler angle representations. Probably the most common representation is using yaw, pitch and roll, as defined in Figure 9. From position, yaw, pitch and roll of the platform in the water, and the known position and orientation of the camera on the platform the absolute orientation of the camera can be computed (e.g. Morris et al. 2014). It is then possible to relate local measurements from the camera in an image frame to a geo-referenced position.

The angular resolution of modern cameras is better than 0.1°. Such precision is not generally necessary, but is of great value for later image-based refinements (e.g. in photogrammetry). Small errors will propagate and accumulate through the relative transformations from the camera to world coordinates and small angular offsets can produce a large leverage. A well-defined common reference system including documented layout of the system is important. To our knowledge there is no real standard for 3-dimensional orientation in the marine world (e.g. sign for pitch and roll etc.).

In many cases, metadata are stored in association with a time code, so the synchronisation of independent clocks, such as those in the ship's positioning system, the imaging platform and the camera can greatly improve the data quality of the location and view direction. This is particularly important in the recording of video data, or in situations where still images are captured at a high rate.

Camera (internal) calibration

Camera calibration can be divided into geometrical and radiometric calibration. The latter is helpful in colour correction routines and will not be considered further in this section. Geometric calibration facilitates image-based measurements and simplifies photogrammetry. Current methods for geometric calibration involve capturing a set of images of a known calibration target (such as a checkerboard) from different points of view (see Figure 10A). Even if measurements or the application of photogrammetric methods are not planned for a particular survey, it may be useful to calibrate the system - it may be impossible to re-establish the same camera configuration after the fact.

The major goal of geometric camera calibration is to determine which light ray in 3-dimensional space is represented by each individual pixel in the image (Hartley & Zisserman 2003, Szeliski 2011). Basic calibration parameters are usually classified into extrinsic and intrinsic types. The extrinsic parameters describe the camera pose, such as rotation and translation in 3-dimensional space, but also

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relative poses within a rigidly coupled camera rig in case more than one camera is used in a synchronised manner. The set of intrinsic parameters depends on the type of camera optics. In the case of an oblique camera, intrinsic parameters include focal length, principal point, and parameters for lens distortion. Using the checkerboard images, all corners may be detected in all available calibration images. The known configuration of 3-dimensional corner points is then used to estimate camera pose and a set of intrinsic parameters such that all 3-dimensional rays from the corner points are imaged by their corresponding pixels according to the camera model depicted in Figure 10B. In a second step, the initial camera parameters are improved by non-linear optimisation. Zhengyou (1999) and Schiller et al. (2008) describe exemplary approaches for perspective camera calibration, while Scaramuzza et al. (2006) describe an approach for wide-angle cameras. Calibration of stereo cameras is described by Shortis et al. (2008).

In the case of underwater cameras, calibration is usually complicated by the additional optics of the glass port/window. Ports are typically flat or spherical, but may have other shapes (see Lenses). Light passing through the glass and into the air enclosed in the underwater housing is refracted. With a flat port and standard camera, the common pinhole model used for perspective cameras becomes invalid as a result of this refraction under certain circumstances. Even though the refractive effect can be approximated to some extent using calibration images captured under water, a systematic, geometric modelling error occurs when using a simple pinhole model (Sedlazeck & Koch 2012). Examples for refractive calibration can be found in Treibitz & Schechner (2006), Agrawal et al. (2012) and Jordt-Sedlazeck & Koch (2012). In case of a perfect dome port, no net refraction occurs if the centre of projection is perfectly aligned with the centre of the dome sphere. However, imperfect alignment and imperfect dome ports can also cause distortion, though with generally smaller systematic errors (Jordt-Sedlazeck & Koch 2012) and the dome acts as a lens itself that changes the focus.

Capturing the necessary checkerboard images for camera calibration is not time-consuming and facilitates high accuracy image-based measurements. Recalibration will be needed if there is any change to the optical arrangement of the system. The date and time of such calibration data should be archived in conjunction with the image data.

Future advances

Advances in image acquisition technology (cameras and platforms) continue to be power-limited, and thus follow the development of battery technology. As that technology improves, marine image acquisition from permanent and/or long-term mobile observatories or platforms is likely to steadily increase. Similarly, some ship-borne platforms are likely to be replaced by autonomous vehicles. Long-range/long-term AUVs are in development, with the prospect of hibernation capabilities to allow

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long-term time series and large-scale areal surveys to be completed over a period of up to 6 months (Wynn et al. 2014). Intermediate data can be sent back to the scientist via satellite, which will enable interaction with the vehicle during operation. Such multi-month and basin-scale observation will allow marine scientists to observe biological processes at temporal and spatial scales currently only available to terrestrial scientists. These new technologies will enhance multidisciplinary studies of the oceans, integrated across the complete depth profile, including all pelagic and benthic environments.

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Image enhancement

Image enhancement involves processing an image following capture to improve its visual quality. Tuning of individual images for better visual quality is often desired, but not feasible manually with large image volumes. The visual quality of an image may be adjusted for a variety of reasons (Figure 11): to more accurately represent the colours of the organisms and habitats in the image, to enhance the colour contrast, to compensate for lighting or other effects in the image capture, and/or to facilitate better detection of items of interest either by humans (see **Image annotation**) or automated detection algorithms (see **Automated annotation**). A variety of methods have been developed to correct for different effects, some of which are reviewed by Kocak & Caimi (2005), Kocak et al. (2008) and Schettini & Corchs (2010). Here the focus is on recent and common techniques for underwater image enhancement, concentrating on methods developed for large image collections. Methods are categorised by their field of application, as a guide for selecting a suitable image enhancement method for a particular set of underwater images (Table 10).

Natural illumination

In shallow waters, where images are illuminated by sunlight, pixel intensities are not only dependent on the distance between the camera and the object of interest, but also on the distance between the object and the water surface. Images captured with a vertical orientation of the camera (perpendicular to the seabed) under natural illumination can suffer from illumination flickering caused by refraction at the air-sea interface (see e.g. Gracias et al. 2008). Image enhancement methods developed for shallow water model the influence of natural illumination, with some methods additionally modelling an artificial light source.

The image enhancement proposed by Chiang & Chen (2012) using the dark channel prior method (He et al. 2011), considered both images captured with natural light only, and with an additional artificial light source. Schechner & Karpel (2005) demonstrated the use of a dual image circular polarisation filter approach to backscatter reduction. Trucco & Olmos-Antillon (2006) considered the forward scattering problem using a simplified Jaffe-McGlamery model (Jaffe 1990). The Duntley et al. (1957) image transmission model was adapted by Carlevaris-Bianco et al. (2010) to remove backscatter from underwater images. Colour correction, by modelling light attenuation using quaternations, was considered by Petit et al. (2009). The particular case of stereo photography was examined by Mahon et al. (2011) and Bryson et al. (2012), using a grey-world model by Lam (2005) and the grey-world assumption (Buchsbaum 1980). Other colour correction methods have been developed by Beijbom et al. (2012) and Åhlén et al. (2007).

Artificial illumination

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The artificial light used to illuminate objects in deep water, or to augment natural light in shallow water, can cause artefacts in images. Enhancement methods to remove the effects of artificial illumination can be applied if the natural illumination effects are negligible. Illumination by an artificial light source often results in non-uniform illumination effects, such as the existence of an illumination cone in an image.

Backscatter reduction using polarising filters was examined by Treibitz & Schechner (2009) and Schechner & Karpel (2005). Equalisation of illumination in stereo photography was considered by Johnson-Roberson et al. (2010), providing a method also likely applicable to single-aspect images. A combined method for colour and illumination correction, *fSpICE*, was developed by (Schoening et al. 2012a). Morris et al. (2014) provided a simple combined methodology for noise reduction, illumination correction and colour correction. More sophisticated approaches for colour-shift and illumination variance correction were given by Singh et al. (2007) and Kaeli et al. (2011).

Other methods

Several methods use techniques for contrast enhancing or sharpening only and do not depend on a specific camera orientation or type of illumination. Garcia et al. (2002) provide a comparison of four different illumination correction methods: an illumination-reflectance model, local contrast limited adaptive histogram equalisation (Zuiderveld 1994), standard homomorphic filtering (Oppenheim et al. 1968), and a two-dimensional polynomial spline (Rzhanov et al. 2000). Eustice et al. (2002) extended these methodologies. Chambah et al. (2004) improved the automatic identification of fish species using the Automatic Colour Equalization (ACE) method (Rizzi et al. 2004, Stark 2000). Several authors have addressed colour correction (Arnold-Bos et al. 2005, Bazeille et al. 2006, Iqbal et al. 2010).

Assessment of enhancement methods

Quantifying the quality of image enhancing methods for a set of images can be challenging. Åhlén et al. (2007) reconstructed colours with a reference colour plate. The difference between the original colour of the plate imaged in air and the reconstructed colour gave an objective assessment. Usually there exists no real ground truth or a reference object/signal in the images to assess the quality of the image enhancement, so the majority of authors use a visually subjective quantification (e.g. Garcia et al. 2002, Morris et al. 2014). Some authors have assessed the quality objectively by measuring the global blur of an image (e.g. Trucco & Olmos-Antillon 2006) estimating the range of visibility (e.g. Schechner & Karpel 2005) or comparing the rates of classification for particular objects (e.g. Chambah et al. 2004).

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In the mapping context, similarity measurements on mosaic bounds of similar objects could be used to quantify the quality of an image enhancement method especially for this specific application. In the context of machine learning-based automated classification in underwater images (see **Automated annotation**), the approach by Osterloff et al. (2014) could be applied to rate different image enhancement methods for a set of images. In this approach, cluster indices rank different image enhancement methods by measuring the ability to discriminated between distinct classes on differently processed images.

Many image enhancement methods have been developed to overcome a variety of problems occurring in underwater imaging and obviously there cannot be one single best solution to enhance all kinds of underwater images. Image enhancement can be divided into two main intentions (or tasks) that are correlated: colour correction and illumination correction. Colour correction is often carried out adopting the grey-world assumption (Bazeille et al. 2006, Bryson et al. 2012, Johnson-Roberson et al. 2010, Schechner & Karpel 2005), using histogram stretching and equalisation methods (Arnold-Bos et al. 2005, Beijbom et al. 2012, Iqbal et al. 2010), or by estimating the attenuation coefficients directly (Kaeli et al. 2011). These adaptations of common techniques are also used to enhance images recorded in air. The illumination is corrected by either modelling the illumination by a polynomial model (Mahon et al. 2011, Rzhanov et al. 2000, Singh et al. 2007), Gaussian filtered images (Garcia et al. 2002, Schoening et al. 2012a) or mean/median images (Gracias et al. 2008, Morris et al. 2014). Other methods use localised histogram equalisation (Eustice et al. 2002, Zuiderveld 1994) or localised adapted grey world assumptions and white balancing methods (Bryson et al. 2012, Johnson-Roberson et al. 2010, Schechner & Karpel 2005) to even the illumination. Only a few methods apply direct filtering in the frequency domain (Bazeille et al. 2006, Garcia et al. 2002, Gracias et al. 2008, Trucco & Olmos-Antillon 2006) or attempt to estimate the illumination pattern directly (Kaeli et al. 2011).

Evaluating image enhancement results is itself a subject for discussion, as is the question of parameter optimisation in the aforementioned methods. Some methods use subjective visually-assessed criteria to optimise the parameters of the methods, while others use more objective criteria, for example measuring the global blur, classification rates, or the ability to discriminate between different annotated classes of objects of interest. To increase the robustness of estimated parameters, they are optimised over a set of images, either overlapping stereo images (e.g. Bryson et al. 2012, Mahon et al. 2011), video (Gracias et al. 2008) or consecutive images of a transect (e.g. Bryson et al. 2012, Morris et al. 2014, Schoening et al. 2012a). Only Schoening et al. (2012a) considered the achievement of colour constancy over a whole set of images as an optimisation criterion, a major requirement for an automated detection and classification system. One reason for this might be that although the number of images has increased exponentially, most

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object detection and classification is still carried out manually by experts (see **Image annotation**), but it is expected to become a major driver of underwater image enhancement in the future.

One fundamental problem for image enhancement is that it is not considered prior to image capture. Image enhancement is problem-dependent, and the choice of a suitable image enhancement method is not only dependent on the images, but on the data context (i.e. the question raised in front of the data). The more precisely this question is formulated and integrated in the development of an underwater imaging study, the easier is the development of an appropriated image enhancement method.

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Image annotation

Annotation, the process of documenting what is observed in marine imagery for the extraction of physical, biological and ecological data, has been used in many environments and for multiple purposes. Qualitative annotation for biological or ecological studies may involve general categorisation, or more detailed observations, for example specific behaviours. Quantitative annotation involves the identification of organisms, while often establishing counts of each organism in a defined sample unit (see **Survey design**). In recent years, quantitative annotation has expanded to include the specific location of organisms or features, and the measurement of objects of interest. Such measurements include organism body lengths for biomass estimation (e.g. Durden et al. 2015a), distances of transit (e.g. Smith et al. 2005, Smith et al. 1993), and life trace (Lebensspuren) size (e.g. Bett et al. 1995). Annotation for abiotic factors, such as seabed or substratum type, employs similar techniques.

Consistency in annotation

One major advantage of modern annotation systems is the potential persistence of data. Many studies are designed for immediate specific data needs, but if we deliberately design annotation schemes to provide consistency over time, these data can be used in numerous studies and future comparisons between studies, regions or times. Consistency is valuable within individual research groups, institutions, and across institutions internationally.

Understanding the limitations of image annotation is essential. Identification of species from stills and video can be a challenging task. Complications include object distance from the camera, inability to see an organism from all angles, and taxa that are visually indistinguishable from each other (taxonomic differences occur in features that are not visible in imagery, see **Imagery and Taxonomy**). Ensuring that identifications are not over-reaching is inevitably balanced with finding ways to document as much information as possible in case species-level characteristics can be established at a later stage.

Documentation in image datasets can include the definition of the terms used and at the individual annotation level. Documenting what is unknown is just as important as documenting what is known. Images or video need not be fully annotated at the outset of a particular project, but a flexible structure and the ability to expand annotations for future investigations is critical. Annotation data should be accompanied by metadata (also see **Metadata**), which specifies what has been examined, and what has been omitted or is considered to be outside the scope of the study (see **Survey design**).

