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Evaluating the potential of using parallel-paired lasers in on-board camera systems for fisheries-dependent data capture in the Isle of Man Crustacean Fishery.

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Abstract

Most crustacean fisheries are data poor, relying exclusively on either observer or landings data. As a result, there is inadequate data to inform management advice so as to ensure the sustainable exploitation of stocks. A growing burden of evidence collection, in the form of increasing European Union legislation, combined with diminishing public resources has led to the need to consider Electronic Monitoring (EM) solutions as an alternative to traditional data collection methods, to fill data deficits. The present study was a proof of concept and demonstrated possible applications for data collected using parallel-paired lasers in on-board camera systems in the Isle of Man Crustacean Fishery. Data derived from footage recorded by the cameras was found to provide information on the damaged component of the *Cancer pagurus* catch, the sex ratio of *C. pagurus* and the size frequencies of both *C. pagurus* and *Homarus gammarus*, comparable in accuracy to that collected by an observer *in situ*, indicating that the cameras can be used to monitor these aspects of the fishery.

The magnitude of error attributable to measuring the size of both species remotely from stills rather than *in situ* was within an acceptable tolerance, sufficient to detect growth increments in both species (*C. pagurus:* median=0.05mm*; H. gammarus*: median= -0.13mm, with an inter quartile range of ±1.2mm for both species). However, all analysts will need to collect data to validate their own calibration models before measuring animals from stills taken using the cameras. The Isle of Man provides a unique opportunity for this data collection method to be implemented at a national level in order to create a comprehensive evidence base for management. A five-month fishery-dependent data collection program demonstrated the ability of the cameras to increase the spatial and temporal coverage of the data collected on the fishery, relative to current data collection methods.

Key words

Homarus gammarus, *Cancer pagurus* crab, lobster, on-board camera, Electronic Monitoring technology, parallel-paired laser photogrammetry, Isle of Man.

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Abbreviations

ANCOVA Analysis of Covariance

AW Abdominal width (lobster)

BNC Bay Ny Carrickey Isle of Man

CL Carapace length (lobster)

CPUE Catch per unit effort

CV Coefficient of variation

CW Carapace width (crab)

DEFA Department for Environment, Food and Agriculture, Isle of Man

EM Electronic Monitoring

EU European Union

F Fishing mortality

FOV Field of view of a camera

GPS Global Positioning System

LPUE Landings per unit effort

MLS Minimum Landing Size

MSAL Monthly Shellfish Activity Logbooks

MSY Maximum Sustainable Yield

N Natural mortality

nm Nautical miles

R Recruitment

SD standard deviation

SOM Size at maturity

SS Spawning Stock

VMS Vessel Monitoring System

Z Total mortality

1.0 Introduction

The majority of information that currently informs static-gear fishery stock assessments comes from fishery-dependent data sources, such as self-reported catch data in the form of log books and landings declarations, port sampling, on-board sampling by fisheries officers and point of first sale data (Cambiè *et al.*, 2016; Course *et al.*, 2015; Hold *et al.*, 2015). All these sources provide information about the part of the catch that is legal to land but not the part that is discarded at sea, including prohibited life stages that are essential to assess Maximum Sustainable Yield (MSY), animals not suitable for commercial sale and bycatch. Fishery-independent surveys and on-board observer programs can be used to supplement data collected from these fisheries-dependent sources (Hold *et al.*, 2015), but they are time-consuming and costly in terms of time, money and manpower (Kraan *et al.*, 2013). As a result, they tend to be carried out infrequently, providing only a snapshot of population status at one point of the year. They also tend to be restricted to collecting data about commercially important quota species (Cambiè *et al.*, 2016; Hold *et al.*, 2015). This has led to commercially important quota species being characterised by regular monitoring programs that combine both fishery-dependent and independent data. Whilst most commercially important non-quota species are termed 'data-poor' as they are characterised by inadequate data to inform management advice, so as to ensure the sustainable exploitation of stocks (Hold *et al.*, 2015). This data deficit is particularly acute in inshore shellfisheries, such as those for *Homarus gammarus* (Linnaeus 1758) and *Cancer pagurus* (Linnaeus 1758), due in part to the rural and often inaccessible locations of the fleets, which restricts the potential for fishery-independent data collection even further. In addition, such fleets often land catch in multiple small fishing ports, making it logistically difficult and expensive to get a representative sample of the landed catch (Course *et al.*, 2015).

Data derived from existing data collection programs has its limitations. Faunce and Barbeaux (2011) compared groundfish vessel landings from fishing trips with and without observers and found evidence to suggest that data collected during observer trips could be biased and non-representative of normal fishing activities, due to fishers modifying their practices in the presence of observers. The aim of observer programs is to make inferences from multiple trips from an entire fleet. However, observers have to stay on-board a single vessel for the duration of each fishing trip and a deployment effect, defined as a non-random deployment of

observers, has been observed in several programs (Faunce and Barbeaux, 2011; Hilborn *et al.*, 2009). As a result, observer programs tend to produce effectively small sample sizes that are clustered spatially and temporally (Kraan *et al.*, 2013). Whilst fishery-independent surveys within European Union (EU) waters tend to be restricted to collecting data on offshore finfish stocks (Course *et al.*, 2015).

