Giving eyes to pelagic trawls

Acoustic and optical techniques measure behaviour, species, and sizes of fish in situ

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Contents

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Abstract

Trawling, towing a cone-shaped net behind a moving boat, is a widespread fishing method both in commercial fisheries and to collect fish for scientific investigations. It combines filtering effect with herding behaviour of fish in response to the vessel and components of the trawl to concentrate them in its path. For pelagic trawls, designed to be fished in the water column with little or no contact on the seabed, mesh openings in the forward and belly sections can be metres across making them relatively inefficient filters and reliant on herding to guide fish into the codend where meshes are small enough to prevent fish from escaping. Nevertheless, few studies have focused on the behaviour of fish, particularly large gadoids, during pelagic trawling and as a result trawl designs and fishing strategies are likely not optimized either for commercial harvest or research sampling.

The first investigation described in this thesis revealed that shoaling Atlantic cod (*Gadus morhua*) captured in a commercial fishing setting using a pelagic trawl dove following vessel passage and swam towards the approaching trawl, with a significant proportion of fish escaping beneath the trawl. Once they were inside the trawl, the cod turned and swam slowly in the direction of trawling but were carried deeper into the trawl by its greater speed through water. They remained in the lower portion of the trawl, suggesting the top panel played little role in retaining fish and could be modified to reduce drag without reducing the catch. Despite the use of three acoustic sensors and multiple mechanical catch sensors mounted to the trawl, poor information was available during trawling on the species, sizes, and quantity of fish entering and already inside the trawl. In a commercial fishery, this would likely result in bycatch and discards.

In response to this information gap, an in-trawl camera system, DeepVision, was developed to identify and measure all fish as they passed into the codend. Stereo photogrammetric techniques were developed to calculate lengths of fish from the images, and counts by species and individual fish lengths match well with standard physical sampling of the catch. The system has generated significant interest within the fisheries research community as a tool to provide enhanced information during research trawling and was tested during an annual ecosystem survey in the Norwegian Sea. Benefits shown during this trial included documentation of fine-scale patterns in spatial distribution by species and sizes, documentation of external parasites on Atlantic cod and saithe (*Pollachius virens*), and positive identification of the species and size composition of acoustically visible layers. The mis-identification of whiting (*Merlangius merlangius*) as pollack (*Pollachius pollachius*) during routine catch sampling was uncovered during review of the DeepVision data, demonstrating its value as a tool to quality check data even after the catch has been discarded. The technique opens the possibility to reduce sampling mortality while still registering large numbers of fish by trawling with an open codend or in conjunction with multisampler equipment to collect small, directed, biological samples for physical analysis.

List of publications

Paper I

Rosen, S., Engås, A., Fernö, A., and Jörgensen, T. 2012. The reactions of shoaling adult cod to a pelagic trawl. ICES Journal of Marine Science 69: 303-312.

Paper II

Rosen, S., Jörgensen, T., Hammersland-White, D., and Holst, J.C. 2013. DeepVision: a stereo camera system provides highly accurate counts and lengths of fish passing inside a trawl. Canadian Journal of Fisheries and Aquatic Sciences. 70: 1456-1467.

Paper III

Rosen, S. and Holst, J.C. (in press). DeepVision in-trawl imaging: Sampling the water column in four dimensions. Fisheries Research.

Introduction

Trawls in commercial harvest and aquatic research

Trawling is the most widely used method for harvesting wild marine resources, accounting for nearly 40 % global marine catches (Watson *et al.*, 2006) and 50 % of commercial fishing effort (Anticamara et al., 2011). Trawls are also used in biological and ecological investigations of freshwater and marine systems, either to collect a representative sample of the population present or to sample specific species or sizes. The results are commonly used to establish indices of abundance, and verify species and sizes of objects detected acoustically (Pennington, 1985; Gunderson, 1993; Walsh, 1996; Dingsør, 2005; Simmonds and MacLennan, 2005).

Discards in commercial fisheries and sampling mortality during surveys

While trawling is an effective method of capturing organisms for both commercial and research purposes, the identity and sizes of the organisms captured is in most cases unknown until the catch is brought onboard. This results in a waste of resources if the catch is of the wrong species or size, indeed trawl fisheries account for 78 % of total global discards (Kelleher, 2005). Acoustic data from echosounders, particularly the use of multiple or broadband frequencies, can give insight into the likely species and sizes (Simmonds et al., 1996; Kloser et al., 2002; De Robertis et al., 2010), however these results are generally not definitive and multifrequency techniques have not yet been put into widespread use in commercial fisheries.

Current methods for reducing bycatch in commercial fisheries include reducing fishing activities in areas where bycatch is likely to be high, either through seasonal closures or real-time reporting via “fleet communication systems” (Gauvin et al., 1996; Hall et al., 2000; Gilman et al., 2006) or by designing fishing gear so that it sorts target and non-target individuals based upon behavioural differences (Isaksen and Valdemarsen, 1994; Cotter et al., 1997; Campos and Fonseca, 2004; Beutel et al., 2008) or physical differences in size or shape (Kvamme and Isaksen, 2004; Kvalsvik et al., 2006). If reliable information on the species and sizes entering the trawl were available to the skipper in real-time, decisions could be made about whether to continue or abort trawling depending on whether target or non-target fish were being captured. For example, fish in the pelagic zone are often depth-stratified by species and size (Masse et al., 1996) and real-time information on the fish entering the trawl could be used to best position the trawl to maximize catch of target fish while minimizing bycatch.

While the amount of fish captured as a part of fisheries research is very small in comparison with commercial fisheries, most fish captured in trawls as part of fisheries surveys and other scientific investigations do not survive. They experience stress that can lead to impairment and increased vulnerability to predation if released alive (Ryer, 2002) and are often subject to physical trauma including abrasion and scale loss; crushing against meshes during towing and haulback; baurotrauma if they are brought up from depth; and anoxic conditions when held onboard. Since catch comes onboard all at once, it can take several hours to measure the entire catch during research cruises and most fish are ultimately thrown back dead or moribund. Survey mortality can be of concern when investigating endangered species or populations with low numbers (Douglas, 1993; Nielsen, 1998; Holliman et al., 2003), and represents a waste of resources even when investigating robust populations, creating pressure to reduce the duration or number of sampling hauls conducted.. Research vessels may not be equipped to handle large catches, and discards may lead to negative public perception of research activities.

Shortcomings in trawl sampling

In addition to the negative perception of killing fish to study them, current trawling techniques do not necessarily provide the precisely directed and unbiased snapshot that researchers need to sample marine ecosystems. Problems include loss of spatial resolution as catch that was accumulated along a transect is reduced to a single point of data and selectivity, with varying catching and retention efficiencies depending on species and sizes.

Poor spatial resolution during trawling

Trawls accumulate catch over time, collecting and mixing organisms over a trawl path that is generally kilometres in length and may have captured individuals at multiple depths within the water column. All information is lost about when each individual entered the trawl. With heightened focus on species interactions as part of an ecosystem approach to fisheries management and advances in spatial modelling and geostatistical techniques, this represents a significant loss of valuable data (Kracker, 1999). Acoustic surveys, which use calibrated echosounders to measure fish density and distribution, also rely on trawl samples in order to verify species and calculate target strength for biomass conversions (Simmonds and MacLennan, 2005). But if the catch from a single trawl haul trawl yields a variety of species and sizes, it is impossible to know with certainty which organisms contributed to specific acoustic registrations. Better information on the precise depth and geographic location where each individual was captured would enhance the utility of the trawl data to support interpretation of the acoustic results.

Resolution can be increased by using multi-codend systems (Engås et al., 1997; Madsen et al., 2012; Oozeki et al., 2012), but the number of discrete sampling intervals is limited by the number of codends. Also, each codend can be activated just once, so they fill sequentially based upon the time of activation. More ecologically important sampling units such as depth; oceanographic conditions; seabed type; and overlap between species may be duplicated multiple times within the trawl’s path, making it most appropriate to aggregate data from multiple non-contiguous time intervals.

Loss of spatial resolution during trawling also makes it difficult or impossible to know if the proper portion of the water column is being sampled when targetting pelagically distributed organisms. For example, in Norway at- or near-surface pelagic trawl surveys are carried out for small pelagic species and young of the year fishes (Anon, 2011; ICES, 2012). In these surveys, it is assumed that the species being targeted are distributed in the upper water column but there is generally little information indicating how deep they extend and therefore what depths sampling needs to include in order to encompass the entire distribution. Acoustic data can sometimes indicate if fish are present below the standard trawling depth and trawling should therefore be carried out deeper, but if individuals are small and not distributed in aggregations they may not be apparent in the acoustic record. If, instead, a detailed record of what was passing through the trawl could be sent to the vessel in real time, trawling could be conducted at increasing depth until the target species are no longer encountered. This approach might be too time-consuming to implement at all sampling stations, particularly for species present in low numbers, but could be conducted each time a new geographic area is sampled in order to determine the necessary sampling depth in that particular locale.

Size and species selectivity

Trawls do not have equal catch efficiency for all organisms in their path. Rather, they are selective in the sizes and species captured and retained (Engås, 1994; Wileman et al., 1996; Fraser et al., 2007). In commercial fisheries, trawl selectivity is generally seen as beneficial and is encouraged in order to favour the retention of target species and sizes over non-target ones (MacLennan, 1992; Glass, 2000). The opposite is true for sampling trawls, where the goal is generally to capture a random, representative, sample of all organisms present. In this case, selectivity should be low or selectivity parameters known for all species of interest so that the true population can be calculated from the retained catch.

Modern pelagic trawls, designed to be towed off the seabed at high speed, are constructed with meshes in the forward sections that can be tens of meters in size (Valdemarsen, 2001). These large “herding” meshes do not physically prevent the fish inside the trawl from escaping, rather they create visual and/or sound stimuli which fish avoid with the result that they remain inside the trawl. This non-physical barrier is apparently effective, as large mesh pelagic trawls effectively capture commercial quantities of even small pelagic species. However, when pelagic trawls are used for fisheries surveys even low rates of escape through the forward herding meshes may have important ramifications for estimates of fish density as well as species and sizes. This is particularly true when escapement varies according to fish size (Skúvadal et al., 2011; Williams et al., 2011; Williams et al., 2013), resulting in catches that do not accurately reflect the size distribution in the population sampled.

Codend mesh size is a key factor determining selectivity inside a trawl (Wileman et al., 1996; Glass, 2000) and is often regulated in order to achieve species and minimum legal size goals in commercial fisheries. However, codend selectivity has been shown to vary with the size of the catch. Drag of the trawl in the water causes longitudinal stretching in the extension and portions of the codend ahead of the accumulated catch, narrowing the circumference and reducing mesh opening in trawls constructed of diamond-shaped meshes. As fish accumulate in the codend, the meshes immediately ahead of the catch become stretched laterally so that the openings get larger providing enhanced opportunities for escapement (Jones et al., 2008). Thus, to a point, escapement generally increases with catch size (O'Neill and Kynoch, 1996; Herrmann, 2005). However, at very large catch quantities the retention of small fish has actually been shown to increase (Casey *et al.*, 1992; Erikson *et al.*, 1996). Presumably this occurs because the unsuccessful escapees become gilled in the meshes, reducing the number of meshes available to escape through, and individuals at the centre of the accumulated catch are blocked from the codend meshes.

In order to reduce selectivity in sampling trawls, codend mesh sizes are selected to be small enough to retain all organisms of interest. Traditionally, this has been based upon smallest fish of interest, but as fisheries management moves towards ecosystem rather than single-species surveys there is growing need for techniques that can capture synchronous samples over a broad range of trophic levels and sizes including zooplankton species that pass through even small mesh codends of fish trawls. One solution could be to eliminate the codend altogether. If individuals were instead guided past a detector that could identify, count, and measure them while still inside the trawl there would be no need to retain them and therefore no problems with size-selective retention. This would also address problems of undercounting due to predation inside the codend (Can and Demirci, 2004) and disintegration of fragile species such as jellyfish and other gelatinous organisms due to abrasion against the trawl meshes and other components of the catch (Hamner et al., 1975). If a subsample of individuals is necessary for biological investigations, the technique could be combined with a multisampler or purpose-designed mechanical catch/release apparatus.