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Creating a guide for image analysts

Written or web-based guides (e.g. Jacobsen Stout et al. 2015, Althaus et al. 2013, Gervais et al. 2012) are essential for consistency among image analysts and for the interpretation of data. The methods used by taxonomists in terms of creating hierarchical trees (containing names of species, genus, family, etc.) readily accommodate annotations to the level of certainty to which an individual can be identified. Such hierarchies may follow purely taxonomic classification, or may include 'operational taxonomic units' or morphotypes (see *Field guides, catalogues and identification*). Geological features, habitat descriptions, and other annotations can easily be given a similar hierarchical structure.

The use of a live database for this guide is desirable (see **Data management**). If modifications are recorded, the database provides a means to track nomenclature and other changes. Ideally, such changes are implemented automatically across the entire database of observations. Referencing terms from a database during annotation also ensures that they are consistent, enabling efficient data retrieval. Alternate, obsolete or common names can be cross-referenced to the current preferred species, object, or concept name. Distinguishing characters, colour variations, behaviours, ontogenetic variation, alternate species to consider, published depth and geographic ranges, size, literature references, taxonomic consultants, and molecular information can all be documented at this level. Incorporating images and video for each annotation term (an imagery 'type' collection) displays visual characters that can be used to help identify organisms, particularly when multiple views are included. Researchers may wish to consider constructing imagery keys.

A partnership with taxonomists for corroboration of species identifications is important. Note that specialist taxonomists may never have seen a particular species in its live state or *in situ* (especially from deep-sea or rare habitats), and so may be reluctant to provide a definitive identification. This can be aided by documenting the degree of confidence, for example using the following categories:

- Certain: the organism has been collected and/or has been definitively identified by a taxonomic expert.
- Provisional: the organism is very likely this species/taxon based on investigation (literature search, consultation with outside taxonomic experts, etc.).
- Unconfirmed: the status of the organism is uncertain, pending field collection and further taxonomic investigation, or the description and naming of a new species.
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Taxon identification

Unless animals are collected and expertly identified, the majority of observations in image databases reflect 'morphological' species (morphospecies or morphotypes). For comparative ecological studies this usually proves sufficient. However, care should be taken in reporting extensions to species distributions (geographic and depth). Where morphotypes or morphospecies (sensu Edgar & Stuart-Smith 2009, Howell & Davies 2010, Schlacher et al. 2010) are used, it is essential to document the nomenclature and decision rules used for identification (e.g. Althaus et al. 2015).

In some cases video can provide more information and context to the image analyst when compared to still images (Zhang & Martinez 2006). The ability to view an animal over multiple frames provides additional clues. Organism identification is typically based on form (e.g. size, colour, shape), behaviour (e.g. swimming style, burrowing), and habitat (e.g. demersal, midwater).

Additional information can also be applied to the individual annotation term itself. Secondary terms can include information about symbiotic relationships, gender, habitat, unusual colour or size for this taxon, or behaviours such as swimming or feeding. A level of confidence for a specific observation can also be added (e.g. 'possible', 'likely'). If a database system is available, ancillary data (e.g., observation date, geographic location, depth, temperature, oxygen concentration, etc.) can be merged with each annotation, providing additional clues to aid in identification.

Naming conventions

The use of provisional names is necessary when dealing with observations of organisms that cannot be confidently identified. As an example, an individual fish too distant to be confidently identified might be annotated to the genus level *Careproctus*. For a morphotype that is seen more than once, but whose identity is in question (perhaps the organism has never been collected); a term '*Careproctus* sp. 1' could be assigned. For taxa that are clearly distinguishable, known to be new to science, but remain undescribed, the convention '*Careproctus* sp. A' might be used. Ideally, once the organism is identified or described, these placeholder names would be changed globally throughout the database.

For taxa that cannot be reliably distinguished in imagery, a taxon 'complex' can be created. For example, of forty rockfish species (*Sebastes* spp.), five are visually very similar unless an extreme close-up view of the gill cover and erect dorsal fin are obtained. All five species can be listed as separate terms, along with an additional term '*Sebastes* complex', for use when species-level identification is not appropriate, but where species-level identification can also contribute to '*Sebastes* complex' quantification.

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Geological features and habitat classification

Just as species annotations are based on morphology, geological information is based on what is visible rather than an interpretation of how a feature was formed. For example, the terms 'crack' or 'fracture' can be defined without regard to the processes may have formed them (e.g. faulting). There are many geological and habitat classification systems available for underwater environments (e.g. Greene et al. 1999, Guarinello et al. 2010, Madden et al. 2009). Classification schemes are highly variable depending on the habitat surveyed, country of origin, and organisation, often making it difficult to compare datasets without further annotation or conversion. Development of a standardised hierarchical system within major habitats (e.g. seagrass beds, abyssal plains) that includes grain size (e.g. sand, cobble, boulder), rugosity (e.g. low relief, high relief, hummocky), and descriptive terms (e.g. cold seep, lava punctuated with ponded soft sediment) would be desirable (e.g. National eResearch Collaboration Tools and Resources and the Australian National Data Service 2015).

Software for image annotation

A range of software is available for image annotation. Packages vary from real-time annotation, to programs specific to post-survey annotation. The focus here is on programs that are published, easily accessible, and currently in use. These programs are summarised in Table 11.

Real-time image annotation allows scientists to make annotations during live observations. Often such software is linked to programmable keyboards that allow for user-defined keys allowing rapid data input, and which may, at times, may require a two-person team: an observer and a data scorer. The X-keys Keyboard is one of the main keyboard systems used for data entry, providing geospatial information at each habitat characterisation (Anderson et al. 2007, Post et al. 2010). Anderson et al. (2007) used 'GNav Real-time GIS tracker' software to capture habitat (substratum type, relief and biota presence) and geospatial information (Hatcher 2002).

Data entry programs for real-time annotation are often custom developed, and have included Microsoft Excel® macros and Microsoft Access® databases (Victorian Towed Video Classification Program from Ierodiaconou et al. 2007, Neves et al. 2014). Each of these databases has the advantage of incorporating scoring methods complimentary to their organisation. The Ocean Floor Observation Protocol (OFOP) has been used to log real-time observations of the seafloor and associated biota with geomorphological and biological classes as well as during post-processing (De Mol et al. 2011, Jones et al. 2010).

Marine imagery is often annotated or enhanced after collection in the field, and many post-processing software programs exist to enable experts to annotate

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imagery for percentage cover, presence/absence of biota, or size and abundance of benthic taxa. TransectMeasure™ (SeaGIS 2013) analyses percentage cover and length of biota through still imagery from quadrats of predetermined size using points distributed on the screen. Analysis points can be allocated randomly, systematically, or randomly stratified, with the number of points determined by the user. The advantage of this program is that it allows for the user-allocation of predefined biota labels from nationally recognised classification schemes, with up to eight attributes allocated to a single point. Perpendicular or oblique imagery may be used with TransectMeasure™. Coral Point Count with Excel® extensions (CPCe) is a program that calculates percentage cover of benthic biota from user-allocated points (user defined numbers) spatially distributed over still imagery; it was designed for perpendicular imagery (Kohler & Gill 2006). This software provides automatic descriptive summaries accessible in Microsoft Excel®.

The open source Video Annotation and Reference System (VARS; Schlining & Stout 2006) interface has been used to catalogue marine species, geological features, and equipment use and employs a database for analysing complex observational data in deep-sea environments. It has been used with ROV video and still images from AUVs, benthic rovers and time-lapse cameras. This customisable software allows for the retrieval of descriptive, visual and quantitative data when annotating imagery. It was developed and is employed by MBARI, but is available to interface with other databases. ImageJ (Rasband 2015) is software that can calculate area and pixel values (e.g. percentage cover) for still imagery and is well suited to perpendicular imagery and allows for user manipulation of image processing functions such as contrast, sharpening and edge detection (Haywood et al. 2008). This program is often used for calculating percept cover estimates of area for benthic biota and size distributions of benthic taxa.

Aide au DEpouiLlement Interactif des données des Engins sous-marins (ADELIE; Ifremer 2014) allows for both real-time and post-survey analysis of underwater video with flexible data outputs accessible by Microsoft Access® or Excel®, or spatial programs such as ArcGIS™. Underwater video annotation is available through ADELIE-Observations and the Customizable Observation Video imagE Record (COVER) extension allow for user-defined biological and geological labels to be created within the software. While there are many different programs available for annotation, the goals of the survey dictate the types of data to be acquired from the imagery.

Web-based systems for image annotation require specific metadata to be associated with each image set/survey. Some web-based systems can assist in annotation for ecology, and potentially provide tools for annotation while in the field (if web access is readily available). Collaborative and Automated Tools for Analysis of Marine Imagery (CATAMI; Althaus et al. 2013) and Squidle (Williams & Friedman 2015) are two major tools that can be used (online and freely available). CATAMI

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allows for image annotation to fine and broad-scale schemes, as well as image recognition for matching similar habitat types based on learning algorithms. Squidle allows for random and stratified sampling as well as stratified and random point count distribution on images. Both web-based systems are easy to use and allow data to be annotated using consistent classification labels. While both are functional systems, some sections are under development, and require further support in areas of automated classification of seabed habitats using image recognition algorithms. Benthic-Image Indexing and Graphical Labelling (BIIGLE; Ontrup et al. 2009) is a Flash-player web-based program designed to annotate large sets of image data for biological purposes, created by the University of Bielefeld (Schneider et al. 2012).

Multiple annotators and citizen science

To create a robust data set, annotations of the same images/sample unit by multiple annotators can be combined or compared to improve annotation consistency and quality. Crowd-sourced or citizen science-based marine image annotation has been used to help research scientists generate information about the seafloor and the associated ecology. Here the tactic is similar, involving multiple annotators examining each image, and statistically selecting the annotation from those data. Citizen science projects may not be vigorously vetted and generally offer a limited set of identification options, and thus may limit the scope of scientific questions. However, employed at the appropriate level of required expertise, citizen science can reduce the annotation workload and increase the efficiency in coarse-level image annotation. Exploring the Seafloor is a web-based collaboration citizen science project focused on identifying kelp and sea urchins across Australia (www.Exploretheseafloor.net.au). Zooniverse is a platform for multiple citizen science projects, including Seafloor Explorer, and Plankton Portal for marine imagery. Seafloor Explorer (www.seafloorexplorer.org) is a project for annotation of imagery from the Habitat Mapping Camera System (HabCam) and collects information on habitat type, biota present and size of scallops, fish, sea stars and crustaceans. Plankton Portal involves classifying and measuring plankton in images from the *In situ* Ichthyoplankton Imaging System, which captures continuous images of plankton with a macro-camera as it is towed (www.planktonportal.org). Fish for Knowledge (www.fish4knowledge.eu) is a web-based program for video annotation to ground-truth video annotations for the collation of a database for automatic image detection of marine animals. It should be noted that it can be a challenge to keep citizen scientists motivated to continually score imagery over time, and also to monitor the accuracy of their annotations (Foster et al. 2014).

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Imagery and Taxonomy

Just as on land, species recovered from the ocean may be described in words, numbers, DNA sequences, drawings, *in situ* and *ex situ* photographs or most typically, a combination of all these. As it is impossible to describe every aspect of an organism, the ultimate validation of the species description or record lies not with these data, but with the type specimen deposited in a museum. Thus, the field imagery that is associated with species descriptions is necessarily an imperfect representation of the species concept.

In situ images can provide a range of additional data including taxonomic (e.g. body form in water, colour) and natural history (e.g. habitat, behaviour, life-history, ecological associations). Some of these data can also be captured through the imagery of live specimens kept briefly in the laboratory before fixation, or for longer periods in aquaria. *In situ* imagery can still be of taxonomic value in that it improves knowledge of a species concept, but with the caveat that its taxonomic quality is dependent on the quality of the initial identification, assuming it is not based on type material directly. An increasing number of *in situ* 'species' images uploaded to central databases are of this nature.

High quality taxonomic imagery enables the creation of field guides and catalogues to marine life (Glover et al. 2014). These have the potential to improve our ability to undertake marine ecological research in that they may allow identifications of local fauna to species level by non-specialists. While terrestrial field ecologists can usually start work with a local field guide written by an expert, in the marine realm these mostly do not exist; with the exception of a tiny handful of well-studied sites (e.g. Monterey Canyon), there are no publicly available field guides to the deep-sea fauna.

Here we review the types of marine imaging that are typically undertaken for taxonomy, both *in situ* and *ex situ*, and how these data are made available through field guides, catalogues and increasingly, online databases (e.g. see Figure 12). In addition, we discuss the challenges for identification from *in situ* imagery without physical collection, and the importance of quality *ex situ* imagery in making this possible.

Species description from imagery

A taxonomic species description is the best effort of a scientist to describe a specimen, or series of specimens, that have been deposited in a museum as reference material (or type) for a new species name. The description, the specimen, and the name form the trinity of taxonomy: without one, the taxonomic work is incomplete. In the 250 years since Linnaeus, conventions of the naming system, and the organisation of type specimens in museums or other collections has changed

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little. On the other hand, the methods, technologies and distribution methods for the 'description' part of the taxonomic trinity has changed beyond all recognition.

While DNA sequencing as a descriptive methodology has gained most of the headlines (mainly as it is useful for reconstructing evolutionary trees), there have been equally remarkable transformations in imagery for taxonomy. In the time of Linnaeus, illustrations were in the form of drawings. Imaging methods now employed include digital photography (including underwater), photomicroscopy, confocal photomicroscopy, and photogrammetry in addition to electron microscopy, micro-computed tomography (micro-CT) and nano-computed tomography (nano-CT). These new methods offer three principal benefits: (1) a vastly-improved quality of comparative data to undertake the basis of the taxonomy itself, (2) the data to allow others to identify the organism without needing to study the voucher specimen, and (3) a wealth of important information and clues to the organism's natural history and ecology. It is interesting to note that DNA taxonomy (Vogler & Monaghan 2007), also offers the first two of these benefits, but rarely the third. DNA taxonomy in its purest sense (databasing or publishing DNA barcodes from specimens without morphology) also fails to make the link to past taxonomic methods – in other words ignoring the past several hundred years of accumulated taxonomic knowledge. The majority of taxonomists now working, including those heavily involved in DNA taxonomy, advocate a combined approach of DNA and morphology through imagery.