Self-sampling projects, where fishers report, collect and occasionally process biological samples have been used as alternative, cost-effective fisheries-dependent data collection methods. They can provide information about the discarded component of the catch and a greater temporal and spatial coverage than observer programs and fishery-independent surveys (Course *et al.*, 2015). Self-sampling can result in an increased acceptance of the data by the fleet (Kraan *et al.*, 2013), however, data collection protocols have to produce data that is analytically useful to scientists and fisheries managers, whilst also being practical to implement during commercial operations (Mangi *et al.*, 2015). Concerns have been raised about non-adherence of fishers to data collection protocols and potential bias in the data collected due to fishers having a vested interest in the outcomes of stock assessments (Hold *et al.*, 2015; Kraan *et al.*, 2013; Faunce and Barbeaux, 2011). Data collected by observers and fishery-independent surveys can be used directly in stock assessments whereas data from self-sampling has to be verified to ensure that it is suitable for scientific use (Course *et al.*, 2015).

1.1 Monitoring macro-crustacean stocks and fisheries

Most crustacean fisheries are data poor, relying exclusively on either observer data or landings data. There are numerous crustacea stock assessment methods, that vary in complexity and data requirements, from relatively simple biomass dynamics models that combine life processes such as growth, recruitment and natural mortality, to more complex models that require information about sex ratios, age structure, size structure and catch-at age (Smith and Addison, 2003). However, most methods require a time series of catch data.

C. pagurus and *H. gammarus* are commercially important fisheries in the Isle of Man (Öndes *et al.*, 2016) contributing £615,478 and £724,478 respectively to the Manx economy in 2016, at the point of first sale. Although they are less valuable than other Isle of Man fisheries such as the *Pecten maximus* (Linnaeus, 1758) and *Buccinum undatum* (Linnaeus, 1758) fishery,

they provide a year-round income to a fleet of small inshore vessels that operate mainly within 6nm (nautical miles) of the coast. The fishery is managed using a variety of effort controls:

- a maximum of 500 pots per license, of which no more than 300 can be fished within the 0-3 nm limit;
- mandatory use of escape gaps in traps;
- prohibition of landing egg-bearing 'berried' animals;
- a minimum landing size (MLS): 87 mm (*H. gammarus*; CL) and 130 mm (*C. pagurus*; CW) in most of the territorial waters: 90 mm (*H. gammarus*; CL) and 135 mm (*C. pagurus*; CW) in Bay Ny Carricky.

DEFA has been collecting catch and effort data since 2007 in the form of monthly shellfish activity logbooks (MSAL), that detail date, soak time and Catch per unit effort (CPUE) by landing weight. *C. pagurus* and *H. gammarus* stocks are subject to relatively little monitoring or scientific research compared to mobile-gear fisheries (Table 1). The available data cannot be modelled to project biomass into the future, which is essential to avoid overfishing. The Isle of Man crustacea fisheries are currently unassessed.

Table 1: The availability of data for the Isle of Man C. pagurus and H. gammarus fishery.

Available	Unavailable
Landings	Natural mortality (N)
Effort	Fishing mortality (F)
Landings per unit effort (LPUE)	Total mortality (Z)
Size at maturity	Growth and size-at-age
	Sex-ratio
	Biomass
	Spawning Stock (SS)
	Recruitment (R)
	Habitat-interactions

The appropriateness of a minimum-landing-size for *H. gammarus* can be assessed by understanding the functional maturity of a population. Functional maturity in female *H. gammarus* can be estimated from the ratio of the abdomen width (AW) to carapace length (CL) or by using the incidence of berried females in size-stratified samples to construct the maturity ogive (Lizárraga-Cubedo *et al.*, 2003; Tully *et al.*, 2001).

Sex ratios are an important parameter for assessing the sustainability of commercial stocks (Hold *et al.*, 2015). According to evolutionary theory, any alteration to a 1:1 sex ratio leads to a decrease in the effective population size and therefore a reduction in the genetic diversity within the population; resulting in a decrease in the resilience of a population to stressors such as environmental change (Allendorf *et al.*, 2008; Hold *et al.*, 2015).

Size frequencies of species can provide information about the age composition, growth rates, and mortality of a stock (King, 2007). In the absence of ageing methods for crustaceans, accurate size frequency data from sampled catches can be used to make an indirect assessment of stock status (Ices, 2016). Reliable growth data is needed to calculate accurate estimates of fishing mortality (Addison and Bennett, 1992).