Fish behaviour during trawl capture

Behavioural patterns in animals are the outward expression of the interplay between sensory capacity and reaction to stimuli. However, reaction to a stimulus comes at a cost to the animal in the form of some other activity that must be foregone or in extra energy expenditures (Sih, 1980; Lima and Dill, 1990; Endler, 1991). The presence and strength of reaction to stimuli can vary by group size as well as for individuals within a single group of fish (Fitzsimmons and Warburton, 1992; Magurran, 1993), with “state” factors such as hunger level, perceived predation pressure and reproductive status playing major roles in mediating the response (Lima and Dill, 1990; Fernö, 1993). Interpreting observed behaviours in relation to trawls is further complicated by the fact that “predation” by trawls is an evolutionarily new danger which fish have not developed optimal strategies to avoid (Fernö, 1993).

Fish can likely hear an approaching vessel at a range of hundreds to thousands of meters (Ona, 1988; Handegard and Tjøstheim, 2009) and generally react by both moving laterally and diving if they are in the pelagic zone (Olsen et al., 1983; Ona, 1988; Yousif and Aglen, 1999). Taking into account the hearing thresholds of fish over the range of vessel-generated frequencies, guidelines for "noise quieted" research vessels have been established (Mitson, 1995) and many new vessels have been built to conform to these standards. However, studies comparing fishes' reaction to quieted and non-quieted vessels have shown equivocal and sometimes contradictory results (De Robertis and Handegard, 2013), indicating the response may not be due to vessel noise alone or that "quiet" vessels are not sufficiently quiet. Fish may be quite sophisticated in their ability to recognize stimuli which correspond to recognized situations, and fail to react to stimuli which indicate more novel events. For example, Atlantic herring (*Clupea harengus*) have been shown to react to sounds generated by cetacean predators but not to sounds of similar frequencies and modulation generated by a low frequency sonar (Doksaeter et al., 2009).

Under sufficient light levels, vision is believed to be the most primary sense used by fish when they are in close proximity to a visibly distinct object such as a trawl (Wardle, 1993), and they generally base their movements relative to the fishing gear on "optomotor response" to maintain station with visual reference points on the gear (Arnold, 1974). Fish also perceive their surroundings and initiate movements by tactile stimulus and detection of currents and pressure through the lateral line system, either in place of a visual stimulus in low-light conditions or as simultaneous contributors (Harden Jones, 1963; Partridge and Pitcher, 1980; Janssen and Corcoran, 1993; Montgomery et al., 1997; Liao, 2006).

Extensive literature exists on the behaviour of fish in relation to demersal trawls (Main and Sangster, 1981; Engås, 1994; Kim and Wardle, 2003; Jones *et al.*, 2008; Queirolo *et al.*, 2010). Fish react strongly to visual components of demersal trawls under light conditions and typically perform a "fountain manoeuvre" whereby they are herded either towards the centre of the trawl entrance or away from the trawl by visual perception of the trawl doors, mud clouds, netting, ropes, and floats at front of the trawl (Wardle, 1993). Even under dark conditions, cod, haddock, and saithe have been observed to enter at the horizontal centre of a demersal trawl (Engås and Ona, 1990), suggesting that non-visual stimuli immediately ahead of the trawl opening may play an important role in positioning fish ahead of the approaching trawl. In some studies, fixed lights on trawls have not shown significant effect on catch rates in bottom trawls (Weinberg and Munro, 1999), while catches have been decreased significantly in others but behaviour has appeared to be unchanged from dark conditions (Albert et al., 2006).

Studies of behaviour in pelagic trawls are far fewer. Suuronen et al. (1996) concluded that extended duration of swimming inside a pelagic trawl and contact with the mesh panels was responsible for high mortality of Atlantic herring (Clupea harengus), with small fish experiencing greater mortality than larger fish. Large sardinella (*Sardinella maderensis* and *Sardinella aurita*) inside a pelagic trawl have been observed to actively swim in the direction of trawling at speeds of 2 m sec^{-1}, holding position relative to the trawl for tens of minutes and possibly escaping capture by swimming out of the trawl mouth during hauling (Haugland and Misund, 2011).

The few published observations of the behaviour of demersal species in pelagic trawls have shown less active swimming. Experiments using imaging sonar and video cameras showed that juvenile Walleye pollock (*Theragra chalcogramma*) generally maintain a forward orientation as they pass through a pelagic trawl, moving back continuously with only brief and infrequent attempts to hold position or swim forward (Rose, 2004). Apparently this is not because they lack reference to the meshes of the trawl, as fish were shown to maintain a greater distance from the trawl panels at high light levels relative to nighttime (Williams et al., 2013). Recapture nets used in the latter study showed that escape occurred primarily through meshes in the bottom panel of the trawl. Atlantic cod in the extension and codend of a pelagic trawl have been observed to maintain a forward orientation while being slowly carried back by water flow in the trawl (T. Jörgensen, unpublished data) but formal studies and analyses of these patterns has not been reported prior to this thesis.

Challenges observing fish and fish behaviour in trawls, and a possible way forward

Trawls are an extremely difficult environment to deploy equipment for observing organisms as they are captured. They are flexible structures that come into shape as a result of hydrodynamic forces acting in multiple directions during towing, with varying geometry depending on trawling speed; current; design and adjustment of the trawl doors; and even the quantity of catch inside the codend. This plasticity in shape means that sampling equipment and techniques need to survive significant changes in the trawl's geometry during shooting, towing, and heaving. It can be particularly challenging to mount instruments to a trawl in such a way that they maintain proper orientation to sample all passing fish as the trawl's shape changes during the different phases of towing. Making observations in pelagic trawls is particularly challenging, as the dimensions in the forward section are much greater than for demersal trawls and often exceed the range of optical sensors. Also, with mesh openings of metres to tens of metres it can be difficult to mount equipment securely.

While instruments such as cameras and echosounders/sonars are sometimes placed directly on trawls (Engås and Ona, 1990; Piasente *et al.*, 2004), it is often preferable or necessary to position sensors at some distance from the trawl for purposes of equipment handling or in order to achieve a sufficiently large sampling volume. This can be accomplished by equipping divers with handheld equipment when operating in shallow depths (Workman and Taylor, 1989), using stationary and submersible platforms which the trawl passes at close range (Ona and Godø, 1990; Handegard and Tjøstheim, 2009) or submersible vehicles which can be manoeuvred around the gear (Urquhart and Stewart, 1993; Graham et al., 2004; Churnside et al., 2012). Sometimes multiple techniques are combined, with optical and acoustic devices mounted both on the trawl and towed vehicles (Haugland and Misund, 2011).

Often, tradeoffs must be made between the detail of data collected and the proportion and region of the trawl observed, alterations to trawling techniques or the trawl's performance as a result of adding sensors, and effect of the observation methods on behaviour of the fish being observed. This is of particular concern for optical sensors that employ artificial illumination (Marchesan et al., 2005; Ryer et al., 2009). Artificial lighting can be particularly problematic when studying mixed species assemblages, as reactions may vary by species (Weinberg and Munro, 1999; Marchesan et al., 2005), with some species being attracted while others are repelled. Low-light monochrome cameras can sometimes be used with just ambient natural light, but with the trade-off of low resolution and loss of colour information which can make it difficult to identify the species of individual fish as they pass (Krag et al., 2009). Generally speaking, the ability to positively identify fish increases with image resolution (Lowry et al., 2011; Underwood et al., 2012).

Acoustic equipment including echosounders and high-frequency sonar have been used to detect individual fish inside a trawl (Engås and Ona, 1990; Handegard and Williams, 2008; Rakowitz *et al.*, 2012) and shape information from echograms can be sometimes used to differentiate between species (Rose, 2004). Behaviour can sometimes be inferred from indirect methods such as using collection bags placed outside of the trawl to intercept escaping fish (Weinberg and Munro, 1999; Williams et al., 2013), however this provides only a single measurement for the entire haul and provide no temporal information about when during trawling the fish entered the collection bags.

Study Background and Objectives

The studies presented in this thesis employed both acoustic and optical techniques to describe the behaviours and distribution patterns of fish captured with pelagic trawls, both in the water column prior to capture and once inside the trawl. The first investigation employed a network of vessel- and trawl-mounted echosounders and scanning sonar to track individual shoals of Atlantic cod (*Gadus morhua*) during capture onboard a commercial fishing vessel. Shifting fishing effort for large gadoid species from demersal to pelagic trawls is seen as a possible way to reduce seabed impacts, and may yield additional environmental benefits resulting from reduced fuel consumption per unit of fish captured. For pelagic trawls to become a viable method for harvesting large gadoids, trawl designs and fishing strategies will need to be optimized based upon improved understanding of how these species behave during capture with pelagic trawls. The overarching objective of this first investigation was to improve understanding of these behaviours so that trawl design and fishing strategy can be optimized to make pelagic trawls a viable alternative to demersal trawls for reduced negative environmental impacts.

Since data were collected in a commercial fishing setting, it was not practical to make observations from a remote vehicle or stationary platform/buoy. Instead, robust trawl-mounted acoustic sensors designed for commercial fishing were used (SCANMAR TrawlEye TE40 and SIMRAD FS70 Trawl Sonar). These types of sensors provide valuable information to verify that fish are entering a trawl and a rough estimate of amounts, but cannot be used to positively identify species or sizes. Large catches during the investigation and historic problems with bycatch of undersized fish in pelagic trawl fisheries for large gadoid species emphasized the need to provide detailed information about the species and sizes of fish entering the trawl in real time during fishing. This led to the second objective of developing a technique to identify and measure individual fish during trawling.

At the time this thesis work was started, a company in Norway was in the early stages of development of an in-trawl imaging and analysis system to provide this information. The equipment was still largely in a conceptual stage and making it operational for use inside trawls and verifying identification results was a principal focus of the work described here. Extensive testing was carried out both on land and at sea to develop the image collection equipment as well as techniques for mounting the system inside existing trawl designs and protocols and methods for handling and analyzing the image data. A number of tests were undertaken to evaluate the species and length results from the camera system against results from standard biological sampling. For practical reasons, and in response to requests from the fisheries research community, development and testing work focused on using the technology to improve research sampling methods rather than commercial fishing applications.

The first objective is addressed in **paper I**, The reactions of shoaling adult Atlantic cod to a pelagic trawl. **Paper II**, DeepVision: a stereo camera system provides highly accurate counts and lengths of fish passing inside a trawl, describes an optical system for achieving the second objective of identifying and measuring free-swimming fish inside a trawl. It also verifies count by species and length results against physical sampling of the catch from the codend. **Paper III**, DeepVision In-Trawl Imaging: Sampling the Water Column in Four Dimensions, tests the system during a fisheries ecosystem survey and reports on some of the new types of data generated, including verifying the identities and sizes of organisms detected acoustically and investigating fine-scale distribution and interactions between species spanning multiple tropic levels and orders of magnitude in sizes.

Abstracts of Papers I-III

Paper I

Shale Rosen, Arill Engås, Anders Fernö, and Terje Jörgensen

The reactions of shoaling adult cod to a pelagic trawl

The reactions of shoaling adult Atlantic cod to a pelagic trawl were measured during fishing off the north coast of Norway. Cod remaining in the trawl track dove at rates as high as 0.35 m s^{-1} following vessel passage and swam away from the vessel, in the direction of the approaching trawl, at an average rate of 0.6 m s^{-1}. The fish did not attempt to swim ahead of the trawl as previously documented in demersal trawls, but passed into the lower half of the trawl entrance and swam slowly in the direction of trawling at a rate of 0.2 – 0.5 m s^{-1} as the trawl's greater speed through water carried them deeper into the trawl. Shoals compressed vertically once inside the trawl, indicating packing density increased at least fourfold. Fish remained in the lower half of the trawl as they moved through the tapered section of the trawl towards the codend with little to no clearance above the bottom panel but significant clearance beneath the top panel. Catches were sufficient to support commercial harvest and the behaviours observed suggest that changes in trawl design and fishing strategy might improve fuel economy and species selectivity.