The International Code for Zoological Nomenclature (ICZN 1999) requires that new species are assigned a type specimen, specifically "each nominal taxon in the family, genus or species groups has actually or potentially a name-bearing type". Interestingly, the code is slightly vague as to whether the actual or potential type specimen must be collected and deposited in a national collection. This has caused some debate and confusion in the literature (e.g. Dubois & Nemesio 2007). For example, a new species of capuchin monkey was described with the type specimen "photographed and subsequently released back to his group" (Pontes et al. 2006). In the marine world, deep-sea organisms are routinely observed that may be new species, but without collection the taxonomy is almost never accomplished. An example is the 'lophenteropneust' that was often observed on the seafloor, presumed to be new, but not collected and described until 2005 (Holland et al. 2005) and found to represent a new family, genus and species. The debate as to whether specimen collection is required is ongoing (Donegan 2008, Dubois & Nemesio 2007). As imagery becomes ever more powerful, and species concepts are backed up by DNA evidence, it is likely that some marine species may be described from *in situ* photographs and tissue collection, with the tissue sample (and its DNA) forming a voucher specimen equivalent to a type. In terms of usefulness to science, this approach will always be second best, but a reasonable argument can be made that it may be better than no taxonomy at all for some hard-to-collect taxa.

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Key to the challenge of identifying marine images from AUVs, ROVs or towed systems is initial quality taxonomy that incorporates both *ex situ* and *in situ* photography and archived genetic data (e.g. Alderslade & McFadden 2012, Williams & Alderslade 2011). Taxonomy and identification operate in a virtuous circle: improved taxonomy leads to further identification guides, which themselves lead to further taxonomic descriptions. However, on their own, neither is effective for the advancement of ecological or evolutionary questions. In the case where AUV surveys are being undertaken in poorly-known regions, for which a taxonomy is lacking, there is extremely limited possibility for identifying fauna to species level (Howell et al. 2014). Valuable ecological research does not require species-level identification (Bett & Narayanaswamy 2014). However, this is possible in areas with well-worked taxonomy, and highly-localised field guides. An extreme example is that of cetacean surveys, where species (and even individuals) can be identified from aerial photographs (Schweder et al. 2010).

Online databases are providing the crucial link between taxonomy and new field guides that are of direct use to marine survey work. An example is the World Register of Marine Species (WoRMS; Boxshall et al. 2014) and thematic databases such as the World Register of Deep-Sea Species (Glover et al. 2014) or Codes for Australian Aquatic Biota (Rees et al. 2014). Thematic or contextual databases to a central well-updated source database (e.g. WoRMS) can quickly permit the creation of imagery-based field guides such as Deep Sea ID (Glover et al. 2013). In the future, these could be localised to smaller regions, such as areas of interest for climate-change monitoring (e.g. Porcupine Abyssal Plain) or deep-sea mining (e.g. Clarion-Clipperton Fracture Zone). However, this will not be possible without the fundamental taxonomic work being done in those regions to a high standard and incorporating all types of specimen imagery.

Field guides, catalogues and identification

Field guides are compiled to aid identification in the field, from observation without necessarily collecting specimens. They are usually targeted at non-expert users describing features distinguishing species in a local context using primarily *in situ* photographs, but also illustrations and general descriptions. Field guides ideally show the subject from various angles and in various states (e.g. corals with polyps extended and contracted). Good field guides are usually underpinned by a comprehensive, taxonomic species catalogue for the region they describe (*sensu* Howell et al. 2014), and are often focused on a particular taxonomic group. Restricting field guides to a local context and few taxa allows the *a priori* elimination of potential confusions. In addition, it allows the author to present a comprehensive list of the known taxa at the time of publication, thus allowing field observers using the guide to recognise potentially new additions to the known local species set.

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In the marine realm most available field guides are targeted at divers, thus covering only shallow water depths (e.g. Edgar 2008, Gowlett-Holmes 2008, von Mende 2011). Specific field guides for identification of deep-sea biota are less common (although a few exist, e.g. Jones & Gates 2010), with the exception of guides for the identification to more or less coarse groupings of fishery bycatch (e.g. Gershwin et al. 2014, Hibbert & Moore 2009, Tracey et al. 2014) and most recently Deep Sea ID (Glover et al. 2013) and Deep-Sea Guide (Jacobsen Stout et al. 2015), which make use of online databases. Such taxonomic online species catalogues are an invaluable resource for compiling regional species lists in the absence of area specific field guides, especially where they include photographs of live or *in situ* specimens.

With the increased use of remotely-collected imagery for habitat descriptions as well as biodiversity studies, image guides or catalogues of marine species are being compiled for individual study regions or projects (see **Image annotation**). Some of these have been made available online, for example the Deep Sea ID (Glover et al. 2013) and the deep-sea HURL Animal identification guide (Hawai'i Undersea Research Laboratory 2013a); but also see Mills et al. (2007), Neptune Canada (Gervais et al. 2012) and Howell & Davies (2010). However, the taxonomic rigour varies between these catalogues. Howell et al. (2014) suggest that ideally a census of the biodiversity with cameras and simultaneous collection of specimens for taxonomic examination should precede other image-based surveys, such that a field guide for identification to genus or species level can be compiled. Recent studies of new holothurians at the mid-Atlantic Ridge (Rogacheva et al. 2013) and of new octocorals on Tasmanian seamounts (Alderslade & McFadden 2012, Williams et al. 2011) combined *in situ* and *ex situ* photography of specimens collected for a robust identification. Where this is unfeasible, a guide to Operational Taxonomic Units (OTUs), distinguished using morphology, texture and potentially colour, can be compiled through systematic review of all imagery collected for a survey (e.g. morphospecies sensu Edgar & Stuart-Smith 2009, Howell & Davies 2010, Schlacher et al. 2010). Even though morphology is generally used to identify OTUs in imagery, the terminology is usually project-specific rendering comparisons and data-sharing between studies difficult (Althaus et al. 2013, Althaus et al. 2015). In Australia the CATAMI project has composed a nationally-standardised photo-taxon classification rooted in broad taxonomy but including morphological features. The biological classification is structured hierarchically with descriptions at each branch allowing recording of fine detail, but also aggregation at increasingly coarser levels akin to aggregating species to genus or family level (Althaus et al. 2013, Althaus et al. 2015).

Challenges for identification

Identification of species from imagery is difficult and uncertainty will remain with taxonomic identification from photographs only. The degree of uncertainty is dependent on the extent of the underlying taxonomic knowledge of the species pool and on the taxa involved. Taxa with plastic morphology (e.g. sponges) or where

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distinguishing features are typically microscopic (e.g. sponge microsclere and spicules, or octocoral sclerites) are particularly challenging. This problem is exemplified by the 'unknown' categories within the HURL Animal identification guide (Hawai'i Undersea Research Laboratory 2013a) and in the comments field in the Neptune Canada Marine life Field Guide (Gervais et al. 2012). Often identifying characteristics such as mouthparts (e.g. crustaceans or gastropods), arrangements of spines (crustaceans) or dorsal plates (echinoderms), and details of ventral features are obscured, hidden or out of focus in *in situ* imagery, although field guides with multiple views of identified specimens may help overcome some of these problems. In addition interpretation by different observers can add uncertainty (e.g. Beijbom et al. 2015, Schoening et al. 2012a). In common with conventional specimen-based identification, if identifications are documented using photography and the level of confidence in the identification flagged (see **Image annotation**), it is possible to revise them based on new data regarding the local species pool, corrections suggested by more experienced observers, or availability of better imagery (Howell et al. 2014).

Future developments

Two technologies will underpin future developments in marine taxonomic imaging. Firstly, increased broad-scale and high-resolution imagery both *in situ* and *ex situ* will rapidly advance the description of the morphological and ecological characteristics of species and higher taxa. Secondly, online global databases will allow the ready distribution of these data to scientists, industry, regulators, educators and the general public. The key is to merge these approaches to produce the working tools that are needed to survey and document challenging marine habitats from a new generation of underwater vehicles.

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Data management

Marine imaging is a data-rich discipline, which is moving towards 'Big Data' dimensions and the consequent challenges for management. Management of imagery data encompasses storage, security and access. Strategies for efficient and effective marine imaging data management involve implementing both technologies and protocols.

Marine imaging generates several types of data to be managed, including original and enhanced images and video (see **Image enhancement**), taxonomic catalogues and nomenclature (see **Imagery and Taxonomy**), annotations (see Image annotation) and metadata (see **Image acquisition**). Data associated with each of these, such as feature maps for pattern recognition approaches and visualisations of automated feature detections, provide additional files of multiple types. In addition, data on the creation and modification of all of these must be managed, including information such as the date and time, users involved, and the basis, reasoning or assumptions involved and associated references, all of which must be stored in a searchable format. Each of these data types impact the volume and variety of data and files in the dataset.

Marine imaging data collections have begun to rapidly increase in volume, variety and velocity of acquisition. These three traits are characteristic of 'Big Data' (Howe et al. 2008), seen in other scientific fields such as genomics, meteorology and physics, and in commercial sectors. In marine science these traits represent multiple factors. The volume of data has changed principally by an increase in the number and size of imagery captured; this increase has been a result of a reduction in the physical size and the increase in capacity of energy-efficient storage media, the increase in the pixel resolution of cameras (up to 8K), the independence of image acquisition from ship operation with the use of autonomous vehicles, and the use of multiple cameras on a single platform. The variety of data has increased with the use of both still and video cameras (often simultaneously), an increase in 3-dimensional image capture, better lighting facilitating the use of colour cameras in addition to black and white cameras, the use of multi-spectral cameras, and image capture from multiple angles (e.g. vertical and oblique). The velocity of data generation has also increased with the use of multiple platforms and cameras deployed in parallel (e.g. AUV and ROV), recording of HD videos, the computation of derived data from images, and the use of imaging for environmental monitoring in newly established offshore marine protected areas (e.g. the Marine and Coastal Biodiversity project of the Convention on Biological Diversity) and by industries developing new markets (e.g. deep-sea mining). Despite the increase in the volume, variety and velocity of imaging data created, the use of sophisticated information technology to support management of these data has not been widespread.

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An important feature of data management technology is the ability to manage access to data, allowing collaboration between users. Inputs to data collections benefit from collaborative approaches. Wuchty et al. (2007) showed that the degree of collaboration has increased considerably to target research projects of higher complexity. This trend has been paralleled by a rapid development in internet connections and bandwidth, and researchers have proposed new ways of collaborative data sharing and interpretation in research, called “Science 2.0” (Shneiderman 2008, Waldrop 2008).

Imaging data are stored using a variety of types of infrastructure. Many image data collections are stored on personal computers or portable hard disk drives. Small volumes of data are usually stored on external hard drives or on Network Attached Storage devices (NAS) that provide higher data capacities. In some institutions the data are stored on larger server infrastructures managed by an IT department, but often the field experts handle the physical drives and take care of backups. For analysis, data are then either accessed over a network or back-transferred to laboratory computers. Data centres (e.g. Pangaea) and repositories offer storage and retrieval services. Cloud computing services (Armbrust et al. 2010) - large data storage and computer facilities that can be accessed from anywhere around the world and can be scaled to specific needs - are also gaining popularity to achieve sustainability and flexibility in data storage and retrieval.

Currently-used data storage and management strategies/technologies are evaluated in Table 12. Most data are currently stored on laboratory desktop computers, which allow easy use with rapid data access speeds. Also popular are external hard disks, an affordable storage option that allows simple data sharing as they are portable. NAS provides more storage capacity and is usually cost-effective for larger datasets. NAS eases the local sharing of data within an institute, but must be web-accessible to make data sharing with external collaborators efficient. By using a cloud storage provider, the data are moved out of the institute at the cost of data access speed. On the upside, this provides improved data safety and reduces the institutional personnel cost as less support is required. A specialised governmental marine data centre (e.g. the British Oceanographic Data Centre and the Australian Integrated Marine Observing System) can provide cheaper storage, and more efficient collaboration through tools that are streamlined for data access and analysis. One important benefit of a specialised data centre is the tracing of data access and derived data computation to provide data provenance, making interpretation reproducible and more reliable. A hybrid solution of multiple institutional web-accessible storage repositories and a superior marine data centre could combine the advantages of both strategies by easing data access through synchronisation of different repositories, and reducing the cost of storage while increasing data security.

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The sustainability of data management infrastructure and protocols is now being to be considered on longer timescales. The infrastructure is expected to continue to improve with funding provided by public administration and agencies supporting its development, such as the US NOAA data sharing policy (US National Oceanic Atmospheric Administration Environmental Data Management Committee 2011), the US National Science Foundation data management requirements (US National Science Foundation 2010), or the EU Horizon 2020 data management guidelines (European Commission 2013).

A centralised data facility that keeps related data from institutes and projects together, and is accessible by a wide range of authorised users would allow streamlining the complete data management process from acquisition to analysis. Such a facility would hold capacities at least in the Petabyte range to allow storing the huge volumes with backups for multiple imaging-based research projects. A standardisation of data storage would ease retrieval of data for future research. This is paramount as monitoring of environmental changes using images is now a pressing issue. Bringing data to such a facility includes similar methods as for current data sharing. Selected parts of the data should be fused to standardised datasets as benchmarks for manual or automated analysis. A reference would be created to assess automated solutions as well as to assess expertise of researchers and users. One such approach has been taken by the NOAA Fisheries Strategic Initiative on Automated Image Analysis (US National Oceanic Atmospheric Administration). The access to data created in different projects could be granted or rejected on a per-user and/or per-project basis. This would allow for maximum privacy where needed yet, more importantly, for a wider database for research than any individual institution could provide.

An example that combines the challenges of data variety and collaboration, where a centralised data repository is necessary, is the management of the taxonomic catalogue and associated annotation nomenclature (see **Image annotation** and **Imagery and Taxonomy**). Such data are diverse as many different categories can be included (e.g. biological, geological, man-made). Nomenclature needs to be maintained and updated. This makes synchronisation across projects and datasets very difficult. This similarly calls for a centralised repository where the nomenclature is stored and carefully curated and monitored regarding its origin. Individual research projects can select parts from a centralised nomenclature that best fits their question, their annotations will be stored in a standardised way accessible and understandable for other users.

One open challenge particular to marine imaging is the access to a server-based dataset, when no connection to this server is available. This is the case during research cruises where large amounts of image data from various databases must be available. Meaningful software to automatically synchronise new image data and derived data including re-annotation of old images, will be required. Such software

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should be able to copy data to a mobile computer/server and register those data as 'checked out' in the host database. Newly acquired data could be sent back to the central storage facility/server once a broadband data connection is available. If this is not available, a two-step synchronisation could be initiated, where in the first step all new data are prepared by the project assignee to fit the storage scheme and sent to the facility. The data would be added to the repository in the second step.

Many data storage, data management and data access schemes are still being developed; a joined and overarching repository for all image-based marine research is unlikely, but interoperability needs to be established. National funding policies might lead to several repositories that might serve the needs of multiple institutions or even countries. New and updated repositories should aim to enable easy exchange of data and knowledge between projects and users.