Where possible, measurements of the interactions between commercially fished species and habitat loss should be incorporated into stock assessments (Attwood *et al.*, 2005). *H. gammarus* and *C. pagurus* have seasonal distribution patterns that affect their availability to be caught in traps (Hunter *et al.*, 2013). The movement patterns and habitat associations of species are determining factors of stock delineation and distribution (Bowlby *et al.*, 2008). If species-habitat associations are known, the effect of habitat loss or gain, for example as a result of direct physical disturbance of the seabed, can be incorporated into fisheries management strategies and accounted for in stock assessments (Kaiser *et al.*, 2008). There are gaps in knowledge about the movement patterns and habitat associations of both *H. gammarus* and *C. pagurus* (Bowlby *et al.*, 2008), which inhibits the sustainable management of stocks at appropriate spatial scales. Studies have found evidence to suggest that the movement of male and immature female *C. pagurus* is limited (Wedding *et al.*, 2013; Ungfors *et al.*, 2007). However, there is evidence that mature female *C. pagurus* make long distance inshore to offshore migrations that are thought to be associated with reproduction (Hunter *et al.*, 2013; Ungfors *et al.*, 2007). Ondes (2015) studied the distribution of *C. pagurus* around the Isle of Man and found that berried *C. pagurus* were generally found in deeper waters in the south and west, during Autumn months. *H. gammarus* are thought to have a limited home range; the extent of any movement is thought to be size-dependent with larger individuals moving greater distances (Smith *et al.*, 2001). The distribution of *H. gammarus* is thought to be patchy over a large scale and may be random within spatially discrete fisheries (Addison, 1995).

Stock assessments are inherently complex but are often reliant on temporally and spatially coarse datasets, as a result they often do not match the daily observations of fishers (Johnson and van Densen, 2007). There are few existing datasets that enable fine-scale patterns in fishing effort, catchability, sex-ratio, reproductive status, disease and the population structure of target species to be compared spatially, between multiple local fishing grounds, over long time periods (Fisheries & Conservation Science Group). A growing burden of evidence collection, in the form of increasing EU legislation, combined with diminishing public resources has led to the need to consider technological solutions as an alternative to traditional data collection methods to fill these data deficits (Cambiè *et al.* 2016; Hold *et al.* 2015).

1.2 Electronic monitoring technologies

Electronic monitoring (EM) technologies, such as on-board camera systems, have been shown to have the potential to meet the need for cost effective, innovative ways to collect data that is comparable in accuracy to that obtained by observers, whilst increasing the spatial and temporal coverage of data collected, relative to current data collection methods. EM also has the potential to mitigate some of the issues surrounding current data collection methods, including the belief that data collected by observer programs is biased and unrepresentative of normal fishing practices (Faunce and Barbeaux, 2011).

Positional data obtained from Vessel Monitoring Systems (VMS) has been used to map and quantify the impacts of fishing activity (Jennings and Lee, 2012; Lambert *et al.*, 2012). Logbook data can be combined with positional data to examine catch per unit effort (ICES, 2011; Murray *et al.*, 2011) and provide estimates of biomass indices (Murray *et al.*, 2013). However, VMS is only mandatory on specific vessel metiers, which excludes the majority of inshore vessels that target *H. gammarus* and *C. pagurus*. Successive position records from VMS are infrequent so provide information on fishing activity over large spatial scales (Murray *et al.*, 2013). As a result, MSAL data cannot be assigned to spatial data on an appropriate scale to map fishing activity in the Isle of Man Crustacean fishery.

Hold *et al.* (2015) and Cambiè *et al.* (2016) investigated the use of on-board camera systems to collect fishery dependant data, such as sex ratio and size frequency data, in inshore *H. gammarus* (European lobster) and *C. pagurus* (brown crab) fisheries in Wales. Similarly, Course *et al.* (2015) reported success using on-board cameras in Scottish waters. The Isle of

Man provides a unique opportunity to have this method of data collection implemented at a national level, creating a comprehensive evidence base for management.

1.3 Parallel laser photogrammetry

Parallel laser photogrammetry, involving the use of parallel-paired lasers coupled to cameras, has been found to be a simple and accurate method for obtaining estimates of the size of morphological traits (traits) of study animals in the field (e.g. Austin *et al.*, 2017; Lu *et al.*, 2016). The lasers are projected onto, and photographed along with the trait of interest. An estimate of the trait size is made from the photograph, using the known separation distance between the laser projections as a reference scale: the laser scale. Parallel laser photogrammetry works on the principle that the lasers are equidistant regardless of the distance from the source (Bergeron, 2007). As a result, there is no need to take into account the varying distance between the trait and the camera.

Various sources of parallax (distortion of the laser scale) can introduce error into the trait size measured from a photograph. These included parallax as a result of the projection of the lasers onto a three-dimensional surface (Bergeron, 2007) and distortion of the lasers caused by the target surface not being perpendicular to both laser beams (Rohner *et al.*, 2011).

1.4 Known limitations of on-board camera systems

The accuracy of on-board camera systems at producing size frequency and sex ratio data comparable to data obtained by on-board observers has been evaluated in brown crab (crab) and European lobster (lobster) fisheries in Wales. Animals were passed into the field of view (FOV) of the cameras over a measuring board that was photographed along with the animal. Estimates of the size (crab: CW and lobster: CL) of each animal were made from the resulting still images (stills), using the measuring board as a reference scale: the background reference scale.

An error is introduced when a trait is measured from a still. It can be corrected using a calibration model but the associated variation in measurements cannot be corrected (Cambiè *et al.*, 2016). The size of the error is influenced by properties of the camera. For example, different camera lenses introduce different levels of image distortion (Hold *et al.*, 2015). As a

result, each individual on-board camera unit has to be calibrated *in situ*, in order to determine the camera specific relationship between measurements of the trait of interest taken directly from a still: the Still trait size and the corresponding measurement of the same individual animals trait *in situ*: the Real trait size.