Paper II

Shale Rosen, Terje Jörgensen, Darren Hammersland-White, and Jens Christian Holst

DeepVision: a stereo camera system provides highly accurate counts and lengths of fish passing inside a trawl

The DeepVision stereo camera system collects a continuous record of colour images of all fish passing inside the extension of a trawl. Ninety-eight percent of 1729 fish captured while trawling could be identified to species from images and lengths could be estimated from the images of 96 % of the fish identified. A landmark distance

technique developed to estimate lengths from images containing incomplete, curved, or obscured fish introduced < 1 % error for the majority of individuals (maximum 5 % error). The technology can greatly increase the scope of information collected during trawl sampling, including documenting fine-scale distribution of individual fish and species overlap. Such information can aid in interpreting acoustic data and fine-scale community composition, and could be collected with an open codend trawl, greatly reducing sampling mortality. Images are easily archived, providing an opportunity to quality check the raw data and re-visit datasets originally collected for different purposes. Adaptation of the technology for commercial fisheries could reduce the catch of unwanted species and sizes.

Paper III

Shale Rosen.and Jens Christian Holst

DeepVision in-trawl imaging: sampling the water column in four dimensions

An in-trawl stereo camera system (DeepVision) collected continuous, overlapping, images of organisms ranging from krill and jellyfish to large teleost fishes, including saithe (*Pollachius virens*) and Atlantic cod (*Gadus morhua*) infected with parasitic copepods. The four-dimensional position (latitude, longitude, depth, time) of individuals was recorded as they passed the camera, providing a level of within-haul spatial resolution not available with standard trawl sampling. Most species were patchily distributed, both vertically and horizontally, and occasionally individuals were observed at significant vertical and horizontal separation from conspecifics. Acoustically visible layers extending off the continental rise at 250 m depth and greater were verified as primarily blue whiting (*Micromesistius poutassou*), but also included a small proportion of evenly distributed golden redfish (*Sebastes marinus*) and greater Argentines (*Argentina silus*). Small, but statistically significant, differences in length by depth were observed for blue whiting within a single haul. These results demonstrate the technology can greatly increase the amount and detail of information collected with little additional sampling effort.

Discussion

The behaviour of shoaling adult Atlantic cod during capture in a pelagic trawl

The first study undertaken as part of this thesis was initiated in order to improve the suitability and efficiency of pelagic trawls to target large gadoid species of commercial interest and is described in **Paper I.** With heightened awareness about the environmental impacts of demersal trawling on benthic communities and ecosystem functioning, shifting fishing effort into the pelagic zone is seen as a way to reduce seabed damage and improve the sustainability of wild capture fisheries. Shifting from demersal to pelagic trawling may also result in reduced fuel consumption, as pelagic trawl fisheries generally catch more fish per unit of fuel consumed (Schau *et al.*, 2009). While this may be due in part to the large volume characteristics of most pelagic trawl fisheries which capture large numbers of small schooling individuals in dense aggregations, data collected on hourly fuel use while targeting Atlantic cod suggest that the catch (kg l^{-1} fuel) was higher when fishing with a pelagic trawl than with either single or twin demersal trawls (Rosen, 2009).

A persistent distribution of adult post-spawning cod (weighted mean length 79 cm, s.d. 11-12) was located off the north coast of Norway, and their behaviour was recorded during capture onboard a commercial trawler. Catch rates with a pelagic trawl were high, with average catch of 5 tonnes per hour (maximum 11 tonnes per hour). The fish followed a consistent diurnal pattern during the seven-day period of investigation, rising up into the water column where they were available to the pelagic trawl during the day but descending to the seabed at night where they were captured using a demersal trawl. Acoustic instruments were used to record the passage of individual shoals of cod as they passed beneath the vessel, into the trawl mouth, and points 100m and 130 m inside the trawl. Diving and swimming rates, fish orientations, and changes in shoal dimensions were inferred by matching shoals as they passed each of the locations.

Diving

The vast majority of shoals were recorded to be at least 5 m deeper when they passed the trawl mouth than at the time of vessel passage, indicating a consistent diving response. This is consistent with previously published results for Atlantic cod (Ona, 1988; Handegard and Tjøstheim, 2005), and diving rates are within previously reported ranges. With the instruments we were using, it was impossible to measure the horizontal response for any shoals that did not come within range of the sonar mounted at the trawl opening. Fish at the shallowest depths dived at a greater velocity than deeper ones, indicating the strength of the response is related to proximity to the passing vessel. These results are also consistent with reactions measured for schooling Atlantic cod, herring, and Sardinella (Olsen *et al.*, 1983; Gerlotto and Fréon, 1992).

In order to compensate for this diving, the trawl was fished with the headrope at the depth of the bottom of the shoals as indicated on the vessel's echosounder. Even so, most fish entered in the lower half of the trawl and 23 % escaped beneath the footrope with minimal loss above the headrope. Likely, positioning the trawl even deeper in the water column would have led to even higher catch rates, although if diving was primarily in response to the trawl warps as suggested by Handegard and Tjøstheim (2009) or the sonar cable stretching from the vessel to the centre of the headrope this might simply lead fish to dive deeper. In this case, altering the trawl's rigging to achieve a higher opening might be a more effective strategy.

Swimming

Shoals arrived at the trawl mouth more quickly than predicted by the trawl's speed through water, showing that they were actively swimming away from the receding vessel and towards the approaching trawl. Swimming speeds were, however, well below maximum sustainable speeds (Winger et al., 2000). By swimming away from the vessel and towards the trawl, fish maximized the rate at which they placed distance between themselves and the noise radiated by the vessel, suggesting that the primary aversive stimulus in this portion of the catching process is noise generated by vessel rather than sounds or visual registration of the warps, sonar cable, doors, bridles, or trawl. This contrasts with our understanding of how Atlantic cod react to approaching demersal trawls, where the gear's contact with the seabed likely generates significant noise and gadoid fish (including cod) have been observed to orient themselves in the towing direction after the vessel passes (Handegard and Tjøstheim, 2005) and to swim in the direction of trawling in the region immediately ahead of an approaching demersal trawl (Main and Sangster, 1981). Pelagic trawls, which do not make contact with the seabed, should generate less noise and their approach may therefore be perceived as a less threatening and not to warrant evasive swimming.

Once in the trawl mouth, cod appear to have passed directly into the pelagic trawl. Again, this is in contrast to observations in demersal trawls where fish, including cod, accumulate ahead of the entrance swimming in the direction of trawling until they become fatigued and fall back into the trawl (Main and Sangster, 1981; Wardle, 1993; Engås, 1994). The degree to which this ordered reaction depends on light levels is unclear. Glass and Wardle (1989) showed that orientations in the mouth area of a demersal trawl became random at light levels below 10^{-6} lx while Engås and Ona (1990) documented that the majority of gadoid species fish (including Atlantic cod) continued to enter at the horizontal centre of a demersal trawl at night, suggesting they maintained some degree of orientation relative to the approaching trawl.

Once inside the pelagic trawl, cod evidently changed horizontal orientation and began to swim slowly in the direction of trawling. Swimming speeds remained at sustainable levels which were much lower than the trawl's speed through water, and the shoals were carried steadily deeper into the trawl. This is consistent with observations of walleye pollock inside pelagic trawls (Rose, 2004; Williams et al., 2013).

Position within the trawl

Fish entered in the lower portion of the trawl mouth (see discussion above), and maintained a low position as they passed deeper into the trawl. While clearance between the top of the shoals and the upper panel averaged 8 meters at a point 100 m into the trawl and 5.2 m 130 m into the trawl, clearance above the lower panel was just 1.3 m and 0.4 m at the same locations. This suggests that the upper panel of the trawl plays a minor role in retaining cod, while the under panel is a more likely route for escape. Engås et al. (2012) documented that the majority of Atlantic cod escaping through the aft belly of a pelagic trawl during commercial harvest passed through the under panel, consistent with results for juvenile walleye pollock in a sampling trawl (Williams et al., 2013), while haddock escaped exclusively through the over panel.

Graphical summary of cod behaviour during capture with a pelagic trawl

The behaviours observed for cod during capture with a pelagic trawl, including orientation; diving; swimming speed; and position relative to the trawl are summarized in Figure 1.

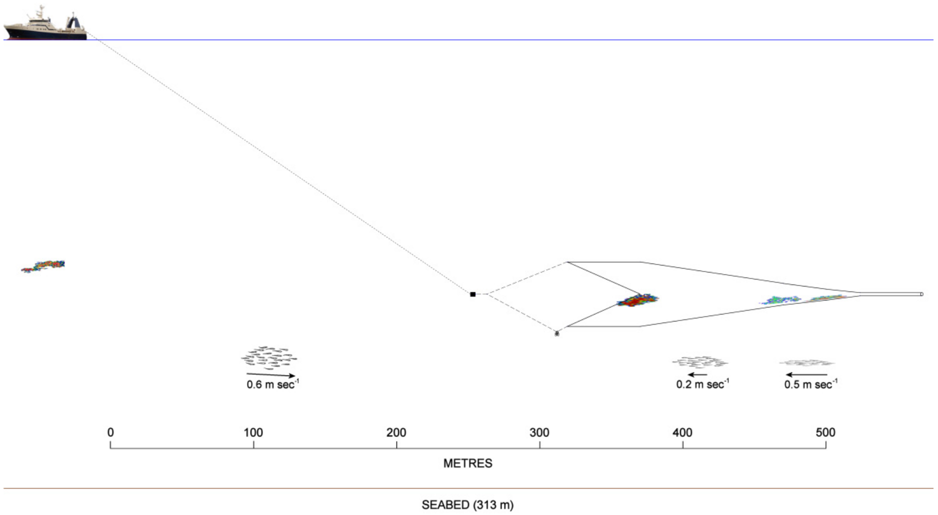


Figure 1. Graphical summary of cod behaviour observed during capture with a pelagic trawl. All elements are shown at proper scale, with the exception of the drawings of schooling fish beneath the trawl. Acoustic representations of shoals beneath the vessel and inside the trawl illustrate the passage of a single shoal, scaled to represent dimensions and positions from **paper I** Tables 2 and 4. Arrows beneath the illustrations of swimming fish indicate swimming velocities and orientations from **paper I** Table 3.

Limitations and uncertainties in interpreting behaviour from acoustic sensors

While we are able to draw conclusions about average behaviour and orientations over the 10s to 100s of m intervals between the acoustic sensors, the techniques used in the study do not provide information on instantaneous behaviour of individuals. For example, passage rates in the interval between the vessel and trawl opening indicate that overall fish dove and swam towards the trawl in this 400 - 500 m interval. But it is impossible to know whether the swimming and diving rates were consistent over the entire interval, or if they varied in magnitude and possibly even direction. And while we have concluded that fish reversed their orientation from swimming against the trawling direction in the region between the vessel and trawl opening to swimming in the direction of trawling once inside the trawl, it is impossible to know precisely where this turn occurred. We also do not have a measure of the degree to which individuals within each shoal deviated from the overall average behaviour, but presumably it was minor as the shoals remained sufficiently intact to be traced over the 500+ m from the vessel to the aft Trawleye.

Follow-up studies would be wise to employ additional techniques to record images of passing fish so that orientation and swimming behaviour can be verified. Techniques such as strobed imaging with long intervals between flashes (Glass and Wardle, 1989) or imaging sonars (Williams et al., 2013) could help to fill this information gap without affecting behaviour. The position of fish inside the trawl during our study indicates that, for investigations of cod, these instruments would be most likely to collect useful information if mounted in the lower portion of the trawl.