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Automated annotation

The onerous, time-consuming nature of visual data interpretation by human observers makes a comprehensive, full-scale interpretation of large image datasets unfeasible. With the rapidly growing volume of data (see **Data management**) and the corresponding lack of human resources available to interpret and annotate the data, less than 1−2 % of collected imagery is ultimately manually annotated (Beijbom et al. 2012). In addition, issues of consistency (both intra- and inter-observer agreement) and objectivity of human annotators lead to erroneous, incomparable results (Culverhouse et al. 2003, Schoening et al. 2012a, Seiler et al. 2012). Consequently, automated techniques may be particularly valuable in developing efficient and effective image annotation methods.

Although there have been great advances in the fields of pattern recognition, image processing and machine learning, there has been a lag in the application of these advances to underwater image datasets. This could be related to the many challenges associated with processing images captured underwater (see **Image enhancement**). Natural scene illumination is usually poor, and there is often little figure-ground contrast. Additional challenges are introduced by wavelength-dependent attenuation that limits the effective range of optical imaging in realistic settings to a few metres and causes the strong colour imbalances often visible in underwater images. In shallow waters, the refraction of sunlight on surface waves and ripples can be problematic, while in deep waters the imaging system needs to carry its own moving light sources resulting in changing illumination in the scene. State-of-the-art camera calibration methods are complex and most practitioners use methods for camera calibration and distortion compensation that do not fully account for refraction of light through the air-viewport-water interface (see **Image acquisiton**). These effects present unique difficulties when working with underwater imagery. Despite these challenges, there have been a number of attempts at using pattern recognition algorithms to extract useful content from underwater imagery (Figure 13), which have achieved varying degrees of success.

Two application domains in automated image analysis are discerned by the image background: midwater images with open water in the background, and seafloor images with sediment, rock or other substratum in the background. The appearance of the background poses challenges for the detection of objects appearing before it, so each requires the application of suitable pattern recognition methods that are tuned to that particular background.

Pattern recognition methods

Pattern recognition combines methods of image processing and machine learning. Machine learning algorithms can generally be divided into supervised classification and unsupervised clustering techniques. Unsupervised clustering is capable of

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processing large amounts of data quickly and requires little to no human intervention. While these methods are useful for quickly summarising and exploring patterns in the data, there are no guarantees that the resultant clusters represent information that is relevant to end users (Friedman 2013). In supervised classification, a human is required to provide semantic information to train an algorithm using human-labelled examples, which can then be used to automatically classify remaining data.

In pattern recognition, elements of image data (i.e. pixels, grid cells or regions of interest) are first transformed into a numerical, non-semantic description, called a ‘feature’. Machine learning algorithms are then used to find relationships and similarities between descriptions of different observations, which can then be used to interpret or group (‘classify’) image data. The transformation of data into features can employ low-level image characteristics such as colour values, mid-level characteristics such as distributions of intensity patterns that form connected regions or high-level objects such as instances of an object of interest. The features of image elements are comprised of n-dimensional feature vectors and are computed by different feature descriptors, reflecting different visual aspects of images (texture, colour or shape). Non-visual features, such as terrain structure from stereo imagery, have also been successfully used for classification of underwater imagery (Friedman 2013). The following provides a brief overview of some of the image descriptors that have proven useful for underwater image classification.

Feature descriptors

Most feature descriptors provide information about the colour, shape or texture in an area around a pixel, to provide a feature vector for that pixel. Texture in images has proven useful and is the most commonly-used group of features for classification of benthic imagery as it helps to alleviate some of the problems with colour in underwater images. Texture refers to the visual patterns that result from the presence of local differences in colours or intensities in an image. Texture in images can be calculated using a variety of different methods and at different scales. Some texture descriptors include Haralick Grey Level Co-occurrence Matrices (GLCM), Gabor filters and Local Binary Patterns (LBPs).

Haralick GLCM features quantify the frequency and amount of grey-tone variation between cells at specified distances and angles. Haralick et al. (1973) defined 14 grey-level difference statistics that can be derived from the GLCM. The five statistics that are frequently used for texture classification include contrast, correlation, homogeneity, energy and entropy (Denuelle & Dunbabin 2010, Gleason et al. 2007, Haralick et al. 1973). Gleason et al. (2007) used Haralick’s GLCM features for multispectral underwater images. They concluded that the results may improve from a more thorough analysis on the textural properties of reef benthos and by using more sophisticated texture descriptors. Denuelle & Dunbabin (2010) extended

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the GLCM descriptor to operate on pairs of colour channels to classify kelp in underwater images. They used green/green, blue/blue and green/blue channels, omitting the red channel owing to its strong attenuation in water. They effectively created a colour-texture descriptor that uses the differences in intensities of colour channels to quantify texture.

The Gabor filter (or Gabor wavelet) is a linear filter used for edge detection (Fogel & Sagi 1989). Frequency and orientation representations of Gabor filters are said to be similar to those of the human visual system (Daugman 1985). Gabor features have been widely used for texture representation and discrimination. For texture analysis, a set of filters is constructed at chosen frequencies and orientations. The standard Gabor filter is highly orientation-specific, so in order to generate rotation-invariant filters, it needs to be computed at a range of different orientations. Johnson-Roberson et al. (2006a,b) used the mean and standard deviation of Gabor wavelets at six scales and four dimensions for texture discrimination in classification of underwater images.

Ojala et al. (2002) introduced LBP as a global/local image texture descriptor. LBP can be computed at multiple scales and made to be uniform and rotation-invariant and are also reasonably invariant to monotonic transformations in illumination. This makes them useful for texture classification in underwater imagery with non-uniform illumination conditions. Compared to Gabor wavelet texture classification (Fogel & Sagi 1989), LBP have been found to yield similar levels of performance with much lower computational cost and without the need to predefine a filter bank (Caifeng et al. 2005). Clement et al. (2005) compared LBP against Gabor wavelets and a Hough transform. They found that LBP out-performed both of the other texture descriptors. Caifeng et al. (2005) also compared LBP to Gabor wavelets for the purpose of facial recognition. They found that LBP features provide excellent discriminatory power at a much lower computational cost.

The use of colour information for classification is often hampered by variations in illumination and inconsistent colour representation. Consequently, the majority of benthic image classification approaches use texture-based features to describe the content in the imagery. Colour is not often used in many vision-based classification problems, but it is used in classification of biota in marine imagery (van de Weijer & Schmid 2006). Pizarro et al. (2008) showed examples of underwater habitats that are extremely difficult to discriminate without colour information. It has also been shown to be an indispensable feature in the taxonomic classification of megafauna (Schoening et al. 2012a), and the image segmentation of polymetallic nodules (Schoening et al. 2012b). Obtaining images with stable illumination is crucial to provide data that can effectively be assessed automatically. In some rare cases, colour is a strong feature and can be use to quantify biota by their light reflection (Purser et al. 2013), or to detect laser markers.

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Histograms provide a compact summary of the distribution of colours in an image or region. They typically represent the number of pixels that have colour values within specified ranges. Colour histograms can be computed for a wide variety of different colour spaces. Many different histogram types have been used, including but not limited to red-green-blue (RGB) histograms, hue histograms, opponent colour histograms and other accumulative colour features (van de Weijer & Schmid 2006).

Classification in midwater images

Marine imagery in midwater environments presents some unique challenges for the application of computer vision techniques. Imagery is often used to follow the movement of biota in the water column, and this movement adds a temporal factor that can be used to track individuals. This movement can also lead to occlusion, and requires the gathering of additional depth-of-field data to allow the detected objects to be scaled appropriately. Alteration of camera settings (e.g. zooming) often occurs in capturing imagery of moving objects, causing challenges for automated classification of objects in the imagery, such as varied illumination patterns and a variation in the pixel size of the object.

Automated methods have been published for images captured in the midwater environment (e.g. Edgington et al. 2003, 2006, Walther et al. 2004, Spampinato et al. 2010), where fish and jellies are often the objects of interest. Plankton detection has also been an area of research, with specialised hardware developed to image individuals in a small aliquot of water, where illumination conditions are controllable, enabling higher quality imaging and thus facilitating successful classification (Sosik & Olson 2007, Tang et al. 1998).

Classification in seafloor images

The application of computer vision to seafloor imagery has received more attention. Approaches have again been tailored to the scientific objectives of the studies: some aim to automate broad-scale habitat mapping and to describe the dominant substratum in the whole image (Friedman et al. 2010, Friedman et al. 2011, Marcos et al. 2005, Olmos & Trucco 2002, Pizarro et al. 2008, Pizarro et al. 2009, Soriano et al. 2001, Steinberg et al. 2010), while others have focused on finer-scale biotic coverage estimation, which involves classification of sub-image regions through segmentation (Friedman 2013, Johnson-Roberson et al. 2006a,b, Kaeli et al. 2006, Mehta et al. 2007, Purser et al. 2009, Smith & Dunbabin 2007) or rectangular-shaped patches (Beijbom et al. 2012, Denuelle & Dunbabin 2010, Foresti & Gentili 2002). Species coverage can also be estimated from singular points in the images that are (semi-)automatically classified and the determined class abundances extrapolated to characterise the complete image (Beijbom et al. 2015, Kohler & Gill 2006). Very specific objectives have involved abundance counts for a particular taxon (Bagheri et

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al. 2010, Clement et al. 2005, Di Gesu et al. 2003). Clustering has been used successfully: unsupervised clustering has been applied to segment images in different applications (Pizarro et al. 2009, Steinberg et al. 2010, 2011), while supervised clustering has been applied in several contexts.

Different approaches to represent image content with appropriate features reflect the large variety of methods used by the image processing community, and the considerable differences between the aims and individual specifications of analysis. Many approaches neglect colour information and focus on intensity and contrast, such as LBP, which have been widely used for underwater image interpretation (Clement et al. 2005, Marcos et al. 2005, Seiler et al. 2012, Soriano et al. 2001).

Smith & Dunbabin (2007) identified salient image regions and then performed binary segmentation based on local greyscale statistics to segment the image. They then used the integral invariant shape features to compute a shape signature for the identification of a specific star-shaped organism. Di Gesu et al. (2003) used adaptive threshholding on greyscale images and also used various shape descriptors for the specific star-shaped identification. Kaeli et al. (2006) performed segmentation using binary greyscale threshholding and a morphological gradient operator for estimating the percentage cover of a major reef-building coral. Friedman (2013) also used segmentation features, such as area, aspect ratio and compactness, to describe homogenous sub-image regions (or superpixel) shape.

Several studies have attempted to use segmentation-based approaches for delineating superpixels in underwater images. The shape and size of the image regions may contain descriptive information that can be used to aid the classification (Sahbi 2007, Stojmenović & Žunić 2008, Yoshioka et al. 2004).

These attempts use features extracted from monocular images to derive descriptors. Their success is ultimately limited by the 2-dimensional nature of the images and the lack of scale. Features such as spin maps (Johnson & Hebert 1999) or local feature histograms (Hetzel et al. 2001) have been used for 3-dimensional object detection, but they are not well suited for unstructured 3-dimensional scenes. Habitat complexity indices, such as rugosity and slope, are often used as a proxy for marine biodiversity (Alexander et al. 2009, Commito & Rusignuolo 2000, McCormick 1994, Sleeman et al. 2005). These measures are typically extracted from bathymetry data, or collected *in situ* by divers using chain-tape methods or profile gauges, but can also be extracted from stereo images (Friedman et al. 2012). It is then possible to combine these terrain complexity descriptors with the visual appearance-based descriptors discussed above. These terrain complexity measurements have already proven very useful descriptors for image-based habitat classification (Bridge et al. 2011, Friedman 2013, Seiler et al. 2012, Steinberg et al. 2010, 2011), and have been

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found to be more useful for habitat classification than competing vision-based descriptors (Friedman 2013).

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Challenges and outlook

Marine imaging is entering a very exciting period, with a huge increase in interest in the technology. The use of imaging in marine science has expanded rapidly: in the last 25 years, the number of publications related to marine photography and video has grown by an order of magnitude (Figure 1). This increase in interest has led to substantial improvements in the technologies and management involved in obtaining, using and archiving the data, but also poses some challenges. Here we examine the overarching challenges in a future where marine imaging is a mainstream method of data collection.

As the marine imaging community expands, the primary challenge will be to establish and maintain good communication between members. Previously, marine imaging experts operated in local, autonomous groups, with limited communication. The exponential growth of researchers in the field has resulted in rapid development in expertise in different fields of imaging, and yet the conduits for successful dissemination of those new developments in the field are currently lacking. Thus, to build an effective community, the disconnect between technology developers and those biologists and ecologists using image data must be overcome. A second major disconnect exists between researchers and technology users outside academia, such as commercial entities, industry representatives, regulatory bodies, stakeholders, and the public. Communication between all parties is critical to the coordination of development that is data-driven, and to maximise innovation through the exchange of ideas, technology and data, thus accelerating the overall advancement of the science. Developing partnerships that are mutually beneficial can be especially challenging given that the applications of the technology and outcomes often differ substantially.

The Marine Imaging Workshop (www.marine-imaging-workshop.com) held in Southampton in April 2014 was the first of its kind to involve scientists, engineers and computer vision experts from academia, industry and regulatory bodies. The workshop allowed the communication of new developments in the field and shared challenges among these groups. Another timely example of such collaboration is the involvement of imaging experts and taxonomists with the International Seabed Authority (ISA) with seabed mining companies involved in the potential exploitation of polymetallic nodules in the Pacific. In 2013, the ISA convened a group of image experts and taxonomists to meet with mining company representatives to discuss the use of imaging in ecological monitoring in the target area and the collaborations needed between groups to achieve those scientific objectives (International Seabed Authority 2013). As with any interdisciplinary field, progress is a result of collaboration, and healthy communication will be the key to long-term success.

The progression of marine imaging will require the development of both technical and social infrastructure to cope with the increase in users, images, related

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data, and applications. To facilitate these advances in infrastructure, communication throughout the community will need to address data acquisition, use, and reuse, dissemination and reproducibility, access and preservation, and sharing and discovery. Common challenges will include prioritisation of these factors to the needs of the community, costs associated with the infrastructure development, and balancing privacy with disclosure.