When a background reference scale is used to estimate the size of an animal from a still, the varying distance between the animal and the scale needs to be accounted for in the calibration model. This distance is determined by the body depth of the individual animal and the height at which it is passed into the FOV of the camera. Hold *et al.* (2016) included a term to account for it in the camera calibration model whilst Cambiè *et al.* (2015) determined that the calibration model changed from a linear to a non-linear relationship when the camera mounting height approached the height of the animal above the background reference scale. Estimates made directly from stills using the background reference scale were found to overestimate the size of both crabs and lobster (Cambiè *et al.* 2016; Hold *et al.* 2015).

Poor video resolution is associated with errors in measurements taken directly from stills. Due to the change in camera resolution and perspective with the distance of the camera from the subject, Hold *et al.* (2015) found that it was also necessary to include a term in the calibration model to account for the different camera mounting heights: defined as the height of the camera above the surface over which the animals were passed in to the FOV of the camera.

Cambiè *et al.* (2016) evaluated if a laser scale improved the accuracy of size estimates of crab and lobster from stills, relative to size estimates made using the background reference scale. A smaller error was introduced into measurements taken directly from stills when the laser scale was used. In addition, there was less variation in the measurements, indicating that the laser scale provided a reliable mechanism for eliminating the errors associated with the variable distance between the subject and the camera (Cambiè *et al.* 2016). The relationship between the Real size measured by an observer and the corresponding Still size measured using the laser scale, could be approximated by a linear model for both crab and lobster.

Cambiè *et al.* (2016) found that paired green lasers were only clearly visible when projected onto an animal's body on cloudy days and identified potential problems in locating green laser projections on species other than brown crab and lobster, for example spider crabs. They suggested two possible solutions; green lasers with a greater intensity or a different colour

laser. Cambiè *et al.* (2016) also recommended that the laser separation distance should not exceed 5cm, to ensure both lasers are projected onto even the smallest crustaceans, allowing a precise size estimation for all species and all age classes.

When using a photographic method to remotely estimate the size of a trait there is a degree of subjectivity in determining the anatomical features that demarcate the start and end points of the trait. Variation has been observed amongst repeat measurements of the same trait in the same still by a single analyst: the intra-analyst effect, and amongst measurements of the same trait in the same still made by multiple analysts: the inter-analyst effect (Galbany *et al.*, 2016). In Hold *et al.* (2016), the same observer who measured an individual animal *in situ* passed the individual under the camera and measured it remotely from the stills. The researcher identify was included in, and found to be a significant term in the camera calibration model. This suggested that all researchers who collect and analyse stills per Hold *et al.* (2016), need to collect data to validate their own calibration model. Subjectivity in identifying anatomical features can be mitigated by providing training to analysts and by improving the resolution of the cameras (Cambiè *et al.* 2016; Hold *et al.* 2015). Mounting on-board cameras above head height helps to ensure that they do not cause an obstruction and impact normal commercial operations, however this makes them more difficult to operate and is at the expense of camera resolution (Hold *et al.*, 2015)

Crabs are traditionally sexed by observing the size and shape of the dimorphic abdominal flap, whilst lobsters are traditionally sexed by visually assessing the first of the dimorphic pleopod pairs. Sex allocation from still analysis has been found to be 100% accurate for crabs provided there is a clear view of the abdominal flap of each animal (Cambiè *et al.* 2016; Hold *et al.* 2015). However, Hold *et al.* (2015) found that it was not possible to reliably observe lobster pleopods in the extracted stills or raw video footage recorded by on-board cameras.

Hold *et al.* (2015) utilised the fact that the lobster AW:CL ratio becomes sexually dimorphic at maturity. Measuring the Still CL and AW of lobsters enabled Hold *et al.* (2015) to estimate the ratio from the stills. Sex was then allocated to each lobster based on the Real AW:CL ratio cut off value between male and female lobsters, determined using Real AW and CL measurements made by an observer *in situ*. This method of sexing lobsters from stills was accurate for all sizes of male lobster and all female lobsters larger than 86mm CL. However, the accuracy decreased to a low of 51% for females less than 70mm CL due to juvenile females

having a similar morphology to males. Sexual dimorphism has been observed in all lobsters above 80mm CL and some lobsters between 75mm and 80 mm CL (Brown, 1982). However, the Real AW:CL ratio cut of value may vary amongst geographically distinct locations if the size at maturity (SOM) varies (Hold *et al.*, 2015).

1.5 Objectives

The objectives of this project were to determine if size and sex data obtained from footage taken by the on-board camera systems was comparable to size and sex data obtained by a human observer for the same individuals *in situ*. To investigate the error and variability of measurements taken directly from stills. To investigate the possibility of using the on-board cameras to monitor other important aspects of the Isle of Man Crustacean Fishery, for example the presence of shell disease (black spot) in brown crabs and the functional maturity of European lobster.

To investigate the type and quality of information that can be taken from fishery-dependent footage collected by fishers during their normal fishing activities, in order to investigate the feasibility of rolling the camera systems out on a sentinel fleet of vessels. To demonstrate how data obtained from the camera systems can be utilised alongside environmental data and data provided by fishers, such as MSAL, to investigate spatial and temporal variations in the Isle of Man Crustacean Fishery.