Recommendations for optimizing the capture of Atlantic cod using a pelagic trawl

In order for changes in fishing methods or gear to be attractive and voluntarily adopted, it is important that they do not result in reduced earnings for the vessel (Valdemarsen and Suuronen, 2003). Thus, if gadoid species such as Atlantic cod are to be targeted commercially using pelagic trawls the trawl designs and fishing strategies should be optimized to catch fish as efficiently as possible with respect to aspects such as time spent searching for fish and trawling, proportion of the fish entering the trawl that are retained versus escape, fuel consumption, and quality of the fish following processing onboard. Catch rates with a pelagic trawl were indeed high during this investigation, averaging over 18 tonnes per haul. This sometimes led to problems with catch size exceeding the vessel’s capacity to process fish before quality deteriorated. The problem was that the catch sensors, which measure latitudinal stretching of the codend as it fills, were activated during haulback rather than at the towing depth were they would have provided a signal to stop trawling. If the skipper had a real-time measure of the amount of fish entering and passing through the trawl rather than waiting for it to accumulate in the codend, a more informed decision could have been made about when to stop trawling.

While cod were in the pelagic zone and available to a pelagic trawl during daylight hours, they descended to the seabed at night where only demersal fishing gear was effective. This suggests that pelagic trawls are unlikely to be able to completely replace demersal trawls for harvesting cod in the conditions encountered and underscores the importance of having flexibility in fishing strategy, either with a fishing gear that can be used in both demersal and pelagic situations or by switching between demersal and pelagic trawls. Nonetheless, any fish taken with pelagic trawl represent a reduction in demersal trawling effort with corresponding decrease in seabed impacts.

Diving following the vessel's passage meant that the trawl had to be fished at depth greater than where shoals were detected by the vessel's echosounder. Even fishing with the headrope at a depth corresponding to the lower edge of the shoals, entrance patterns in the trawl mouth show that fish entered primarily in the lower portion of the trawl opening and a significant amount escaped beneath the footrope. Increasing the fishing depth even more or making adjustments to achieve a higher trawl opening would likely have captured at least a portion of these fish.

Since shoals entered the trawl readily, without first swimming to exhaustion as previously described for demersal trawls, it appears that trawling speed could be reduced while maintaining high catch rates. As decreasing vessel speed results in significant reduction in fuel consumption (Ellingsen and Lønseth, 2005; Gulbrandsen, 2012), this could lead to improved profitability while reducing emissions of greenhouse gases. Another way to reduce fuel consumption is by designing trawls with larger meshes, reduced twine area, and lower drag. Since cod were concentrated in the lower half of the trawl, the upper panel appears not to have been important for preventing escape and mesh size could likely be increased or the large front meshes could be extended even farther back without losing a significant amount of the catch. This may not be true for other co-occurring species such as haddock, which have been shown to escape through the upper panel (Engås et al., 2012), and could lead to improved species selectivity but may be a disadvantage in a multispecies fishery.

DeepVision system for *in-situ* identification of species and sizes inside a trawl

A pelagic trawl fishery for Atlantic cod existed for several years in Norway in the early 1970s, but was stopped by regulators due to concerns about excessive catch sizes and high catches of undersized fish (Hylen, 1973). We also encountered catches in excess of the vessel's processing capacity, due to traditional catch sensors not functioning properly because fish apparently did pack into the codend until heaving. In a commercial fishery this would likely lead to reduced quality of produced fish or illegal dumping and non-reporting of the excess catch. Since size-selectivity devices such as grids, escape windows, and minimum codend mesh sizes lose effectiveness when catches are large, there will likely be a problem with retention of undersized fish in a pelagic fishery targeting dense aggregations of fish of mixed sizes. Thus, a cooperative project was initiated in 2009 between fishing gear researchers at the Institute of Marine Research (Bergen, Norway) and Scantrol AS (Bergen, Norway), a company beginning to develop a camera system capable of identifying and measuring fish as they pass inside a trawl.

The technology, DeepVision, is based upon a system developed previously to measure and identify fish passing on a conveyor belt (White et al., 2006). By performing these identification tasks inside a trawl and sending the results to the vessel in real time, the skipper will be able to make decisions about whether to continue trawling, move to another area, or change the trawl's position in the water column to catch the targeted species and sizes. It may even be possible to combine the identification with an active sorting mechanism such as a controllable door to release non-target portions of the catch. If fish move freely past the camera and information is sent to the vessel in real time, it also has the potential to solve the problems of excessively large catches by giving an indication of the capture rate. As fisheries researchers became aware of the system's development, considerable interest was expressed in testing it for use in fisheries surveys and biological investigations.

Evolution/development of the camera system (**Paper II**)

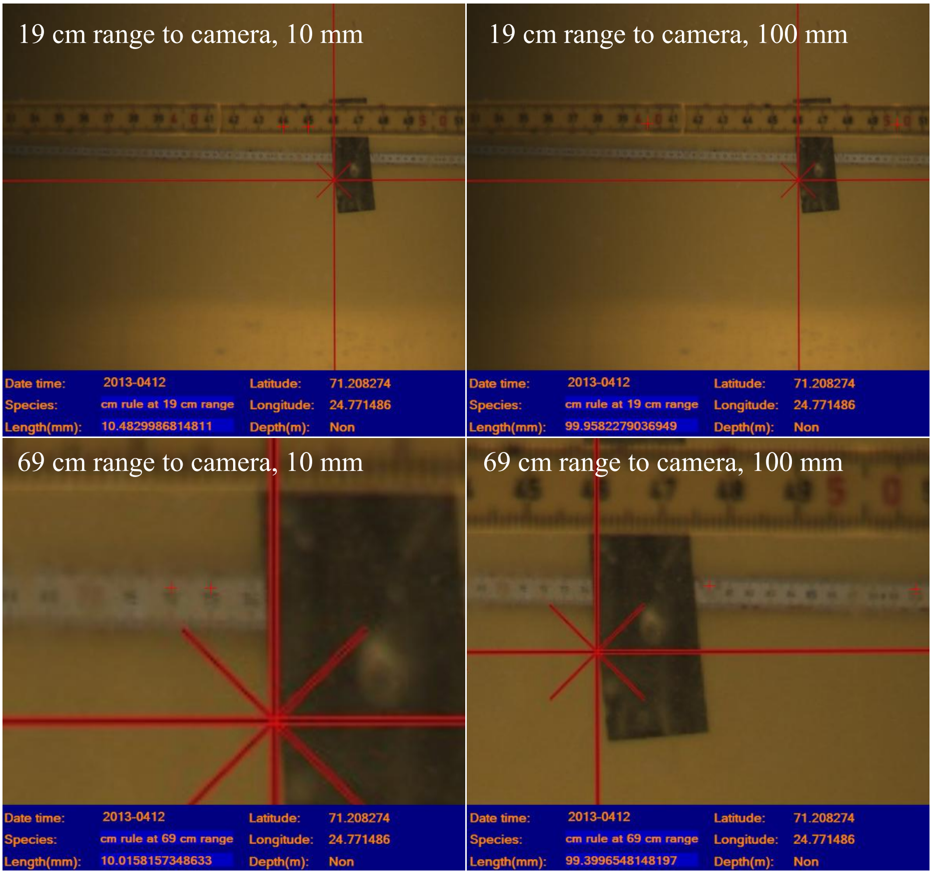
Development of the DeepVision camera system included both technical aspects related to collecting, storing, and analyzing images as well as verifying the species and length results against measurements made using standard sampling procedures. The system's physical design, including overall dimensions and shape and size of the region where fish pass, was developed with consideration for how it would be mounted inside standard pelagic trawl designs while maintaining unobstructed flow of fish and ensuring that all fish pass within the field of view. Many aspects of this development are described in **paper II**, but investigations of camera distortion related to length measurements and water flow and fish orientation inside the system were investigated only in sufficient depth to provide guidance on system design and were not developed into full papers. Results of these investigations are presented in Appendices A and B.

Lens distortion and stereo technique for measuring lengths

A low focal length lens (4.8 mm) was selected as a compromise between achieving a large field of view (65° horizontal by 50° vertical when used with a camera with a 9.0 mm × 6.7 mm image sensor) but reduced light gathering capabilities and increased distortion. Tests quantifying distortion across the image indicated that resolution across the image frame varied by up to 12 % (Appendix A). This created a problem for estimating lengths, as the simple technique of counting pixels and multiplying by a constant resolution could result in errors of the same magnitude. Furthermore, a passage that is large enough to allow fish to move freely past the camera without clogging also means that the range between the camera and fish will vary. Tests showed that a 30 cm variation in range to the camera (the width of the fish passage in an early prototype of the system) resulted in as much as 24 % difference in the actual size represented by each pixel. Since the errors from distortion and range would be additive, as much as 36 % error could be introduced when estimating distances within images.

By adding a second camera and employing stereo photogrammetric techniques, distances can be measured independent of an object's range to the camera. During a calibration process, a target of known dimensions is used to calculate both the optical attributes of the cameras and lenses such as distortion and internal camera geometry (intrinsic properties) and the physical location of the cameras relative to one another (extrinsic properties) (Tsai, 1987). Once the stereo camera system is calibrated, the three-dimensional position of specific points within images can be determined (Bradski and Kaehler, 2008) and the distance between these points can be estimated based upon Euclidian distance.

Baseline, the distance between cameras in a stereo arrangement, is a key factor determining the precision of length measurements. The longer the baseline, the greater the disparity between the left and right images and the more precisely position can be calculated for the measurement endpoints. But as the cameras are moved farther apart, the images become more dissimilar and it becomes more difficult to correctly match the corresponding points in the image pair and overall accuracy can decrease (Okutomi and Kanade, 1993). Trials were conducted with baseline length as great as 23 cm, and were gradually reduced in order to reduce the system's overall size and allow both cameras to be placed inside a single housing, providing less opportunity for the cameras to shift in orientation relative to one another. Using a 12 cm baseline, errors in lengths measured for a rigid target were 1–2 % (**paper II**). More recent tests with a baseline of just 6 cm have shown highly accurate results when measuring distances as small as 1 cm (Figure 2).



Date time: 2013-0412
Latitude: 71.208274
Species: cm rule at 19 cm range
Longitude: 24.771486
Length(mm): 10.4829986814811
Depth(m): Non

Date time: 2013-0412
Latitude: 71.208274
Species: cm rule at 19 cm range
Longitude: 24.771486
Length(mm): 99.9582279036949
Depth(m): Non

Date time: 2013-0412
Latitude: 71.208274
Species: cm rule at 69 cm range
Longitude: 24.771486
Length(mm): 10.0158157348633
Depth(m): Non

Date time: 2013-0412
Latitude: 71.208274
Species: cm rule at 69 cm range
Longitude: 24.771486
Length(mm): 99.3996548148197
Depth(m): Non

Figure 2. Verification of lengths calculated from images of cm graduated rules at 19 cm (top) and 69 cm (bottom) range from camera. Distances calculated by the image analysis software are shown in the "Length(mm)" field. Small red crosses indicate start and end points of the intervals measured. All measurements were made from the same stereo image set, taken in seawater.

Reducing the baseline distance to just 6 cm made it possible to integrate the electronics into a single cylinder tested 2 000 m depth, pictured in **paper II** Figure 1. This has reduced the overall system size and reduced the number of electrical connections that must be made through subsea plugs, a principal weak point in subsea equipment.

One major challenge when estimating lengths from images is that fish may pass the camera in a non-ideal orientation for measuring their length directly. Problems include fish that are curved, occluded by other fish passing nearer to the camera, or positioned so that the snout and tail are not both visible. Thus, the accuracy of length measurements may be determined more by the presentation of the individual fish than by the physical camera setup and calibration. A method for estimating length of poorly presented fish based upon distances between landmark points defined by fin margins is described in **paper II**. This works both for fish that are curved (as long as they are not curved along the distance between the landmark points) and ones where the snout and/or tail are obscured. It is, however, likely to introduce additional error in estimates of length as any error in estimate of the distance between landmark points is multiplied as it is scaled up to fork length. This problem is likely to be most pronounced if using short landmark intervals (Figure 3).