The focus of development in marine imaging has generally been on technical infrastructure, that is on hardware and software to improve image capture, enhancement, preservation, storage, data analytics, visualisation, and management. The advancement of these technologies will certainly continue, but parallel advancements in social infrastructure are also necessary. Social infrastructure development is needed across the field in relation to community practice, policies and standards, community economics, education, and workforce stability. Although still in its infancy, the CATAMI project (Althaus et al. 2013) in establishing a standard framework for the taxonomic and morphological hierarchy used in annotating images across Australia, is an example of a successful collaborative development of social infrastructure. The joint advancement of technical and social infrastructure will ensure the most robust development path for the field. One organisation that assists with managing this type of development is the Research Data Alliance (www.rd-alliance.org), which promotes global, multidisciplinary collaboration to tackle development in fields grappling with 'Big Data' issues through focused working groups.

On a local scale, the most critical need for development involves the adaptation of existing technologies and methods to handle the increased volume of images and associated data being generated. Efficient data management must incorporate storage, maintenance, and security, while allowing access and sharing. Strategies for managing large volumes of data must ultimately involve less human intervention per image, so machine substitutes for time-intensive activities, such as for preprocessing images and item detection, must be further explored and refined. Collaborative decisions are needed to ensure that data are structured in manner that is as straightforward and as convertible as possible to allow for descriptive, temporal, and spatial comparisons to be made across datasets. Metrics for assessing the quality of the data should be identified so that future data collection and analysis methods can be optimised. Importantly, the ability to update data when new identifications or descriptive characteristics are established, and to track these updates, should be incorporated into the data model.

Increased image quality within the normal visual spectrum is rapidly advancing among the commercially available cameras. Future technological improvements to image acquisition equipment that will also be critical for scientific use will be those that capture wavelengths outside the visible spectrum, such as infrared. Improvements in low-light cameras, low-impact lighting, and the use of

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stereo cameras or 3-dimensional equipment to quantify movement will also be necessary for making accurate biological and ecological assessments. Greater access to ROVs, long-range AUVs, and cabled observatories is substantially increasing the area and timescales monitored through imaging. Innovations to processing, annotation, and more detailed analysis could include human-computer partnerships, and the use of touch screen, voice recognition, and virtual reality technologies.

The future of marine imaging is rapidly moving towards visualising the ocean on the global scale, rather than simply advancing individual tools and techniques. Distributed databases and systems of classification of biological information in images are beginning to allow users to access, use, and better understand the collective biological knowledge and overall health of the ocean. The potential barriers to open data sharing are political and financial, in addition to technological. The sharing of images, metadata and extracted data internationally, transcending regulatory, institutional, commercial, and other stakeholder boundaries could revolutionise our understanding of the global marine environment.

We are on the cusp of an exciting step-change in the technologies available for marine imaging, and for its use and application. In addition to looking within the community, there is much to be gained from looking without. Imaging has applications in a wide range of fields, for example in examining deforestation using satellite imagery (e.g. Skole & Tucker 1993, Tucker & Townshend 2000), protein associations in cells using microscope imagery (e.g. Nagy et al. 1998), time-series photometry of supernovae (Astier et al. 2013), computer vision techniques for the detection of tumours (Azhari et al. 2014), and in investigations of marine archaeological sites (Singh et al. 2000) and dinosaur tracks (Bates et al. 2008). There are many challenges and successes common to image use in other fields, and collaboration with these communities has the potential to transform both.

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Conclusion

New technologies have revolutionised marine imaging: video cameras have advanced from film to high-resolution digital, platforms have expanded from simple stationary mounts to autonomous vehicles and multidisciplinary observatories, and data storage has frown from slide box to petabyte server. Future advances in acquisition will parallel improvements in power supply to vehicles. These technological developments have changed the way imaging is applied to ecological problems, both spatial and temporal.

These improvements have implications for the techniques used in the application of these technologies. For example, with the ability to capture more images, we can now design statistically-robust ecological studies covering temporal and spatial scales that were not previously practicable. In addition, the computer vision community now contributes to the workflow, providing efficiencies in new ways. The partnership between marine researchers and computer vision specialists is growing, and the improvements to the data gained through image enhancement and automated annotation have great implications for the workflow and value of image-based surveys in the future, and may also improve the utility of previously-captured images.

An important aspect of marine imaging is its modularity: each of the steps involved constitute decision points for the researcher to select methods and technology, with more options than ever before. These options allow more challenging scientific questions to be addressed, but now require more forethought and planning.

From its infancy and through significant growth in the last few decades, marine imaging is maturing into a viable, well-used method of exploring and sampling marine biota. Despite challenges associated with a step-change in the amount of data collected and the number of data-users, we anticipate that this field will continue to develop and will allow us to examine aspects of the marine environment, and thus understand our world in ways that have yet to be fully explored or exploited.

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Table 1. Number of replicate samples required per stratum in a comparison of two strata for given combinations of coefficient of variation and smallest true detectable difference (at the P < 0.05 and a statistical power of 90%).

Coefficient of variation (CV%)	Smallest true difference to detect (δ%)									
	10	14	20	28	40	56	79	112	158	224
5	7	4	3	3	2	2	2	2	2	2
10			7	4	3	3	2	2	2	2
15				8	5	3	3	2	2	2
20					7	4	3	3	2	2
25					10	6	4	3	2	2
30						8	5	3	3	2
35			**>10**			10	6	4	3	2
40							7	4	3	3
45							8	5	4	3
50							10	6	4	3

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Table 2. Influence of physical sample size (number of pooled photographs) on the coefficient of variation (CV%) of species diversity (d, Berger-Parker index; J´, Pielou's evenness; 1-λ', Simpson's index; α, Fischer's index; ES_{25}, Hurlbert's rarefaction to 25 individuals; H'2, Shannon index, $\log_2$) and density estimates. Spearman's rank correlation parameter values also indicated (ns, not significant). Based on data for the megabenthos of the Porcupine Abyssal Plain (Durden et al. 2015a). *A. rosea* = *Amperima rosea*, *I. vagabunda* = *Iosactis vagabunda*, the two most common species at the Porcupine Abyssal Plain.

	Coefficient of variation (%)								
	Diversity						Density		
Number of photographs	d	J'	1-λ'	α	ES_{25}	H'2	Megabenthos	*A. rosea*	*I. vagabunda*
25	13.3	5.8	6.2	25.4	14.9	9.9	23.3	43.5	23.9
50	10.7	5.0	5.2	13.1	4.4	5.5	21.6	38.9	18.0
100	6.4	3.7	3.2	14.0	5.7	3.9	6.9	23.6	7.9
200	5.8	4.8	3.7	10.7	6.2	5.0	5.8	19.3	6.9
400	2.4	1.9	1.6	8.5	3.2	2.8	3.8	7.7	5.0
Sample size dependence (rank correlation)	P < 0.01	P < 0.01	P < 0.01	P < 0.01	ns	P < 0.01	ns	ns	ns

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Table 3. The influence of sample size (number of pooled photographs) on the estimation of species composition. Based on data for the megabenthos of the Porcupine Abyssal Plain (Durden et al. 2015a), groups compared were original data, and an outgroup created from the same data by switching the identities of the rank 2 and rank 2 species (see *Select sampling unit and sample size*, Figure 5B).

Number of photographs	25	50	100	200	400
Distinctiveness between groups (%)	5.6	6.1	7.2	9.0	9.7
CV% of between-group similarity	19.4	17.2	9.3	6.6	3.5

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Table 4. Examples of currently operational stationary lander platforms operated by academic or research institutions. Modified and updated from Jamieson et al. (2013). Institutes: AberU = Aberdeen University, LDGO = Lamont-Doherty Geological Observatory, NIOZ = Netherlands Institute for Sea Research, NOCS = National Oceanography Centre, SAMS = Scottish Association of Marine Science, Scripps = Scripps Institute of Oceanography; Cameras: TL = time-lapse, D = digital, F = film (35mm unless indicated).

Lander	Institute, Country	Max. depth (m)	Bait?	Deployment duration	Camera system(s)		Reference
					Stills	Video	
Bathysnap	NOC, UK	6000	No	1 year	1 x D	-	Bett (2003), Lampitt & Burnham (1983)
Baited Remote Underwater Video System (BRUVS)	CSIRO, Australia	1000	Yes	6 months	2 x D	-	Marouchos et al. (2011)
Robust BIOdiversity (ROBIO)	Oceanlab, UK	4000	Yes	12 hours	1		Jamieson & Bagley (2005)
Aberdeen University Deep Ocean Submersible (AUDOS)	Oceanlab, UK	6000	Yes	12 hours	1 x F		Priede & Bagley (2003)
Free-Fall Video Vehicle (FVV)	Scripps, USA	6000	Yes	1 day	-	1	Wilson & Smith (1984)
Scripps tripod	Scripps, USA	6000	No	4 months	1 x F	-	Smith et al. (1993)
Camera tripod	MBARI, USA	5000	No	Unknown	1 x TL	-	Sherman & Smith (2009)
Module Autonome Pluridisciplinaire (MAP)	IFREMER, France	6000	No	1 year	1 x TL F	-	Auffret et al. (1994)
Bottom Ocean Monitor (BOM)	LDGO, USA	6000	No	1 year	1 x TL F	-	Gardner et al. (1984)
Large Abyssal Food Fall (LAFF)	AberU, UK	6000	Yes	11 days	1 x TL F	-	Jones et al. (1998)
ICDEEP (Previously ISIT)	AberU, UK	6000	Yes	12 hours	-	1	Priede et al. (2006)
Deep Ocean Benthic Observer (DOBO) Mk 1/2	Oceanlab, UK	6000	Yes	6 months	1 x TL F	-	Kemp et al. (2006)

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Free-falling Bottom Boundary lander (BOBO)	NIOZ	6000	No	>1 year	1 x TL	-	
Autonomous Lander for Benthic Experiments (ALBEX)	NIOZ	6000	Yes	1 year	-	2 x D	Jeffreys et al. (2010)
Deep Ocean Visualisation Experimenter (DOVE)	Scripps, USA	10000	Yes	4 days	1 x D	--	Hardy et al. (2002)
Eye-in-the-sea (EITS)	MBARI, USA	6000	Yes	2 days		1 x D	Raymond & Widder (2007)
Fish RESPirometry (FRESP) Mk2	Oceanlab, UK	6000	Yes	3 days		1 x D	Bailey et al. (2002)
DOS (Deep-sea Observatory)	GEOMAR, Germany	6000	No	1 year	1 x TL D	-	
Hadal-landers A and B	Oceanlab, UK	11000	Yes	12 hours	1 x D	1 x D	Jamieson et al. (2009a,b)
Photolander	SAMS, UK	6000	No	1 month	1 x D	-	Roberts et al. (2005)
SPRINT	Oceanlab, UK	6000	Yes	12 hours	-	1 x D	Bailey et al. (2003)

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Table 5. Examples of currently operational towed platforms operated by academic and research institutions. Modified and updated from Jamieson et al. (2013). Institutes: AberU = Aberdeen University, DFO = Department of Fisheries and Oceans, JAMSTEC = Japan Agency for Marine-Earth Science and Technology, LDGO = Lamont-Doherty Geological Observatory, NIOZ = Netherlands Institute for Sea Research, NOC = National Oceanography Centre, SAMS = Scottish Association of Marine Science, Scripps = Scripps Institute of Oceanography, UConn = University of Connecticut; Cameras: D = digital, F = film (35mm unless indicated), HR = high resolution, S = stereo

Towed platform	Institute, Country	Max. depth (m)	Camera system		Reference
			Stills	Video	
Deep Tow 4K (4KC)	JAMSTEC, Japan	4000	1 x D	-	JAMSTEC (2015a), Momma et al. (1988)
Yokosuka Deep Tow (YKDT)	JAMSTEC, Japan	4500	1 x D	1 x D	JAMSTEC (2015a), Momma et al. (1988)
Wide Angle Seabed Photography (WASP)	NOC, UK	6000	1 x F	1 x D	Jones et al. (2009)
Seafloor High Resolution Imaging Platform (SHRIMP)	NOC, UK	6000	1 x D	2 x D	Jones et al. (2009)
Interactive camera system SCAMPI	IFREMER, France	6000	1 x D	1 x D	Lefort (2015)
Ocean floor Observation system (OFOS)	GEOMAR/AWI, Germany	6000	1 x D	-	Bergmann et al. (2011)
Deep towed imaging system (DTIS)	NIWA, New Zealand	6000	1 x D	-	De Leo et al. (2010)
CAMPOD	DFO, Canada	500	1 x F	1 x HR	Gordon et al. (2000)
Instrumented Seafloor Imaging System 2 (ISIS2)	UConn, USA	1000	1	1	Northeast Underwater Research (2015b)
CSIRO Deep Video System	CSIRO, Australia	2000	1 x D	2 x D, S	Shortis et al. (2007)

https://www.nespmarine.edu.au/document/perspectives-visual-imaging-marine-biology-and-ecology-acquisition-understanding

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Table 6. Examples of HOVs suited to imaging operated by academic and research institutions. Updated and modified from Jamieson et al. (2013). Institutes: HURL = Hawaii Undersea Research Laboratory, JAMSTEC = Japan Agency for Marine-Earth Science and Technology, Shirshov = P.P. Shirshov Institute, WHOI = Woods Hole Oceanographic Institution; Cameras: D = digital, HD = high definition, LL = low-light

HOV	Institute, Country	Max. depth (m)	Personnel	Camera system		Reference
				Stills	Video	
Alvin	WHOI, USA	4500	3	2 x HD	2 x HD	WHOI (2014a)
Nautile	IFREMER, France	6000	3	2 x D	2 x D	Levesque (2008)
MIR I& II	Shirshov, Russia	6000	3	-	1	U.S. National Oceanic Atmospheric Administration (2013)
Argus	Shirshov, Russia	600	3			Russian Academy of Sciences Experimental Design Bureau of Oceanological Engineering (2013)
Osmotr	Shirshov, Russia	200	5			Russian Academy of Sciences Experimental Design Bureau of Oceanological Engineering (2013)
PISCES IV and V	HURL, USA	2000	3	2 x LL	1 x HD, 1 x D	Hawai'i Undersea Research Laboratory (2013b,c)
JAGO	GEOMAR, Germany	400	2	1 x D	1 x HD	GEOMAR (2015b)
Jialong	China	7000	3	1 x D	2 x HD, 2 x D	Liu et al. (2010)
Shinkai 6500	JAMSTEC, Japan	6500	3	-	2 x HD	JAMSTEC (2015b)