1.6 Hypotheses

H_1: Morphometry of European lobster and brown crab estimated from still images obtained by each of the on-board camera systems are comparable to, or within an excepted tolerance (sufficient to detect growth increments) to corresponding direct measurements made by a human observer of the same individuals *in situ*.

H_2: Sex allocations from the still images will be in agreement with sex allocations made by a human observer of the same individual *in situ*, for all sizes of brown crabs and for male and female European lobsters that are over a certain size.

H_3: The condition of European lobster; assessed by the presence and type of damage and the presence-absence of eggs, and the condition of brown crabs; assessed by the presence and type of damage, the moult state and the presence-absence of black spot, made from still images obtained by the on-board camera systems are comparable to assessments of the condition of the same individual made by a human observer *in situ*.

2.0 Method

2.1 Camera design

The on-board cameras used in the present study are the third generation trialled by Bangor University; the second to utilise parallel-paired laser photogrammetry. Each unit comprised a Nextbase 412GW camera with integrated GPS, two parallel-paired lasers (Odiforce, 5mW Red Laser Modules) connected via a single power input cable to an external 12V battery box (Figure 1). The cameras had a 140 degree wide angle view and were set to video mode at 1440p resolution at 30 frames per second. The lasers were focused for maximum intensity at approximately 100cm from the source. The electronics were housed in a waterproof box, the integrity of which was reliant on all lids, connectors and waterproof caps being fitted correctly. Each system cost approximately £400 to construct and install on each vessel using bespoke mounting brackets.

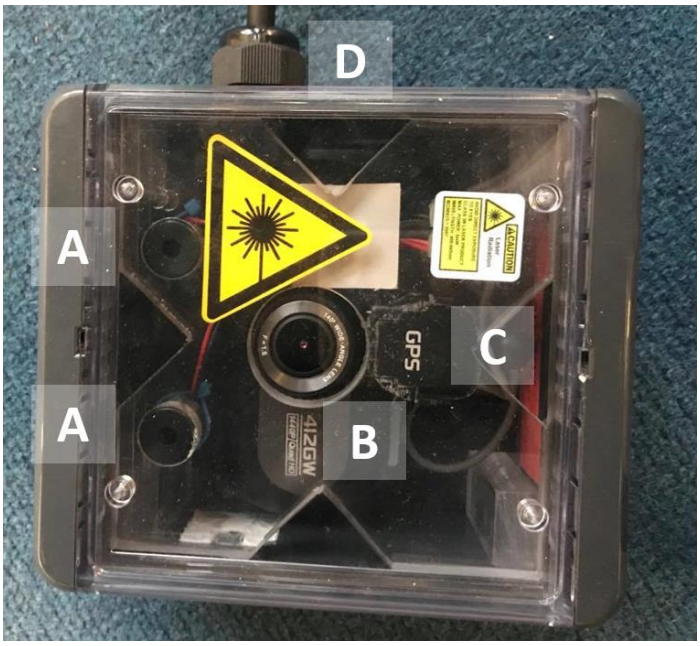

Figure 1: Labelled image of the third generation of on-board cameras trialled by Bangor University in the present study. Units comprised; A: two parallel-paired lasers (Odiforce, 5mW Red Laser Modules), B: the Nextbase 412GW camera with C: the integrated GPS logger and D: the external power source. Credit: Claire Lambden (Bangor University).

The lasers were fixed at approximately 50mm separation distance at the source, however precision engineering was not used in the construction of the camera units so the lasers were not precisely parallel from the source to the surface that they were projected onto.

Footage collected using each camera, and the resulting extracted stills, contained a unique code for each vessel, comprising the GPS coordinates of the location of the vessel; in degrees, decimal minutes and a date and time stamp. Once the cameras were turned on there was a delay of approximately one minute in the GPS recorder activating and triangulating. The date and time stamps in the footage and extracted stills were only accurate once the GPS recorder had triangulated, unless the date and time were also set manually on the camera.

2.2 Camera installation

Three camera systems were installed on three commercial potting vessels, for differing time periods in 2017. The camera units were assigned the same identifying number as the vessel that they were installed on. The layout of gear on deck varied for each of the vessels participating in the study, necessitating vessel specific camera installations that took into account operational and safety issues relevant to the normal working practices of each vessel. As a result, the camera mounting height, areas of the vessel and fishing activities carried out in the FOV of each camera varied. All the cameras were mounted above head height and positioned directly above the catch sorting area. This was achieved using a bespoke fixture welded to the gunwale on two vessels (Figure 2) and a bespoke mounting bracket attached to the wheel house on the third vessel. When in use the cameras were powered by an external portable battery, with a battery life adequate to power the camera for a full day. The mounting height of the camera units was greatest on Vessel 1 (140cm) and similar on the other two vessels (approximately 100cm). The cameras could be removed from the mountings and stored on-board the vessel when not in use. On one vessel, Vessel 1, the camera was left mounted to the wheel house even when not in use.

Each camera system projected the paired red lasers onto a pre-existing surface that was in the FOV of the camera: the defined surface (Table 2). The surface was not modified in any way for the purpose of this study. For each individual camera, the magnitude of the laser scale was determined to the nearest millimetre by measuring the distance between the two laser projections when they were projected onto a black matt placed on the defined surface.