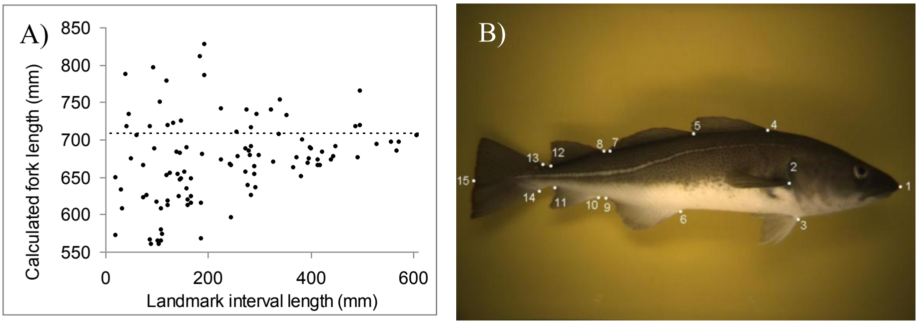


Figure 3. A) Fork length calculated for a 709 mm Atlantic cod by scaling up from 104 landmark intervals defined by fin margins. Broken line indicates actual fork length calculated directly as distance from snout to end of tail. B) Location of the 15 landmark points defining the 104 landmark distances.

If the landmark distance technique is used going forward, investigations will be necessary to verify if it can be used for all species, which landmark distances perform best, and whether new models must be developed each time a new population of fish is investigated. This seems likely, as morphometric variations between individuals from different stocks can be sufficiently large to differentiate between populations (Cadrin and Friedland, 1999), however the actual magnitude of the effect may be small relative to the required precision in length measurements.

Another option for fish that pass without providing a single image suitable for calculating length is to calculate overall length as the sum of a series of shorter lengths along the midline measured on sequential images of the same individual (Figure 4). A similar technique is used when physically measuring especially large fish on a standard measuring board (Øvredal and Totland, 2002). This may be the only strategy for species with an insufficient number of images of well-presented individuals to develop a morphometric model.

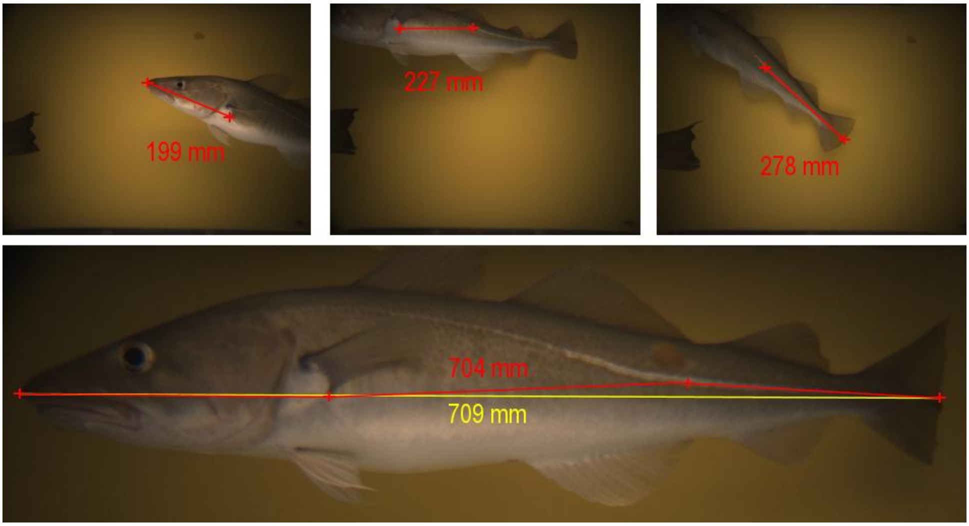


Figure 4. Comparison of length estimated from summing shorter intervals from sequential images (red) and entire interval from tail to snout (yellow). All images are of the same Atlantic cod (*Gadus morhua*).

It is also important to note that the stereo measurement technique cannot be used to accurately estimate total length of species with forked tails, since it relies on matching physical locations located on the fish. Total length of forked-tailed fish is defined by drawing a line between the dorsal and caudal tips of the tail, therefore the actual posterior end point is empty space not located on the fish and therefore cannot be matched between images. Another option is to measure standard length (length from snout to caudal peduncle). Indeed, for species or life stages with highly transparent caudal fins the posterior margin of the caudal fin can be difficult to identify with certainty and standard length will provide a more reliable measure (Figure 5.).

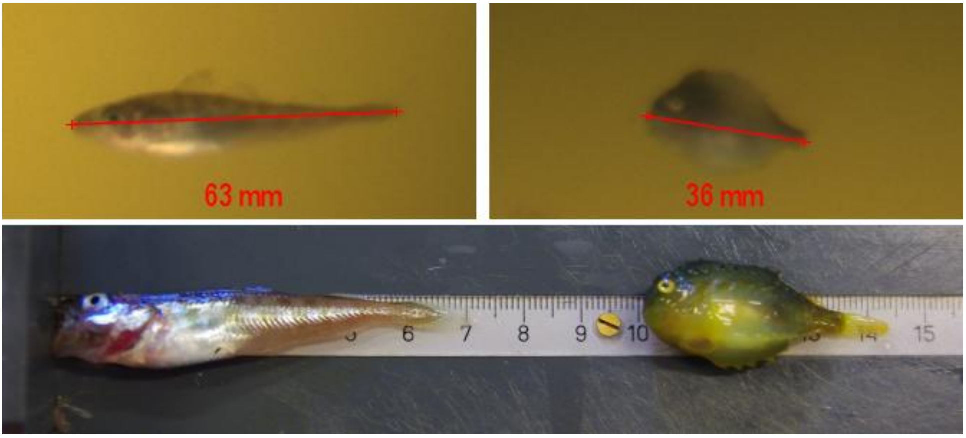


Figure 5. Juvenile Atlantic cod (*Gadus morhua*) (left) and lumpsucker (*Cyclopterus lumpus*) (right). Images and measurements at top were collected during trawling with the DeepVision system. Lower image shows the same individuals in air, placed on a rule numbered every 10 mm. Caudal fins are impossible to resolve in underwater images, and difficult to see for the cod even in air.

Water flow and fish orientation and passage through the DeepVision

Analyses were undertaken early in the system's development to quantify the reduction in waterflow inside the fish channel relative to the trawl entrance as well as orientation of fish as they pass through the DeepVision unit, since good presentation to the camera is critical to collecting images that can be used to identify species and measure lengths. For most fish, a side-on view provides maximum colour and pattern information for species identification, as well as the clearest definition of snout and tail for measuring length. It is also important that fish pass quickly through the DeepVision without first accumulating ahead of the entrance if results are to be used to reduce bycatch in commercial fishing settings or to map the spatial distribution of fish during research investigations.

Water flow through the fish channel in the DeepVision was measured and compared with flow 5.8 m forward in the trawl. The overall reduction in flow was on the order of 0.3 - 0.4 m sec^{-1} at trawling speeds of 1.1 – 2.6 m sec^{-1} speed over ground, but was not even across the width of the channel (Appendix B). The orientations of fish passing through the DeepVision system were also analyzed. During trials early in the system's development, nearly half of the Atlantic cod passing through the system were oriented towards the codend or changed orientation as they passed through the field of view whereas 93 % had a forward orientation just 2 m ahead of the DeepVision (consistent with forward orientation inferred in **paper I**). By re-designing the panel guiding fish in front of the cameras and ensuring it was taut during towing, the proportion of cod passing through the DeepVision in a forward orientation was increased to > 90 %. This made it easier to identify species quickly and to measure lengths, as fish swimming forward (against the trawling direction) remain in the field of view longer than ones swimming aft and swimming individuals present themselves in an extended, straight orientation.

Performance of the DeepVision system and example results

The vast majority of fish imaged with the DeepVision system mounted inside a pelagic trawl were successfully identified to species (98 % in **paper II**, > 99 % in **paper III**). Furthermore, it was possible to measure lengths for 96 % of the identified fish (**paper II**). Comparisons of counts from DeepVision images and traditional sampling of the codend catch matched within 1 % for the cruises analyzed in **paper II**. Significantly more small fish were counted in images than in the codend catch for the cruise analyzed in **paper III**, most likely due to escape through 40 mm meshes in the section between the DeepVision and beginning of the small-mesh codend.

There was also good match between lengths calculated from images and those physically measured from the codend catch. Results from **paper II** demonstrated that for individual fish that could be matched in images and codend catch, the maximum difference was 10 % (median 2 %). When comparing length frequency distributions, differences were statistically significant only for species with extremely narrow length distributions (75 % of individuals spanning seven or fewer 0.5 cm length categories).

For the remaining 19 species, length distributions calculated from the images were indistinguishable from manual measurements of the catch. Figure 5 (this thesis) demonstrates high accuracy in lengths measure for juvenile fish < 10 cm in length.

Physical rigging of the system inside pelagic trawls has not presented major difficulties. It has been successfully integrated with trawls ranging from a small surface smolt trawl to a 960 m circumference design adapted from commercial designs for the blue whiting fishery. Reduction in the overall size of the frame has made handling on deck easier, still having the DeepVision does slow the rate at which the trawl can be deploying and retrieved. Slowing the rate at which the trawl is set out is probably less of a problem than delays during retrieval, as a significant proportion of escape from the codend is believed to occur during haulback (Madsen et al., 2008). The principal reasons that retrieval takes longer with the DeepVision installed are the extra care that must be taken when taking the system onboard and the fact that the trawl can only be wound onto the net drum as far as the DeepVision, with the remaining extension and cod end brought onboard using a gilson winch.

The system has not been used in seas in excess of 4-5 m, so its performance, durability, and effect on deck logistics in these high sea state conditions has not been tested. The majority of the vessels used to deploy the system have a stern ramp, allowing the system to transition easily between the sea surface and trawl deck. Deployments from vessels without a stern ramp require lowering and raising the system using a crane positioned off the stern, a manoeuvre which makes deployment more difficult, particularly in inclement weather.

Studies have not yet been conducted to assess what effects, if any, the DeepVision has on trawl performance or catchability. The greatest opportunity for altering catch is likely the system’s reliance on high intensity (38 400 lumen), strobed, artificial lighting which may affect fish behaviour and their passage into the codend. This could be tested by conducting tests with the strobes turned off for periods of time while rates of fish passage through the system are quantified using another technique such as low-light cameras or a multisampler codend. Similarly, reduced waterflow through the system or clogging by large objects or at very high catch rates may affect how readily fish pass through and into the codend. Measurements and experiments in Appendix B show that the reduction in water flow reduction is not dramatic, and can likely be controlled by carefully tapering the panels leading fish through the imaging channel. To date, clogging has not been observed ahead of or inside the imaging channel.

An example of a fish (an adult haddock) identified, measured, and matched with depth and location from its passage time is presented as Figure 6.

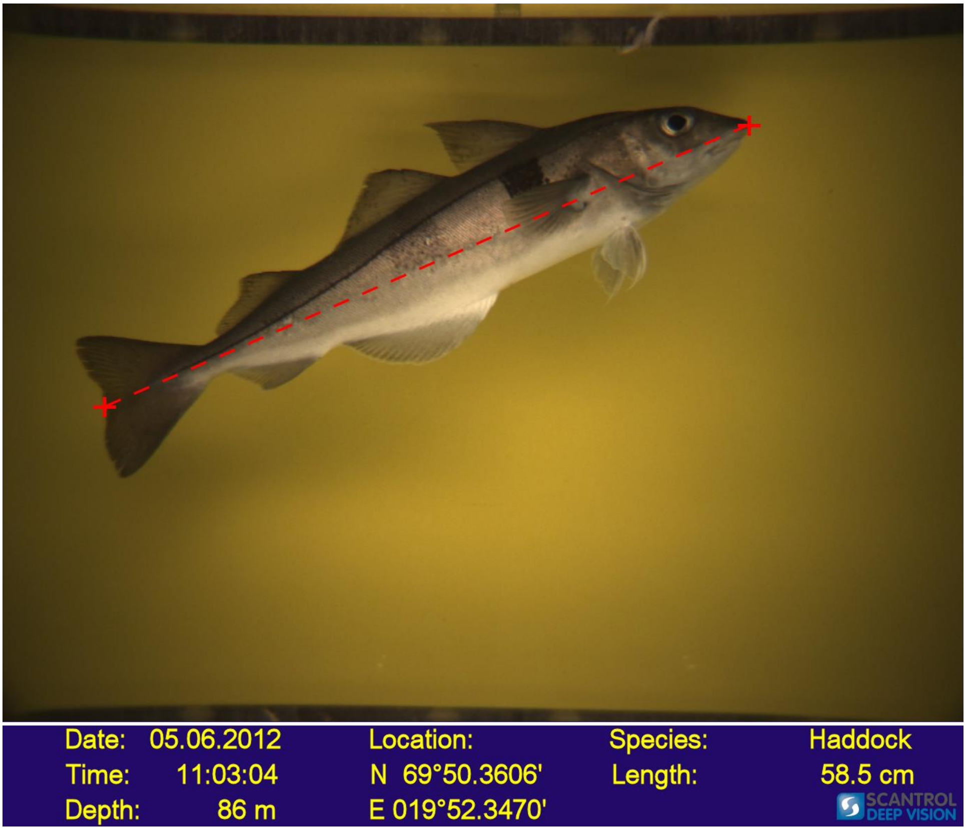


Figure 6. Example of a haddock (*Melanogrammus aeglefinus*) identified and measured using the DeepVision system while trawling. Depth and location were matched based upon the image's timestamp.