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Table 7. Examples of ROVs suited to imaging operated by academic and research institutions. Updated from Smith & Rumohr (2013) and Jamieson et al. (2013). Institutes: CSSF = Canadian Scientific Submersible Facility, HURL = Hawaii Undersea Research Laboratory, IE = Insitute for Exploration, JAMSTEC = Japan Agency for Marine-Earth Science and Technology, HokkaidoU = Hokkaido University, MBARI = Monterey Bay Aquarium Research Institute, MI = Marine Institute, NOC = National Oceanography Centre, UBerg = University of Bergen, UConn = University of Connecticut, WHOI = Woods Hole Oceanographic Institution; Cameras: D = digital, F = film (35mm unless indicated), HD = high definition

ROV	Institute, Country	Max. depth (m)	Camera system		Reference
			Stills	Video	
Hyper-Dolphin	JAMSTEC, Japan	3000	1 x D	1 x HD	
Kaiko 7000II	JAMSTEC, Japan	7000	1 x D	1 x HD	Lindsay et al. (2012)
Miniature remotely controlled vehicle (MROV)	JAMSTEC, Japan	1000	-	1 x HD	
Plankton Investigatory Collaborating Autonomous Survey System Operon (PICASSO-1)	JAMSTEC, Japan	1000	-	3 x D, 1 x HD	
Crambon	JAMSTEC, Japan	1000	1 x D	1 x HD	
HUBOS-2K	HokkaidoU, Japan	2000	-	1 x HD	
HDTV-LEO500	HokkaidoU, Japan	500	-	1 x HD	
ISIS	NOC, UK	6500	1 x D	1 x HD	
VICTOR 6000	IFREMER, France	6000		1	Ifremer (2010)
Jason/Medea	WHOI, USA	6500	1 x D	3 x HD	WHOI (2014b)
Remotely Operated Platform for Ocean Sciences (ROPOS)	CSSF, Canada	5000	1 x D	2 x HD	CSSF (2014)
Hercules/Argus	IE, USA	4000	2 x D	1 x HD	U.S. NOAA (2014)
Little Hercules	IE, USA	4000	-	1	

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DOER H6000	HURL, USA	6000		1 x D, 1 x HD	University of Hawai'i at Manoa School of Ocean and Earth Science and Technology (2015)
Ventana	MBARI, USA	1850	2 x D	1 x HD	MBARI (2014c)
Doc Ricketts	MBARI, USA	4000	1 x D	1 x HD	MBARI (2014b)
Max Rover	HCMR, Greece	2000	1 x D	1 x D	
KIEL 6000	GEOMAR, Germany	6000	1 x D	4 x D, 1 x HD	GEOMAR (2015c)
PHOCA	GEOMAR, Germany	3000	1 x D	3 x D, 1 x HD	GEOMAR (2015d)
Bathysaurus	UBerg, Norway	7000	1	1 x D	Mar-Eco (2015)
Holland I	MI, Ireland	3000	3	1 x HD	Huvenne et al. (2005)
Kraken2	UConn, USA	1000	2 x D, 1 x F	6 x D, 2 x HD	Northeast Underwater Research (2015c)
Hela	UConn, USA	330	1 x D	6 x D, 1 x HD	Northeast Underwater Research (2015a)
Quest4000	Marum, Germany	4000	2 x D	6	MARUM (2014)

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Table 8. Examples of AUVs suited to imaging operated by academic and research institutions, with operational details. Institutes: ACFR = Australian Centre for Field Robotics, UGirona = Universitat de Girona, HURL = Hawaii Undersea Research Laboratory, IE = Institute for Exploration, JAMSTEC = Japan Agency for Marine-Earth Science and Technology, NOC = National Oceanography Centre, UTokyo = University of Tokyo, WHOI = Woods Hole Oceanographic Institution; Cameras: D = digital, HD = high definition, S = stereo

AUV	Institute, Country	Max. depth (m)	Max. speed ($m.s^{-1}$)	Endurance (h)	Hover capable	Camera system		Reference
						Stills	Video	
Otohime	JAMSTEC, Japan	3000	1	6	Yes	2 x D S	2 x D, 1 x HD	Ishibashi et al. (2012)
MR-X1	JAMSTEC, Japan	4200	1.5	8	Yes	2 x D, 2 x D S	1 x HD	Yoshida et al. (2009)
TriDog I	UTokyo, Japan	100	1.4	3	Yes	4 x D	-	Kondo et al. (2005)
Tuna-Sand	UTokyo, Japan	1500	0.9	8	Yes	1 x D	1	Nishida et al. (2013)
Autosub6000	NOC, UK	6000	2.0	70	No	2 x D	-	Morris et al. (2014)
Sentry	WHOI, USA	6000	1.2	20-40	No	1 x D	-	WHOI (2015)
SeaBED	WHOI, USA	5000	0.25	24	Yes	1x D	-	Singh et al. (2004)
Imaging AUV (IAUV)	MBARI, USA	6000	1.5	18	No	1 x D	-	MBARI (2014a)
Girona 500	UGirona, Spain	500	0.5	8	Yes	-	1 x D	Ribas et al. (2012)
ABYSS	GEOMAR, Germany	6000	2	16		1 x D	-	GEOMAR (2015a)
Sirius	ACFR, Australia	700	1		Yes	2 x D S	-	ACFR (2015)
Iver2	ACFR, Australia	1000	2	14	No	2 x D S	-	OceanServer Technology Inc. (2015)
Nessie2012	Heriot-Watt, UK	100	2.6	3	Yes	-	4	Heriot-Watt University Ocean Systems Laboratory (2015)

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Table 9. Examples of currently operational submarine cabled observatories (all with video imaging) operated by academic and research institutions, with operational details. Institutes: ONC = Ocean Networks Canada, JAMSTEC = Japan Agency for Marine-Earth Science and Technology, MBARI = Monterey Bay Aquarium Research Institute.

Observatory	Institute, Country	Location	Depth (m)	Operation date	Reference
Hatsushima	JAMSTEC, Japan	Sagami Bay, Japan	1174	09/1993	Iwase et al. (2003)
MOMAR	European Multidisciplinary Seafloor and water column Observatory	Mid-Atlantic	1700	07/2010	FixO3 (2015)
ALOHA cabled observatory	University of Hawaii, USA	Station ALOHA, north of Hawaii	4800	2011	University of Hawai'i (2015)
Monterey Accelerated Research System (MARS)	MBARI, USA	Monterey Bay, USA	891	2009	MARS, 2014
Victoria Experimental Network Under the Sea (VENUS)	ONC	Salish Sea, Canada	100-300	02/2006	ONC (2015)
North-East Pacific Time-series Undersea Networked Experiments (NEPTUNE)	ONC	NE Pacific	23-2660	06/2008	ONC (2015)
Kristenberg Underwater Observatory	University of Gothenburg	Skagerrak, North Sea	5-30	07/2008	Glover et al. (2010)

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Table 10. An overview of image enhancement methods. Characteristics of the individual image domains (camera orientation: O=oblique, V=vertical, A=any; natural and/or artificial illumination; and additional parameters needed from metadata), and the primary correction objective (colour, illumination, or sharpness) are indicated. Methods adaptable to the characteristic are denoted as (✓).

Method reference	Image characteristics				Correction type		
	Camera Angle	Natural illumination	Artificial illumination	Metadata	Colour	Illumination	Sharpness
Chiang & Chen (2012)	O	✓	(✓)		✓	✓	
Schechner & Karpel (2005)	O	✓		✓	✓	✓	
Trucco & Olmos-Antillon (2006)	O	✓			✓		
Carlevaris-Bianco et al. (2010)	O	✓			✓		
Petit et al. (2009)	O	✓			✓		
Mahon et al. (2011)	V	✓	✓	✓	✓	✓	
Bryson et al. (2012)	V	✓	✓	✓	✓	✓	
Beijbom et al. (2012)	V	✓	✓		✓		
Åhlén et al. (2007)	V	✓		✓	✓		
Gracias et al. (2008)	V	✓		✓		✓	
Treibitz & Schechner (2009)	O		✓		✓	✓	
Johnson-Roberson et al. (2010)	V		✓		✓	✓	
Schoening et al. (2012a)	V		✓		✓	✓	
Morris et al. (2014)	V		✓	✓	✓	✓	
Singh et al. (2007)	V		✓	✓	✓	✓	
Kaeli et al. (2011)	V		✓	✓	✓	✓	
Garcia et al. (2002)	A	✓	✓		(✓)	✓	
Rzhanov et al. (2000)	A	✓	✓		(✓)	✓	
Eustice et al. (2002)	A	✓	✓		(✓)	✓	
Arnold-Bos et al. (2005)	A	✓	✓		✓	✓	✓
Bazeille et al. (2006)	A	✓	✓		✓	✓	✓
Iqbal et al. (2010)	A	✓	✓		✓		
Chambah et al. (2004)	A	✓	✓		✓		

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Table 11. Currently-used software developed for the biological and ecological annotation of marine imagery, categorized by their use (RT = Real-time or at-sea, PP = Post-processing), data type (CTS = counts, CVR = coverage, S = size) and catalogue type (UD = User-defined, PG = Programmable, DB = Database).

Software	Reference	Use	Input	Marker	Type	Output-data	Catalogue
Microsoft Excel®, Access® databases		RT	Video, stills	Events	Desktop	CTS	UD
GNav GIS tracker	Hatcher (2002)	RT	Video	Events	Desktop	CTS	PG
Adelie	Ifremer (2014)	RT, PP	Video	Events	Desktop	CTS	UD
OFOP	Huetten & Greinert (2008)	RT, PP	Video	Events	Desktop	CTS	PPG
VARS	Schlining & Stout (2006)	RT, PP	Video, stills	Events	Desktop	CTS, CVR, S	DB, UD
Delphi		PP	Video	Events	Desktop	CTS	UD, DB
CPCe	Kohler & Gill (2006)	PP	stills	Random points	Desktop	CVR	UD
ImageJ and plugins	Rasband (2015)	PP	Still	Points, segments	Desktop	CVR	UD
TransectMeasure™	SeaGIS (2013)	PP	Stills	(Random) points	Desktop	CTS, CVR	UD
NICAMS	Wood & Bowden (2008)	PP	Stills	Points, 2-D shapes	Desktop	CTS, CVR, S	UD, DB
BIIGLE	Ontrup et al. (2009)	PP	Stills	Points, 2-D shapes, tiles	Web	CTS, CVR, S	DB
Squidle	Williams & Friedman (2015)	PP	Stills	Points, segments, 2-D shapes	Web	CTS, CVR, S	DB
Digital Fishers	Neptune Canada (2015)	PP	Stills	Points, 2-D shapes	Web	CTS, CVR, S	DB

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Table 12. An overview of seven possible data storage and management strategies, with performance graded from low (--) to high (++).

	Data access speed	Storage Cost	Ease of data sharing	Storage capacity	External access cost	Data safety	Data provenance	Personnel cost
Desktop PC	++	--	--	--	--	--	--	-
External Hard-disk drives	++	+	+	--	--	--	--	-
Network Attached Storage	+	+	-	+	--	-	--	-
Institutional, web-accessible storage	+	+	+	+	+	+	--	-
Cloud Storage Provider	--/-	+	+	++	++	++	-	++
Marine data center (e.g. Pangaea)	--/-	++	++	++	++	++	+	+
Hybrid of marine data centre and institutional web-accessible storage	+	++	++	++	++	++	+	+

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Figure 1. Published scientific works using marine photography and video have increased by two orders of magnitude over the period 1980 to 2013. Number of works listed by Google Scholar for the search terms 'marine video' and 'marine photography' are shown annually, and 5-year means are shown for the combined search terms in Web of Science.

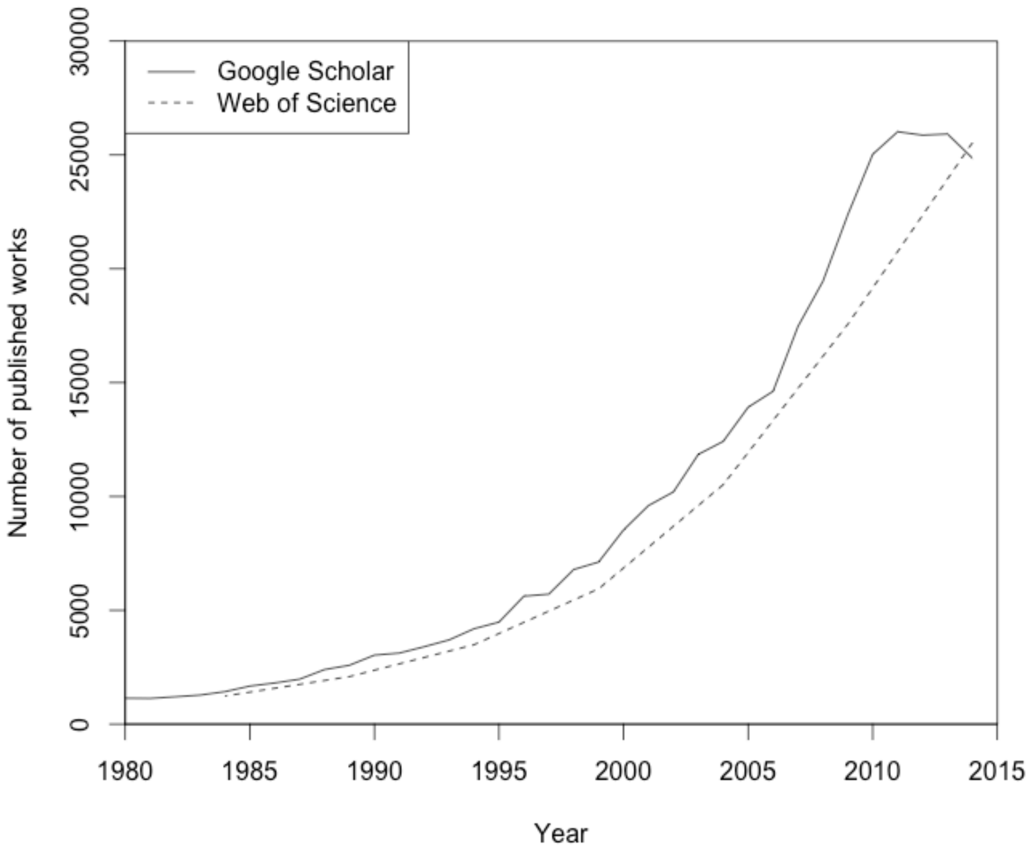

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Figure 2. Steps in the use of marine imaging for biology and ecology. Note that not all steps are employed in every study, but survey design, image acquisition, annotation (using taxonomy to some extent) and data output are essential core steps shown in black. Optional steps are shown in grey, and steps with data to be managed are shown with dashed connectors.