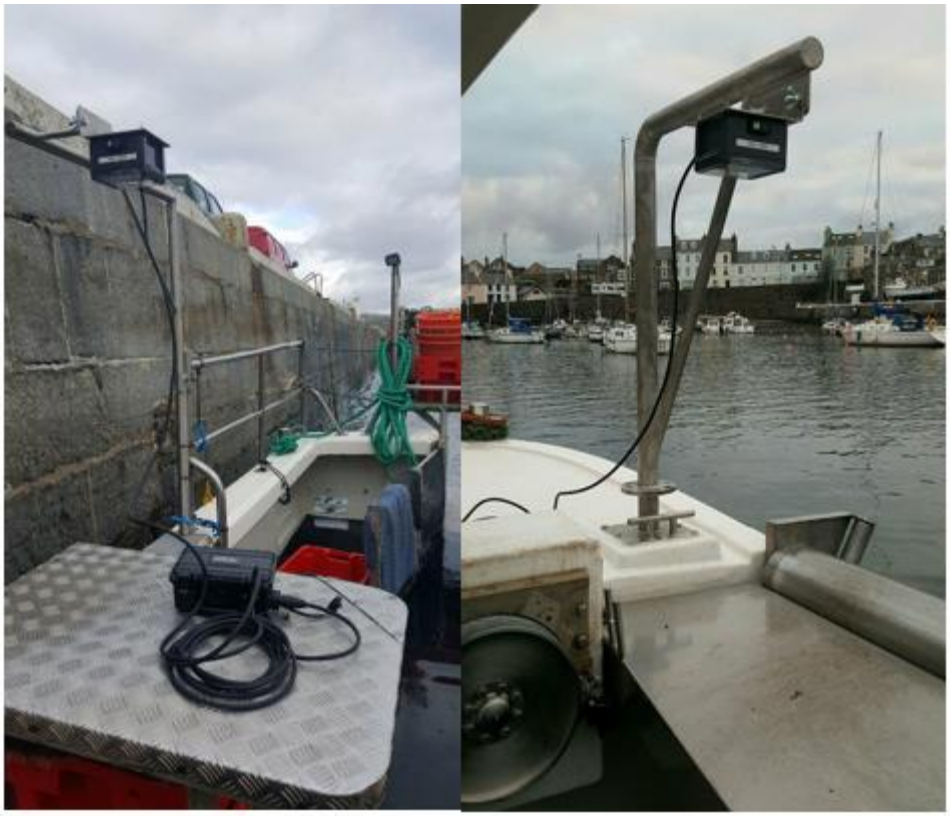

Figure 2:The two bespoke fixtures used to install on-board camera units on Vessels 2 and 3. The fixtures were welded to the gunwales on both vessels. N.b. Vessel 1 was sold part-way through the fishery-dependent data collection program, so the camera set-up on this vessel is not shown here. The camera on Vessel 1 was fitted to the wheelhouse using a custom attachment.

Table 2: Table detailing the vessel specific set-ups and installations of the three on-board camera units installed on three commercial vessels in the Isle of Man Crustacean fishery. Vessel names were anonymised using identifying numbers. The camera units were assigned the same identifying numbers as the vessel that they were installed on. The defined surface is the pre-existing surface that was in the field of view (FOV) of the camera, which was not changed for the purpose of this study. For each individual camera unit, the laser scale was determined to the nearest millimetre (mm) by measuring the distance between the two laser projections when they were projected onto a black matt placed on the defined surface.

Vessel/Camera identity	Date installed (month/year)	Mounting	Defined surface	Laser scale (mm)
1	01/2017	Mounting bracket attached to the wheel house	Pale grey plastic compartmentalised sorting table	49
2	03/2017	Fixture welded to the gunwale	Metal sorting table	50
3	02/2017	Fixture welded to the gunwale	Metal sorting table	66

2.3 In situ calibration of the individual camera units

An error is introduced when a trait is measured from a still (Cambiè *et al.*, 2016). This error is influenced by properties of the individual camera units and the vessel specific camera installations. As a result, each camera unit had to be calibrated separately *in situ*, in order to determine the camera specific relationship between measurements of crab CW, lobster CL and lobster AW made remotely from stills and corresponding direct measurements of the same individuals made by an observer *in situ*: the Still CW, CL and AW measurements and Real CW, CL and AW measurements respectively. Calibration of the cameras determined if it was necessary to apply predictive models to Still trait measurements in order to obtain accurate estimates of the trait sizes; the Predicted CW, CL and AW. To control for observer identity, a single experienced observer (JE) determined the *in situ* data used to validate all three on-board cameras and presented all the animals to the respective cameras.

Each camera was calibrated using a sample of crab and lobster caught as part of the respective vessels normal fishing activities, including animals that were illegal to land, such as animals that were below the MLS and berried and soft-shelled animals. The number, size range and condition of each species used in the calibration of each camera varied depending on the composition of the respective vessels catch on the day that the calibration was carried out. Lobsters and crabs were measured and sexed by the observer *in situ* before being presented to the camera, both dorsal and ventral side up. The Real CW of each crab was measured as the widest part of the carapace, parallel to the end of the carapace (Figure 3). The Real CL of each lobster was measured as the distance from one eye socket to the distal joint of the carapace (Figure 4).