Outstanding technical challenges when using DeepVision

Most of the technical challenges related to collecting and storing images have been solved, but work remains to optimize the system's operation and to reduce analysis time when identifying, counting, and measuring the fish imaged. Methods for improving the transfer rate of images from the trawl to vessel in real-time have been developed, but have not yet been integrated into the control software or tested at sea. The method currently used is resource intensive for the PC controlling the cameras and storing the images, and reduces the maximum frame rate from 5 to 2.5 images per second. Consequently, data are generally collected with the system running in an autonomous mode without data sent live to the vessel. This also eliminates competition for use of the net sonar cable, which cannot operate a traditional analog trawl sonar while maintaining DSL connection to the DeepVision system (currently the data feed must be changed using a physical switch on the bridge, although simultaneous transmission will be possible with new digital trawl sonars under development).

Automatic selection of fish in images

Software development to improve the accuracy and speed of the image analysis software is also ongoing. Sorting images containing fish from empty ones, a task done manually for the analyses presented in papers II and III, has now been automated and can be accomplished at a rate of nearly 19 images per second (nearly four times faster than data are collected). This translates to roughly a 25 % reduction in the time required for analysis, although total analysis time depends on additional factors such as the total number of fish imaged and whether they pass singly or in aggregations of overlapping individuals.

One challenge with automating the selection of objects in images (segmentation) is defining the minimum size for a valid object. If this threshold is set too low, non-fish objects such as large zooplankton and fish scales will be identified as valid objects and the automatic selection will save less time. If the threshold is set too high, images containing small individuals may be classified as “empty”. The automated selection routine is therefore likely to perform best for applications where only large fish are of interest. For investigations such as ecosystem surveys aimed at sampling over a wide range of trophic levels and sizes, a large number of false-positive matches may need to be allowed for with manual review of the selected images to identify all organisms of interest.

Single fish in multiple images and multiple fish in single images

After the images containing fish have been identified, it is necessary to review them to select each individual fish for analysis. Since most fish are imaged multiple times, just one image must be selected in order to avoid double-counting. Object tracking techniques (Yilmaz et al., 2006) may reduce the need for a human operator to follow fish between images, but have not been tested and will likely require higher frame rates than the current system is capable of. Images frequently include multiple fish, which may appear to overlap from the perspective of the camera making it difficult to accurately count how many individuals are present.

By creating point cloud representations of the surfaces within the stereo images, each fish’s three-dimensional position can be calculated. When rotated to simulate an above view of the passing fish, separation in the z-dimension becomes apparent (Figure 7). It may also be possible to use distances across the generated surfaces as an alternative method for estimating lengths of curved fish, where the Euclidian distance between snout and tail would result in an underestimate. Volumetric estimates based upon the surfaces may also provide a way to measure fish condition (relative fatness) without having to retain and weigh individuals.

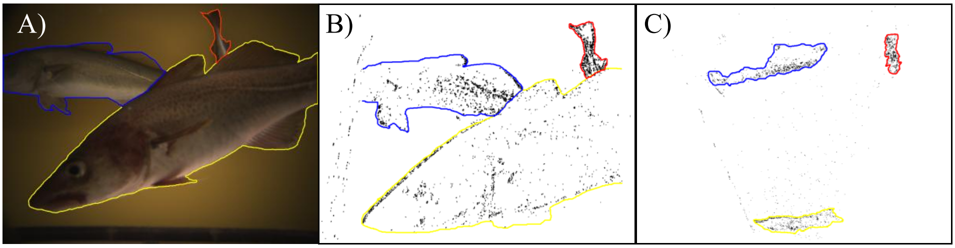


Figure 7. Use of point clouds to separate overlapping fish. A) Original image with three overlapping fish, each outlined in a different colour. B) Point cloud representations of the surfaces of each fish, same perspective as panel A. C) Point cloud rotated to show view from above illustrates the separation between each fish.

Automating species identification and length measurement

Presently, species classification and selection of measurement start- and endpoints is done manually by an operator reviewing archived data. In order for the system to provide real-time results during trawling, and to speed up analysis, automatic techniques will need to be implemented. Preliminary tests have been carried out using discriminate analysis techniques for automatic species identification based upon shape and colour and yielded promising results from a subset of in-trawl images of well-presented fish, but fish that pass in orientations where they do not present a clear side-on view to the camera will likely present a significant challenge. Techniques to automate length measurements have not yet been tested with images from inside a trawl.

Subsampling for large catches and size ranges

In many applications, particularly when catch rates are high, it may not be necessary to identify and measure every fish. Rather, analyzing a portion of images or a portion of the fish in each image may provide sufficient information to generalize catch composition and lengths for the entire catch. Such subsampling is routine for large trawl catches and can provide a robust representation of species and sizes (Heales et al., 2000). It is possible that the fish passing in orientations most conducive to identification and measuring length accurately with automated techniques can be treated as a random subsample. This approach could be particularly useful when entrance rates are extremely high and a large proportion of the fish imaged are partially occluded by individuals nearer the camera. Investigations will, however, be necessary to ensure there is no bias by species or size for the well oriented fish. It will also be necessary to subsample relative to entrance rates, rather than evenly across trawling time, in order to weight the subsampling effort appropriately.

Another type of subsampling may be necessary in order to collect images of sufficient quality to identify species of vastly different sizes. Resolution in the current system is sufficient to identify and measure fish tens of cm in length, but is inadequate for small individuals and most zooplankton species. Options include having a secondary camera system with higher focal length lenses, or diverting a portion of the flow through a smaller channel nearer the camera where resolution is higher.

Operating in areas of low visibility

Obtaining high quality images is critical to achieving accurate results for species identification and length measurements. Being able to detect and recognize distinct patterns and colours is also vital to automated analysis techniques. This is, in part, the reason that development of the DeepVision system has been done in pelagic trawls. Water clarity is generally better mid-water than near the seabed, particularly considering that the trawl doors, sweeps, and ground gear of a demersal trawl will suspend sediments directly in the path of the system. Indirect lighting and relatively short (< 2 m) range from the cameras to passing fish reduce light scattering, improving contrast and clarity. Example images from both DeepVision cameras and a monochrome observation camera (with direct lighting) are presented in supplemental materials to **paper II**, and demonstrate that images suitable for identifying species and measuring lengths can be collected even in relatively turbid conditions.

Trials carried out in April, 2013 tested the system in a demersal trawl with ground gear that tended very close to seabed. During trawling in an area with fine-grained sediments, over 90 % of images were of sufficient quality to quantify species, counts, and lengths. The periodic instances when visibility was too low to yield useful data seldom lasted for more than 10 seconds. In cases such as this, one solution may be to analyze only the high quality images and define the sampling effort to include only those times. Establishing criteria for when image quality is too low for useful data to be obtained will likely be an ongoing process as the system is put into more widespread use.

DeepVision for improved scientific surveys and biological investigations

DeepVision equipment was tested in a standard survey during the 2012 annual coordinated ecosystem survey (IESSNS) in the Norwegian Sea (ICES, 2012), providing a continuous record of all objects passing through the trawl from the time the trawl entered the water until it was brought back onboard the vessel. Results of this investigation are presented in **Paper III**. The water column was sampled during oblique pelagic trawl hauls from the surface to 350 m depth, recording the vertical distribution; patchiness; and species overlap of finfish and zooplankton ranging in size from < 2 cm krill to > 70 cm saithe. During one haul, review of the image data revealed that all catch passed once the trawl was on the surface during heaving. Examination of the trawl's rigging revealed that a twist had been introduced when the extension was joined to the trawl, a problem that severely affected the trawl's performance but likely would not have otherwise been noticed. Large differences in counts by species for small species and young fish also revealed that there was a significant loss of fish in the region immediately ahead of the codend. In both of these instances, results from the DeepVision revealed problems with the sampling equipment that could have important ramifications for quantitative analysis of the catch results.

Patterns in distribution by species

Fish were generally imaged in association with other individuals of the same species and similar sizes. Greater Argentines and golden redfish provided an interesting exception, as they were were imaged primarily in association with a deep layer comprised of > 99.9 % of blue whiting by count and tended to pass the camera singly (**paper III** Figures 7 and 9). Possibly their ability to locate conspecifics and form or maintain aggregations was hindered by the sheer number of blue whiting present.

In one area sampled, the deep distribution of blue whiting formed two distinct layers: one just off the seabed in 320-360 m depth and another at 250-280 m depth. Small, but statistically significant, differences in average length were measured for each layer suggesting the fish segregate by size. This result is interesting both biologically and when considering that acoustic surveys are often used to assess this species, since the difference in average length means that slightly different target strength values should be used for each layer for calculating biomass.

Association between species

Juvenile fish (haddock, Atlantic cod and one individual that could not be identified) were imaged within 25 m of the surface and were associated with jellyfish (**paper III** Figures 3-4), potential sources of shelter from predators (Lynam and Brierley, 2007). Euphausiids (*Meganyctiphanes norvegica*) were present in highest concentration at depths where the fish (many of which are potential predators) were least numerous. This could represent either the euphausiids migrating vertically to avoid potential predation or alternatively that their population has been grazed down at the depths where fish were present, a mechanism hypothesized to potentially explain offset between planktivorous fish and areas of maximum plankton density (Maravelias et al., 2000).

Identification of small and fragile species inside a trawl

The ability to use a pelagic trawl designed for fish to examine distributions of krill represents an advance in sampling technique, allowing both krill and adult fish to be surveyed simultaneously. Traditional plankton trawls used to sample for krill are too small and slow moving to capture fish beyond larval stages, while fish trawls do not retain krill in the codend. In order to sample across this size range, two gears must be deployed sequentially, resulting in non-synchronous sampling of slightly different water masses and making it impossible to explore species interactions at fine scale. Deployment of two gears also increases cost due to additional ship time and may reduce the number of stations or total area that can be surveyed.

Other similarly sized zooplankton species encountered and quantified during the investigation included parasitic copepods (sea lice) affixed to both saithe and Atlantic cod. Overall, 16 % of saithe had at least one visible louse as they were imaged (though the number was likely twice this high since only one side of each fish was imaged and average infestation rate was 1.2 lice per side on infected fish). Since lice are believed to be scraped off by abrasion in the codend (Holst et al., 1993), quantifying the number of infected fish and their infection load before they enter the codend may be a more effective technique for quantifying infection rates of wild stocks than measuring fish in the codend catch.

Representing distributions of fish by species, depth, and density

The types of data extracted during investigation, including integration of species identification; fish densities; individual sizes; position within the water column; and integration with acoustic data are illustrated from one station in Figure 8. This represents a first suggestion of how the data may be represented, but other methods will doubtless emerge as the data collection technique is put into use to answer more specific research questions.