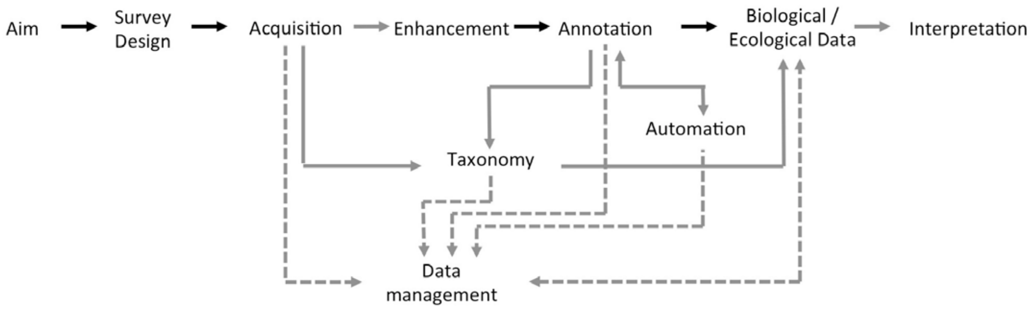

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Figure 3. An illustration of the relationship between sampling strata (e.g. comparing two bathymetric units), samples collected to represent each stratum, and the types of images captured as sample units. Image sample units include (1) a single still image, common in time-lapse studies; series of non-overlapping (2) or overlapping (3) still images; or (4) video transect.

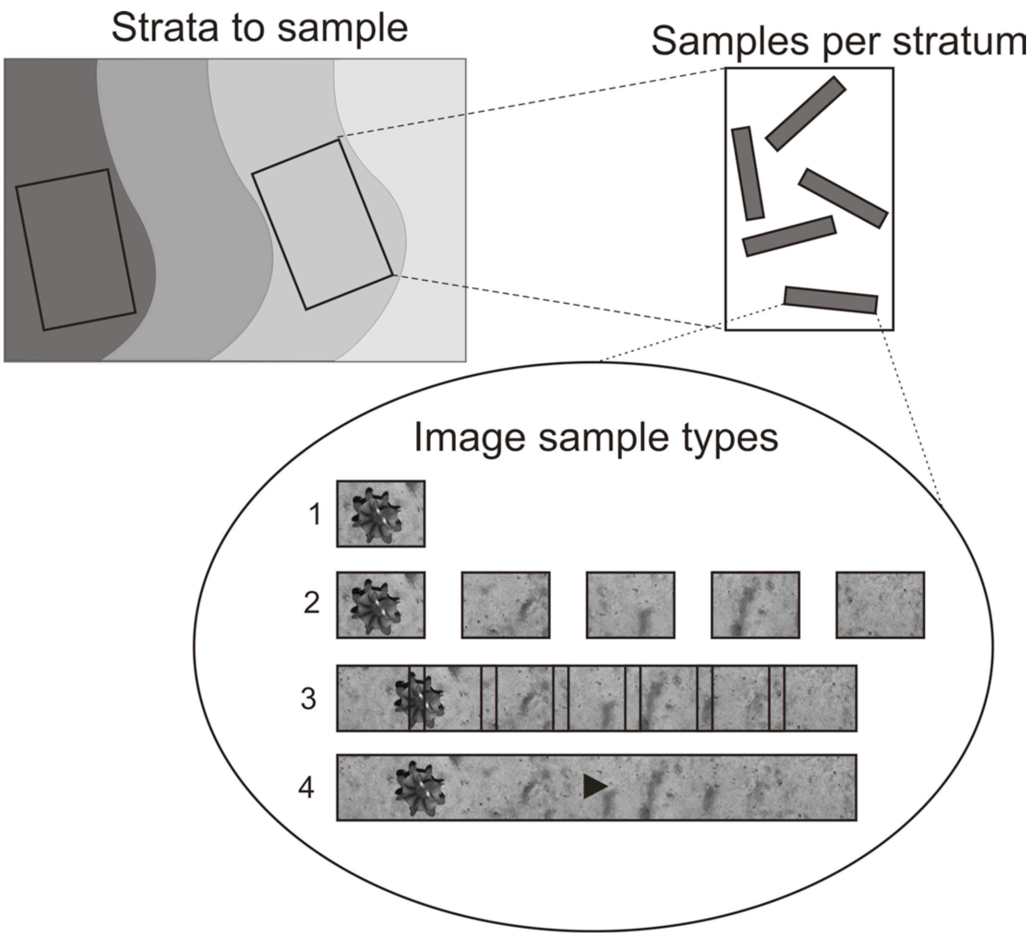

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Figure 4. The influence of physical sample size (number of pooled photographs) on the value and variability of species diversity and density estimates. Based on re-sampling of field data on the megabenthos of the Porcupine Abyssal Plain (Durden et al. 2015a). Individual images from four photo transects were combined, randomised, and pooled without replacement into sample units consisting of 25,50 ... 400 images.

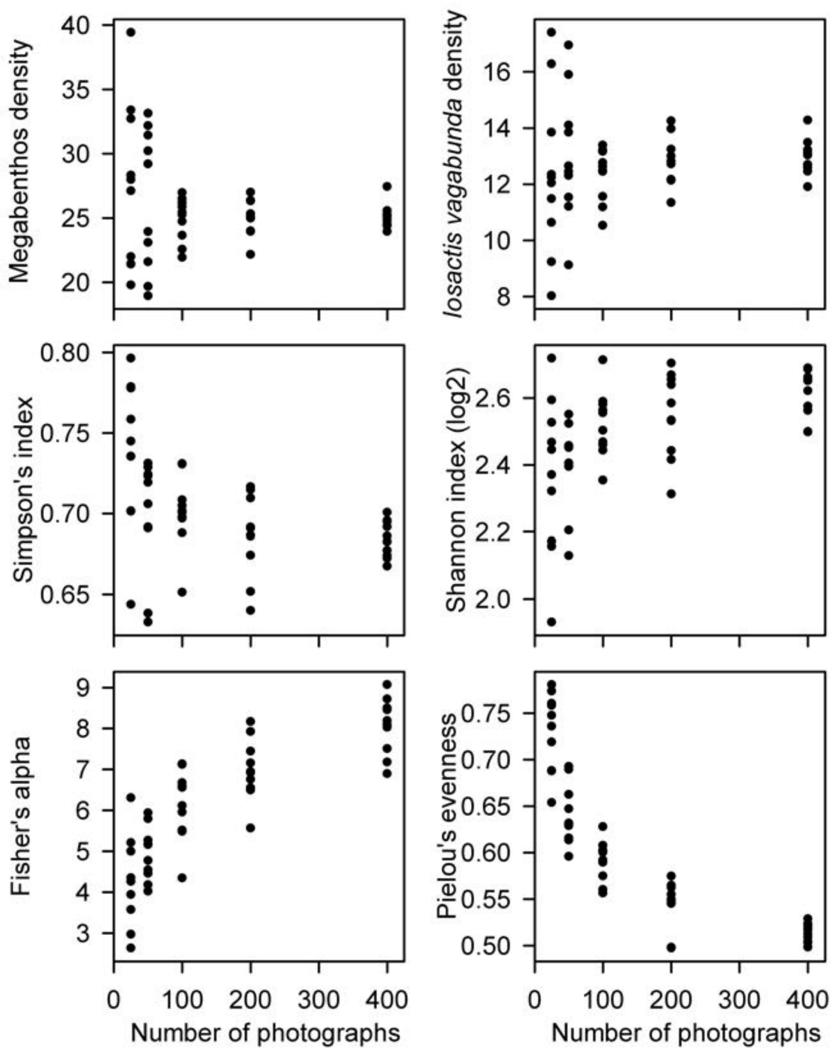

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Figure 5. The influence of physical sample size (number of pooled photographs) on the estimation of species composition. (1) A non-metric multi-dimensional scaling ordination of species density data (log[x+1] transformed, Bray-Curtis similarity measure), based on re-sampling of photo-derived community data on the megabenthos of the Porcupine Abyssal Plain (Durden et al. 2015a). (2) The ranked densities of the megabenthic species used to assess the precision of this description of species composition (see Table 3). (3) A non-metric multi-dimensional scaling ordination of species density data of the original data and the artificial sample generated by switching the identities of the first- and second-ranked taxa in (2).

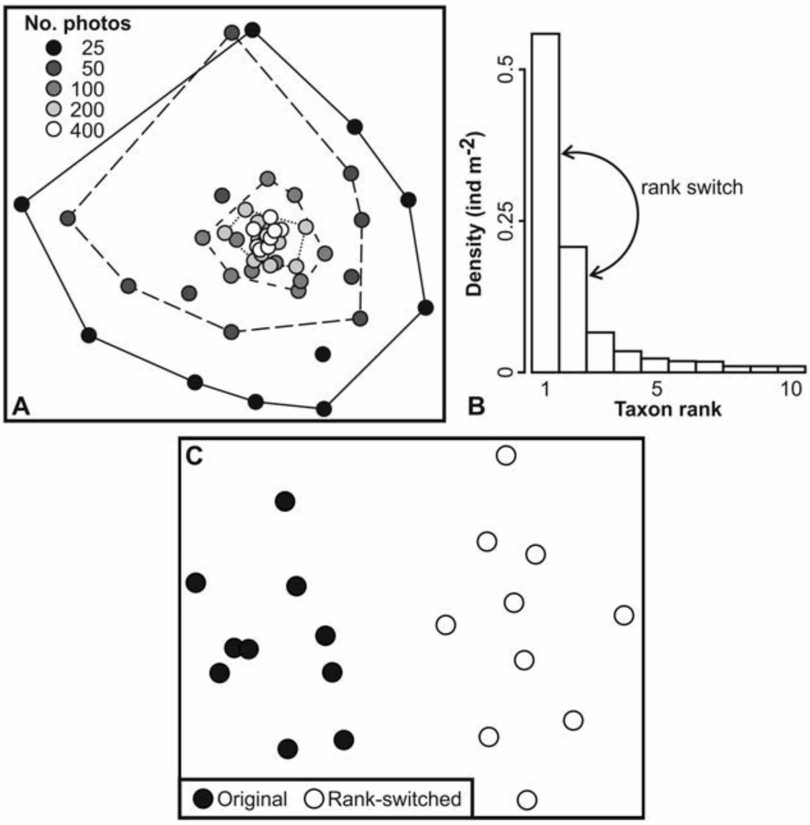

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Figure 6. Camera orientations to the object, area or volume of interest, and the resulting image shapes (A). Dimensions used in the calculation of dimensions in a perspective grid (B), after Wakefield & Genin (1987). Image corners are identified A-D, with mid-points added as E-I. Corresponding seafloor locations are identified as A-I. Location J is the camera focal point and the vertical acceptance angle (35°) is indicated as α (the horizontal acceptance angle, β, of 45° is not illustrated). Locations L and M fall on the central axis of the camera such that JL and JM represent the appropriate object distances for seafloor points on lines AB and CD, respectively. The resultant seafloor area imaged is the shaded area ABCD, the same area estimated by the Wakefield & Genin (1987) methodology is shown as the corresponding dashed line. Note that they use distance JF rather than JL to represent the distance to the camera of objects along CD, and likewise use JH rather than JM as the distance of objects along AB. In this example, the latter method overestimates lengths DC and AB, and area ABCD by 5%.

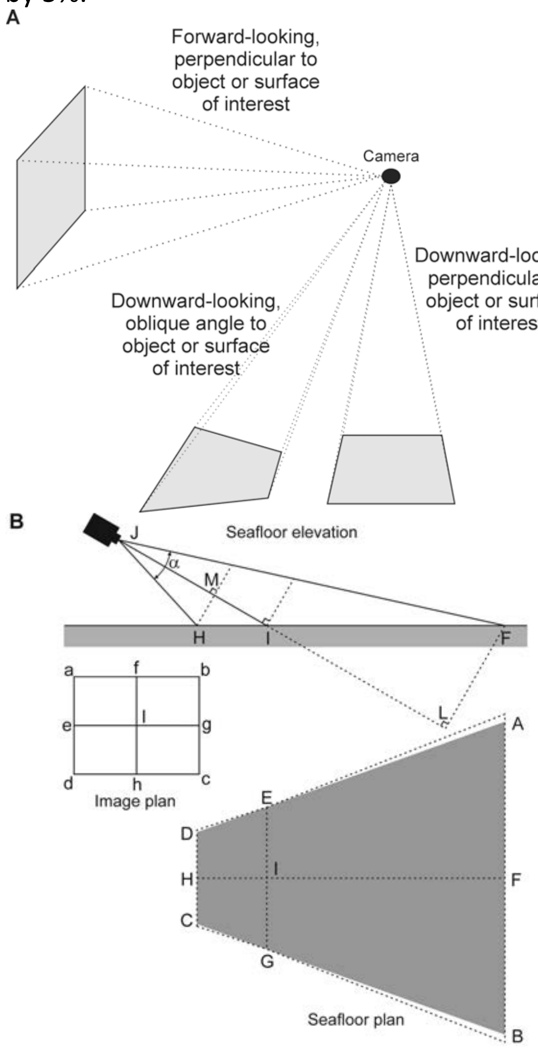

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Figure 7. Focussing distance and corresponding range of acceptable focus with varying aperture, based on 8 mm focal length lens and 1/1.7” [7.44 x 5.58 mm] image sensor size, a common commercially-available deep-water camera system.

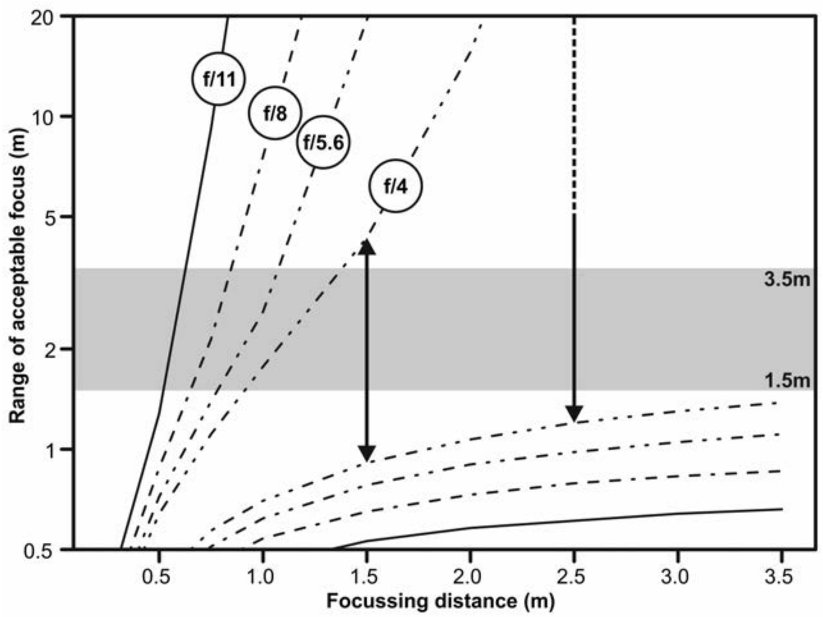

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Figure 8. Camera platforms, with cameras circled, and strobes and auxillary equipment indicated: (A) AWI's bottom-triggered drop camera, with trigger weight indicated (Credit: Julian Gutt, Alfred Wegener Institute); (B) JAMSTEC's Deeptow towed camera with forward and downward-facing video cameras; (C) tripod/lander; (D) the MBARI Benthic rover, with oblique still cameras (Credit: MBARI); (E) the WHOI HOV Alvin (Credit: Rod Catanach, Woods Hole Oceanographic Institution); (F) Girona-500 AUV with stereo camera system; (G) an industry ROV.