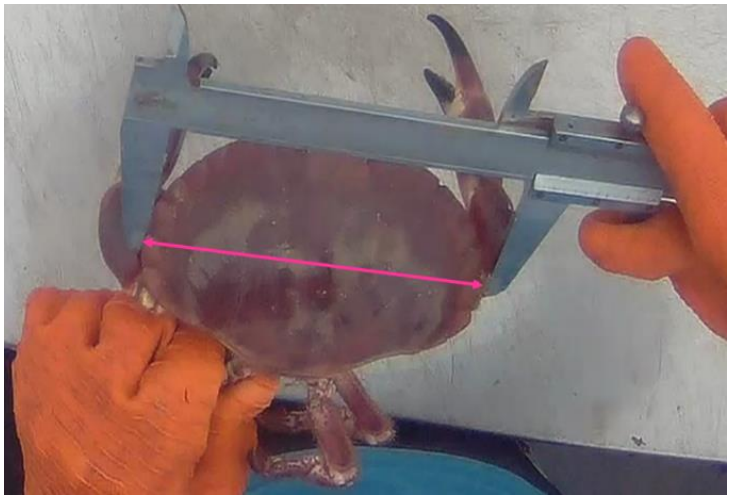

Figure 3: A brown crab being measured by the observer in situ during the calibration of the on-board camera unit: Camera 2. The carapace width (CW) of each crab was measured as the widest part of the carapace, parallel to the end of the carapace (indicated by the pink arrow), to the nearest millimetre using Vernier callipers.

In order to determine the AW:CL ratio cut of value between male and female lobsters, the Real AW of each lobster was measured *in situ* as the widest part of the second abdominal segment, per Brown (1982). Length and width measurements were taken to the nearest mm using Vernier callipers. The observer sexed each lobster *in situ* by observing the first of the dimorphic pleopod pairs: the Observed lobster sex (Figure 4). Whilst each crab was sexed *in situ* by observing the size and shape of the dimorphic abdominal flap: the Observed crab sex.

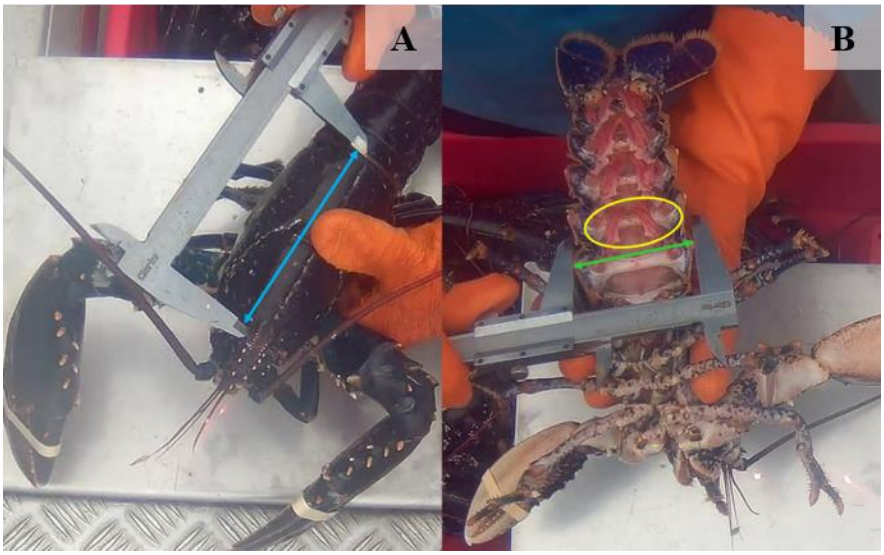

Figure 4: A European lobster being measured by the observer in situ during the calibration of the on-board camera unit: Camera 3. The carapace length (CL) of each lobster was measured as the distance from one eye socket to the distal joint of the carapace. The abdomen width (AW) of each lobster was measured as the widest part of the second abdominal segment (B: indicated by the green arrow). The sex of each lobster was determined by the observer in situ via a visual assessment of the first of the dimorphic pleopod pairs (circled in yellow).

The dorsal sides of each crab and lobster were presented to the respective camera so that the laser scale was projected along the width or length of the carapace, respectively (Figures 5 and 6) whilst it was held perpendicular to the axis of both lasers. The ventral sides of each lobster were presented so that the laser scale was projected along the length of the abdomen whilst it was held perpendicular to the axis of the lasers. Animals were held in position for at least one second; determined by Hold *et al.* (2016) to be the minimum time necessary for accurate visual capture. It was not necessary for the lasers to be projected onto the ventral sides of crabs, however a clear view of the abdominal flap was required in order to determine sex from the stills.