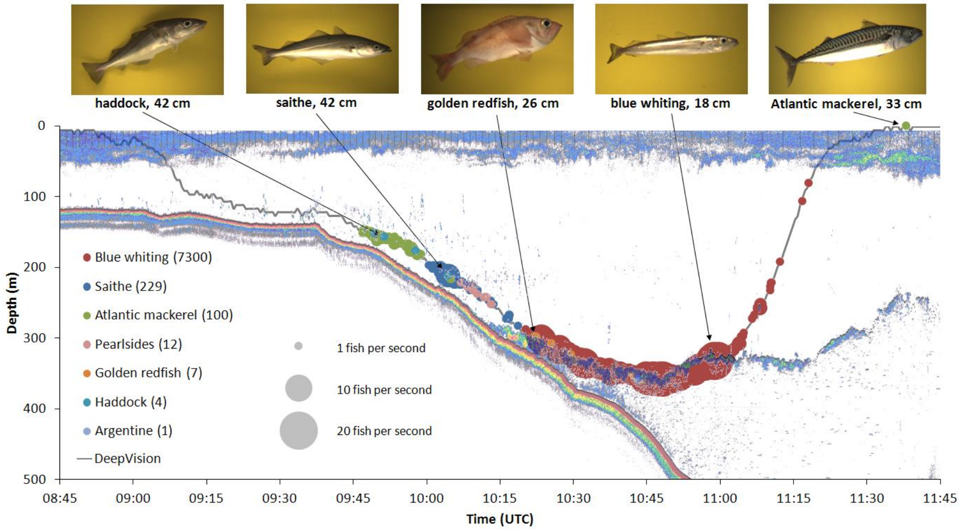


Figure 8. Trawl profile and fish passages overlaid on echogram from vessel's echosounder. Smoothed profile of DeepVision depth is indicated by the thin grey line, time and depth of fish passages by coloured circles with diameter scaled to indicate count per second. Images above the figure are the specific fish indicated on the depth profile.

Challenges interpreting DeepVision data

One of the principal challenges in interpreting the time-referenced data generated by the DeepVision system is accounting for the time lag of when fish are imaged relative to when they entered the trawl. Quantifying how great this delay is will be critical to understanding how to correct passage times and rates so that the results can be used to accurately calculate the natural distribution. For passive organisms, the speed of water inside the trawl can likely be used to back-calculate the time they entered the trawl. But fish swimming against the towing direction will be imaged sooner than predicted by the trawl's speed while ones swimming in the direction of towing will be delayed. For the example of densely aggregated blue whiting, trends in passage rates generally align well with sA calculated from the acoustic registrations recorded beneath the vessel (**paper III** Figure 8) when applying a time offset calculated from the vessel's speed and assuming no ordered swimming. However, there are indications that Atlantic mackerel may have swam inside the trawl before passing the DeepVision cameras for ~ 30 minutes at trawling speeds of 4 knots (**paper III**).

Strategies to minimize the time lag include trawling at speeds in excess of the target fishes' maximum swimming speeds and continuing to refine the design of the region of the trawl ahead of the DeepVision in order to minimize turbulence and reduction in water flow or visual stimuli that discourage fish from passing directly through. For example, it may be necessary to design a much larger passage for investigations of large and strong swimming individuals even though this will result in loss of resolution in the images for objects passing at increased distance from the cameras. In order to accurately record patterns in distribution by depth, it may be necessary to trawl in a stepwise fashion where the trawl is kept at a constant depth for a period of time and then raised or lowered quickly to the next depth interval rather than tracing an oblique path where depth is varied slowly but constantly and the trawl may be at a different depth when fish are imaged in the extension than when they entered.

The diving response seen for Atlantic cod following vessel passage (**Paper I**), and reports of trawling-induced diving in other species, suggest that fish may also be imaged at greater depth than their original distribution when they are recorded inside the trawl. Assuming the effective depth sampling interval corresponds to the opening height of the trawl, a scale of a few tens of meters in pelagic fish trawls, the effective resolution of depth measurements is of similar magnitude to vertical displacement observed due to diving.

One challenge will be integrating the system into existing surveys, where pains are taken to maintain the comparability of results over time by keeping equipment and procedures consistent. Thorough investigations will need to be undertaken, most likely using paired towed comparisons, to determine what effects, if any, the DeepVision has on the trawl's catchability. The results of such experiments could be used to determine a scaling correction factor or to suggest appropriate deployment procedures such as strobing the lights over long time intervals in order to reduce the effect of artificial light (with the disadvantage that only a small portion of the passing fish would be recorded). Using the DeepVision system may, in fact, improve the comparability of results across hauls by providing a way to isolate just the portion of the catch entering the trawl when it is stable and at the target fishing depth.

Future uses of DeepVision

Scientific investigations

Some of the potential applications of DeepVision for fisheries research are discussed in **Paper III**, and centre primarily on the ability to collect data at much higher spatial resolution than with traditional trawl sampling. This will be a significant advance for interpreting acoustic data, particularly when trawl catches include a variety of species and sizes and scrutinizing the acoustic data requires assigning the correct species and sizes to the corresponding portions of the echogram. By eliminating selectivity and physical damage inside the codend, better quantitative information will be preserved for extremely small or fragile organisms such as zooplankton which can be mixed with fish further complicating the interpretation of acoustic data (McKelvey and Wilson, 2006). The camera unit could also be used outside of a trawl for in-situ investigations of target strength by providing information on fish sizes and orientations in conjunction with collection of acoustic data from individual targets, as recently reported by Kloser et al. (2013).

Catch data collected at high resolution could be combined with techniques such as high-resolution remote sensing and scanning and multibeam sonar to investigate and verify oceanographic, biological, or other predictors for the aggregation of fish. By trawling with an open codend, sampling can be carried out over much greater distances to cross bathymetric oceanographic fronts. Likely this technique will need to be combined with an option to collect periodic, directed, samples using multisampler equipment (Engås et al., 1997; Madsen et al., 2012) or a sorting mechanism with multiple codends developed specifically for the DeepVision system.

One significant advantage of data collected with the DeepVision over standard biological samples is the ease at which it can be archived and re-accessed at later dates either to re-check results or to re-analyze data in new ways or mine datasets originally collected for other purposes. When using data from surveys originally designed to target different species, it is critical to assess the catchability of species being newly considered (ICES, 2013). Here, the higher counts of small fishes in the images as compared with the codend catch and ability to count individual zooplankton (including krill and jellyfish) presented in **paper III** demonstrates how catchability can be increased for these small and fragile species though use of the DeepVision system. Because data are saved in widely used file formats (JPEG images and text files), a variety of third party software applications can be used to access and analyze the data reducing the risk that the data will become irretrievable over time.

While a few potential applications have been suggested, it is impossible to know what additional uses there may be in other areas of fisheries or in non-fisheries marine research. For example, the three-dimensional surface information collected may be useful for measuring size and volume of sessile marine objects such as sponges or corals or for estimating the condition of individual fish remotely based upon body volume or a ratio of morphometric parameters such as length to depth. For some applications, particularly ones where established time series do not exist, it may be most advantageous to design completely new trawls or even non-trawl guidance devices specifically for image collection rather than the retention of physical specimens in a codend. It will be important to simply test the equipment in a number of potential applications, recognizing that it may be a poor fit for some but will likely succeed in others.

Commercial fisheries

While developing a system for use in commercial fisheries has not been a significant portion of the work to date, it remains a key goal for DeepVision technology. In some ways, it may prove to be a simpler analytical task than developing a tool for fisheries research. Less precision will be required in counts by species, and it is unlikely that objects less than 10 cm in length will need to be identified or measured. In addition, it will probably not be necessary to image or analyze every fish and the system can be placed in an area where the trawl's cross-section remains large in order to maintain capacity for through flow of fish and reduce the potential for large objects to form a blockage. A periodic measure of the quantity, species, and sizes passing into the codend will provide sufficient information to better direct fishing effort for improved catch of target individuals while reducing bycatch of unwanted ones.

When this detailed real-time information is available to the skipper, better decisions can be made to increase the ratio of target to not target fish captured. This can be done either by adjusting the fishing area and depth to locations where catch of the target species and sizes are maximized while non-target ones are minimized, or by integrating an active selection device such as a controllable door into the trawl so that catch entering the trawl can be either retained or released during specific time intervals. However the engineering challenges will be more demanding to develop a robust system for reliable operation in commercial fishing conditions where the trawl is typically subjected to rougher handling on deck and during shooting and heaving than during research operations.

In addition, there may be a higher demand for automation of analyses and it will be necessary to provide results in real-time so that decisions can be made to maximize the catch of target fish and minimize the catch of non-target ones during trawling. One major challenge for providing data to the vessel in real-time is competition for use of the "third wire" coaxial cable typically installed for connecting to a sonar placed at the opening of a pelagic trawl to monitor geometry, clearance above the seabed, and the entrance of fish. It is not possible to simultaneously transmit data from both the DeepVision and analog sonars currently in widespread use; however digital sonars currently in development will make it possible to use both instruments concurrently. Prohibitions on the use of third wire systems in order to reduce seabird strikes in some trawl fisheries in the southern hemisphere (Melvin et al., 2011) also provide a challenge for real-time data transfer under current regulations in a limited number of potential applications.

Data could also be archived and used as a form of electronic monitoring, less subject to tampering than cameras placed on deck or in areas where fish are sorted and potentially providing higher resolution images more suitable for identifying the species and sizes of fish and other animals encountered during fishing. Similarly, if in-trawl images are collected ahead of selectivity devices, fishing vessels could be used as vessels of opportunity providing less biased data to researchers and supplying information on species and sizes not normally retained in the codend or reported in catch logs. As with use onboard research vessels, it will be important to test the DeepVision equipment in a variety of applications and different fisheries to determine where it does or does not result in improvements in efficiency and reduced catch of non-target fish.

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Appendices

Appendix A. Effects of distortion and range to camera on lengths calculated from pixel counts.

The method used to calculate lengths in the CatchMeter system described by White *et al.* (2006) assumes uniform pixel resolution across the image. This was accomplished by using a 16 mm focal length lens and cropping only the centre portion of the image where distortion is minimized. In addition, the range from the camera to the passing fish was fixed at the height of the camera over the conveyor belt. Tests were carried out to quantify how much pixel resolution varies in images from the lower focal length (4.8 mm) lens used in the DeepVision system in order to maximize the field of view while minimizing the overall dimensions. In addition, for free-swimming fish inside a trawl it is not possible to fix the range at which fish pass the camera and the effect of camera range on resolution was investigated.

The camera setup consisted of a Luminera Lm165 camera (Luminera Corporation, Ottawa, Canada) fitted with a 4.8 mm lens (Cinegon 1.8/4.8-0902, Schneider-Kreuznach, Bad Kreuznach, Germany). For measuring pixel resolution across the image, a target was constructed from a 100 cm x 145 cm sheet of high density polyethylene with a 5 cm x 5 cm grid. Four threaded rods were used to ensure the target maintained a fixed distance from the camera and was positioned perpendicular to the optical axis. The camera, frame, and calibration target were lowered into a pool filled with seawater and images were collected (Figure A1). The number of pixels in height and width was counted for each 5 cm square visible using an image viewing program (IrfanView v. 4.10). These values were used to create a surface plot illustrating how resolution varied across the image.

Pincushion distortion is most evident at the corners of the image, resulting in resolution values < 0.60 mm / pixel (Figure A2). There are also trends in resolution across the image, with pixels at the left side of the image representing the greatest distance in X and pixels at the top of the image representing the greatest distance in Y. When X and Y resolutions are averaged, this results in each pixel representing a greater distance in the upper and left portion of the image and a lesser distance in the lower and right portion of the image. The maximum difference in resolution over the entire image was 12 %, with 94 % of values ranging between 0.60 and 0.65 mm / pixel (difference of 8 %).