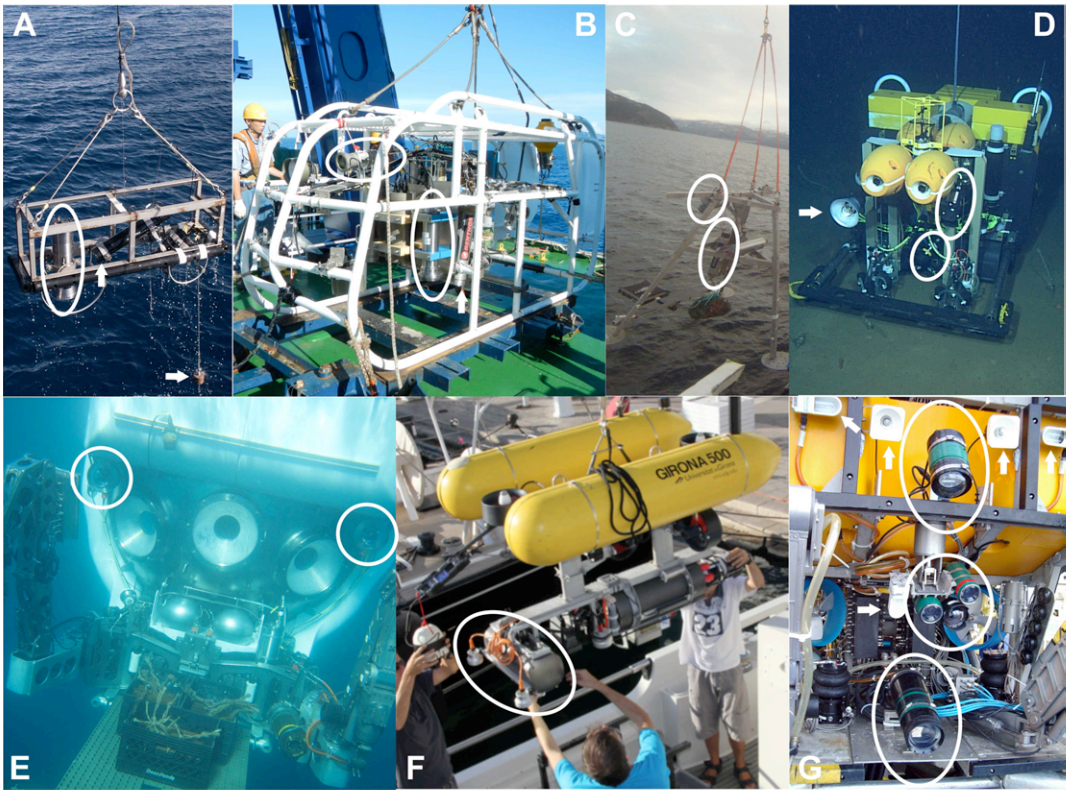

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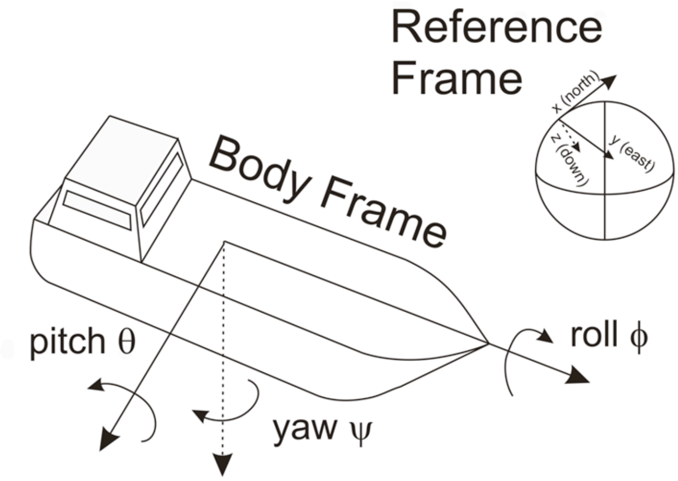
Figure 9. Compensation for pitch, roll and yaw of the camera platform. The body frame is attached to a ship or platform and reference frame attached to Earth. By knowing the position C_{BG} of the body in the world and the yaw, pitch and roll angles, a point X_B in the bodies local coordinate system can be transformed into a point X_G in the global reference frame. The X-axis is positive towards the bow/front of the vessel/vehicle, the Y-axis is positive towards starboard and the Z-axis is positive downward. Consequently, the roll angle around the X-axis is positive when the port-side of the vessel/vehicle come up; pitch angles around the Y-axis are positive when the bow comes up; yaw/heading angles around the Z-axis are positive clockwise.



$$X_G = R_{BG} X_B + C_{BG}$$

$$R_{BG} = \begin{pmatrix} \cos(\psi)\cos(\theta) & \cos(\psi)\sin(\phi)\sin(\theta)-\cos(\phi)\sin(\psi) & \sin(\phi)\sin(\psi)+\cos(\phi)\cos(\psi)\sin(\theta) \\ \cos(\theta)\sin(\psi) & \cos(\phi)\sin(\psi)+\sin(\phi)\sin(\psi)\sin(\phi) & \cos(\phi)\sin(\psi)\sin(\theta)-\cos(\psi)\sin(\phi) \\ -\sin(\theta) & \cos(\theta)\sin(\phi) & \cos(\phi)\cos(\theta) \end{pmatrix}$$

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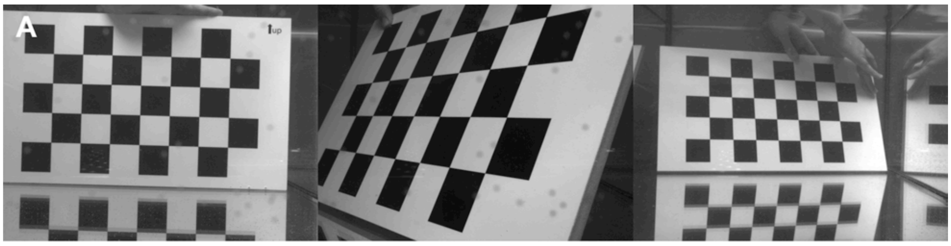
Figure 10. Dimensions involved in camera calibration. Underwater images of a checkerboard in a laboratory tank, captured from different points of view (A); (B) the perspective camera model with refraction at flat port glass interface. Imaged is a corner of the checkerboard. From the glass, the light ray is refracted twice and then enters the camera through the centre of projection before intersecting the image plane. The distance between centre of projection and image plane is the focal length. The housing interface is parameterized by the glass distance, glass thickness, glass normal, and the indices of refraction for air, glass, and water. Note that for simplicity, rotation and translation of the camera with respect to the checkerboard are omitted.



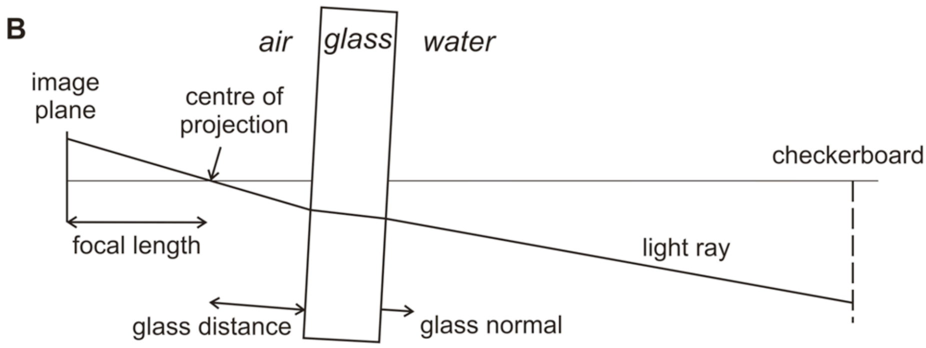


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Figure 11. Examples of image enhancement from the original raw image (A): correction to remove lens distortion (B); frame averaging applied (C); correction for light attenuation alone (D), which is equivalent to a white balance operation, in which illumination artefacts remain; corrections for both attenuation an illumination involving homomorphic filtering (E), an adaptive histogram specification (F), and a lighting beam pattern estimation (G) followed by colour balancing to create a 'dry' scene, as though no water column were present.

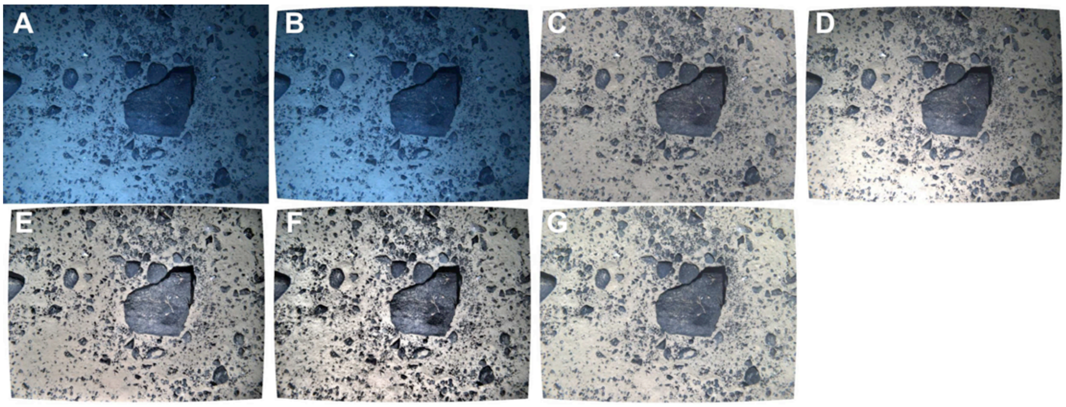

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Figure 12. Specimen imagery for taxonomy. Digital photomicroscopy on live specimens is the new standard for deep-sea taxonomy. (A) *Archinome* sp. fireworm, Cayman Trough hydrothermal vent, (B) *Eremicaster* sp., 4000m abyssal plain (C) *Rimicaris hybisae*, Cayman Trough hydrothermal vent, (D) *Bathykurila guaymasensis* from deep-sea whale fall (Glover et al. 2005); (E) Syllidae worm from Antarctic deep-sea shelf, (F) *Scalibregmata* sp. from Antarctic deep-sea shelf, (G) *Iheyaspira bathycodon,* Cayman Trough hydrothermal vent, (H) *Pachycara* sp., Cayman Trough hydrothermal vent, (I) Nuculidae bivalve from polymetallic nodule province, 4000m depth, (J) *Osedax mucofloris*, bone-eating worm, (K) *Lebbeus virentova*, Cayman Trough hydrothermal vent. Images (B, D, I) © AG Glover, TG Dahlgren, H Wiklund. All other images © AG Glover.

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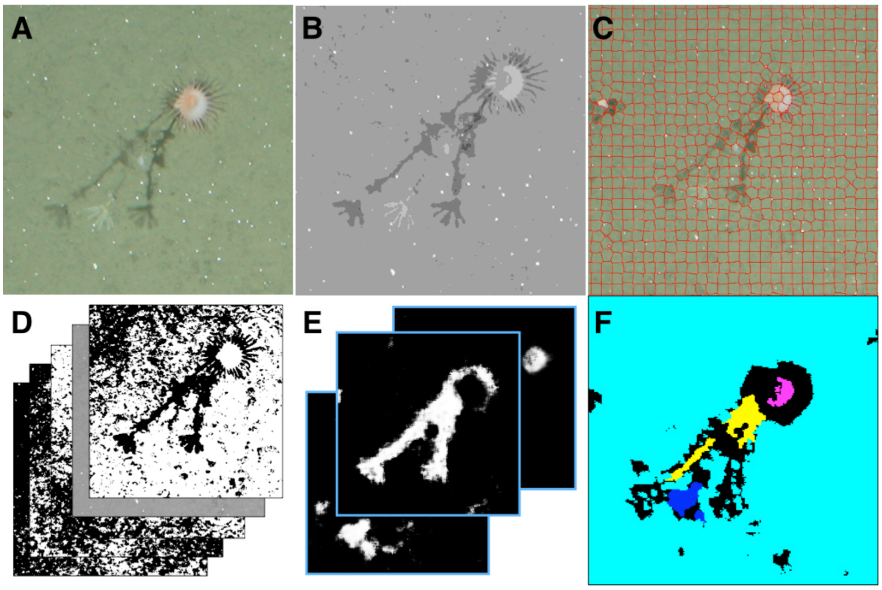
Figure 13. Possible steps in automation. The input is usually a standard three-channel (Red, Green, Blue) image or video frame (A). From this image, a variety of multi-dimensional features can be computed that encode different image characteristics like colour and shape (D). These features are the basis for all supervised or unsupervised algorithms that follow. A common method is to group similar feature vectors, that is group similar pixels with a vector quantisation (VQ) algorithm and to represent the result as an index image (B). A simple method to group pixels from feature vectors is based on their RGB values and their x,y-coordinates to compute so called superpixels that aggregate similar pixels locally (C). To compute super pixels, RGB or multi-dimensional features can be used. Algorithms that are trained with manual annotation (i.e. supervised machine learning) usually create confidence maps (E) that encode for different object types the probability of the occurrence of that object at a given pixel. From confidence maps as well as superpixel-images and index images, classification maps can be computed that encode each pixel with a value for the most probable category at that location (F) (turquoise = background, pink = anemone, yellow = stalk, blue = the crown of the sea lily, black = no clear category). The combination of supervised and unsupervised methods as well as image processing techniques can benefit the automation process.



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