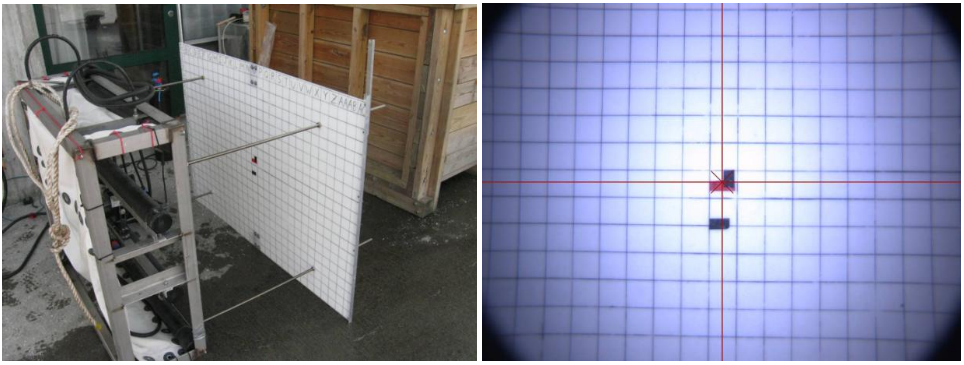

Figure A1. Test frame and target for measuring distortion in water (left) and image taken in seawater filled pool (right). Pincushion distortion is apparent in top horizontal line, which is drawn straight but appears to bow upwards at the ends.

Figure A2. Resolution as a function of position within the image.

The effect of range on pixel resolution was measured by using the same target, but varying the range to the camera between 30 cm and 230 cm. For this test, resolution was measured only at the very centre of the image. A linear relationship between range and resolution was verified, with each pixel representing 1 mm less distance per 1000 mm increase in range (Figure A3). At the time this test was conducted, the frame used for testing the DeepVision inside a trawl allowed fish to pass between 650 and 1650 mm from the camera. Each pixel at the near side of the channel would thus represent 0.65 mm while each pixel at the background (1650 cm range) would represent 1.65 mm, 2.5 times greater distance.

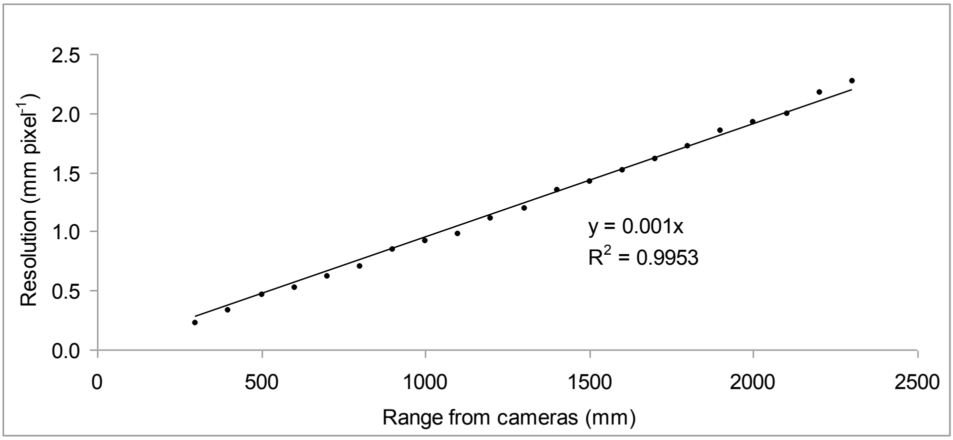

Figure A3. Pixel resolution as a function of range from the cameras. For the 1000 mm channel width being used at the time of this test, each pixel at the near side of the channel would have represented 2.5 × greater distance than each pixel at the far side.

Appendix B. Water flow and orientations of fish passing through the DeepVision system.

Waterflow

Waterflow was measured using propeller-type flow meters (2031H, General Oceanics, Miami) at the entrance to the DeepVision trawl section and inside the fish passage 5.8 m aft. Vessel speed was varied in steps from 1.1 to 2.6 m sec-1 (speed over ground, measured by GPS) and reduction in water flow was calculated as the difference between velocity inside the fish passage and at the entrance to the DeepVision trawl section. Results are presented in Figure B1.

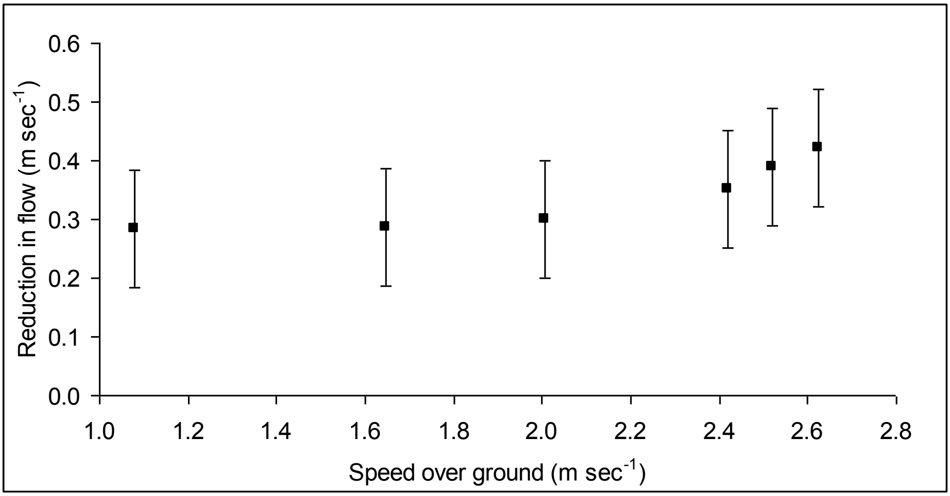

Figure B1. Reduction in water flow between trawl entrance and fish passage channel, 1.1 – 2.6 m sec^{-1} speed over ground. Mean values are plotted (35 – 140 measurements per speed step) with error bars of ± 0.1 m sec^{-1}, resolution of the flow meter measurements.

Later, once the stereo camera system and analysis techniques were developed, the flow field within the fish passage was measured by measuring the distance covered by passive organisms (small jellyfish) in sequential images. Data were analyzed from a period when the vessel kept a constant speed of 1.8 m sec-1 speed over ground (measured by GPS). The trawl's speed through water was also constant, at 1.6 m sec-1 measured by a trawl speed sensor (SCANMAR HC4 - TSS) attached to the headrope of the trawl. Results presented in Figure B2 indicate that waterflow was reduced at the side of the fish channel nearest the camera, while flow at the outer side of the fish channel was equal to the trawl's measured speed through water. It is likely that the reduced water flow is the result of an area of turbulence created in the wake of the guiding panel used to guide fish into the passage (see **paper III**, Figure 1 for an illustration of the frame and guiding panels).

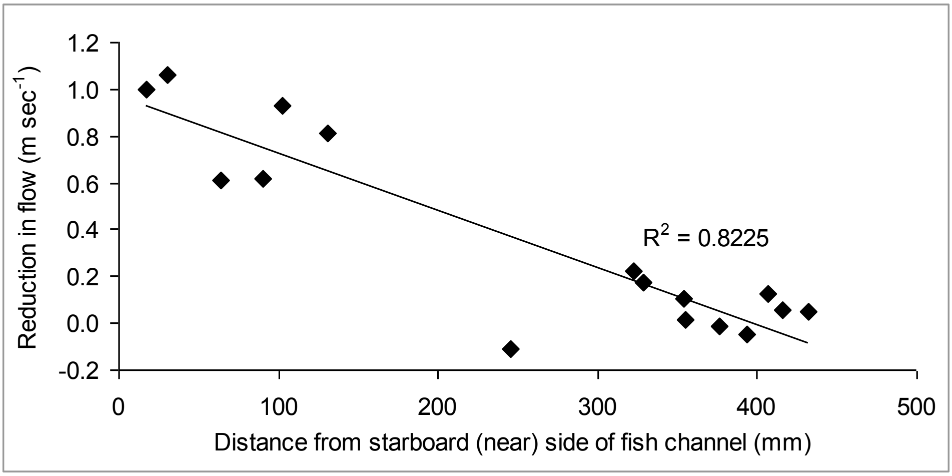

Figure B2. Reduction in flow mapped from starboard (near) to port (far) side of channel using sequential images of passive organisms (small jellyfish). Total channel width was 500 mm. Data are sparse from 130 – 320 mm range due to a lack of jellyfish passing at this range.

Orientation

The orientations of fish as they passed the DeepVision camera were classified as "forward" (head towards the trawl opening and tail towards the codend), "aft" (head towards codend, tail towards trawl opening), or "rotating" (fish oriented perpendicular to the trawl or changing orientation during the image sequence) during two cruises using pelagic trawls. The results revealed differences by species (Table B1). In general, larger strong-swimming fish were more likely to pass through the DeepVision unit in a forward orientation than small or poor swimming species.

Table B1. Orientation of fish passing through the DeepVision system mounted to a pelagic trawl. Trawling speed was 3-5 knots speed over ground measured by GPS.

Species, count	Orientation during passage		
	Forward	Aft	Rotating
Atlantic cod (*Gadus morhua*), 310	54%	27%	19%
Atlantic mackerel (*Scomber scombrus*), 79	56%	24%	20%
Atlantic herring (*Clupea harengus*), 20	55%	30%	15%
Juvenile haddock (*Melanogrammus aeglefinus*), 14	29%	21%	50%
Lumpsucker (*Cyclopterus lumpus*), 11	27%	-	73%
Total, 434	53%	26%	22%

During the cruise that captured Atlantic cod, a second observation camera was placed 2 m in front of the DeepVision. This allowed a comparison between orientations ahead of the DeepVision and inside the chamber (Figure B3). Ninety-three percent of 310 Atlantic cod (mean L = 45.5 cm, SD = 5) were oriented forward (swimming in the direction of trawling) prior to entering DeepVision, compared with just 54 % of the fish inside the DeepVision. The remaining fish either entered the DeepVision oriented aft (27 %) or changed orientation inside the unit (19%).

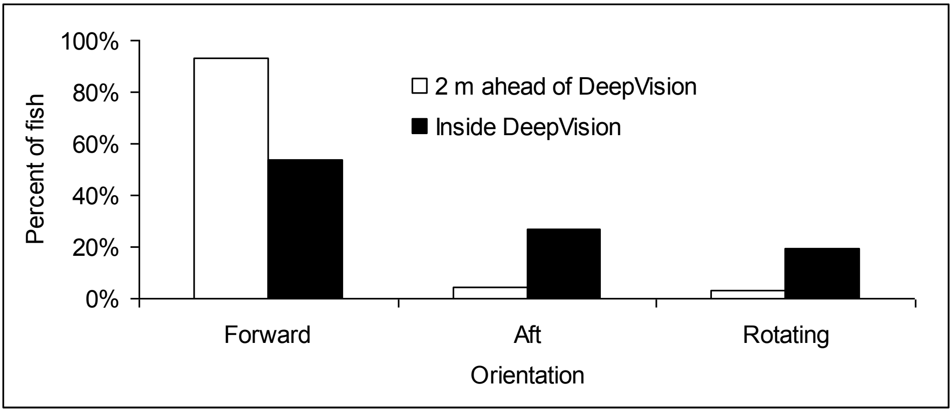

Figure B3. Orientations of 310 Atlantic cod ahead of and inside DeepVision unit. Trawling speed was 3-4 knots speed over ground, from GPS.

The forward orientation of 93 % of cod ahead of the DeepVision unit fits with the orientations inferred for cod inside a pelagic trawl in **paper I**. The much more varied orientations inside the DeepVision unit indicate that something stimulated nearly 50 % of fish to change orientation. We believe that the cause was the leading net that guided fish into the DeepVision not being sufficiently tight, so that an area of low or turbulent flow was created immediately ahead of the entrance. This was verified on a subsequent cruise, which included observations from a towed underwater vehicle to monitor whether the leading net was tight. When the leading net was slack, a pocket formed and the distributions of orientations for cod were similar to the earlier investigation (56 % oriented forward, 22 % oriented aft and 22% rotating as they passed through the DeepVision). When the became redesigned and verified to be tight with observations from a towed underwater vehicle on a subsequent cruise, 93 % of cod were imaged in a forward orientation with 7 % oriented aft and none rotating.