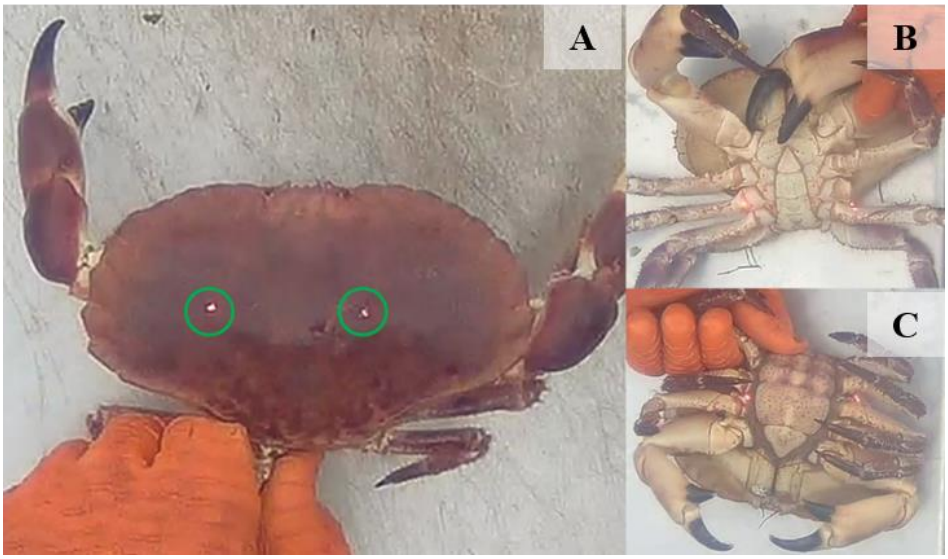

Figure 5: Still images (stills) of the dorsal and ventral sides of brown crab (A: dorsal; B and C: ventral). The dorsal sides were presented to the camera so that the laser scale (the distance between the laser projections: demarcated by green circles) was projected along the width of the carapace whilst it was held perpendicular to the axis of both lasers. The ventral sides of each crab were presented so that there was a clear view of the abdominal flap, to enable sex to be determined from the stills (B: male; C: female). The stills were extracted from calibration footage taken by the on-board camera unit: Camera 2.

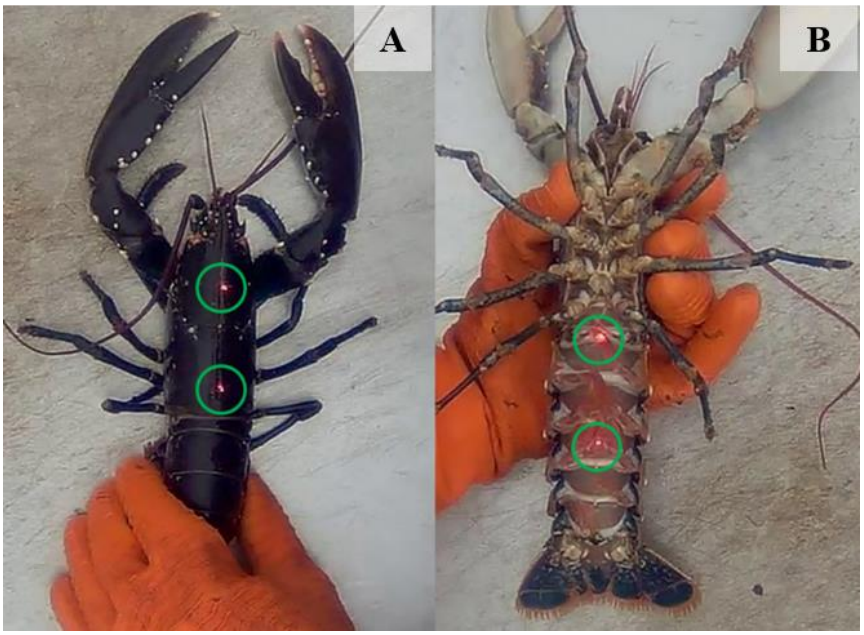

Figure 6: Still images (stills) of the dorsal and ventral sides of a European lobster (A: dorsal; B: ventral)..The dorsal and ventral sides were presented to the camera so that the laser scale (the distance between the laser projections: demarcated by green circles) was projected along the the length of the carapace (dorsal) or abdomen (ventral) whilst it was held perpendicular to the axis of both lasers. The stills were extracted from calibration footage taken by the on-board camera unit: Camera 2.

The observer assessed the condition of each individual lobster by recording the loss of claws and the presence of eggs. The observer assessed the condition of each crab by evaluating if it was exhibiting a physical manifestation of black spot, determined by the presence of at least one black lesion on the exoskeleton and by quantifying damage by the loss of claws and legs and damage to the exoskeleton. The observer also noted if an individual crab was soft-shelled, determined by assessing the pliability of the exoskeleton and by observing the colouration of the ventral side of the exoskeleton; pale colouration was taken to be indicative of soft-shell in an individual. It was not noted if a lobster was soft-shelled because there is no visible manifestation of this moult stage in lobster.

2.4 Calibration footage analysis

The calibration footage recorded by the three camera systems was viewed in VLC media player version 2.2.4 *Weatherwax.* Data was entered directly into a Microsoft Excel (2016) spreadsheet. The default settings in VLC media player and Microsoft Excel were changed as described in Appendix I so as to speed up the still extraction process and reduce the chance of data entry errors. The interactive zoom feature in VLC media player was used when analysing

the footage, with the zoom rectangle focused on the defined surface that the lasers were projected onto (Figure 7).

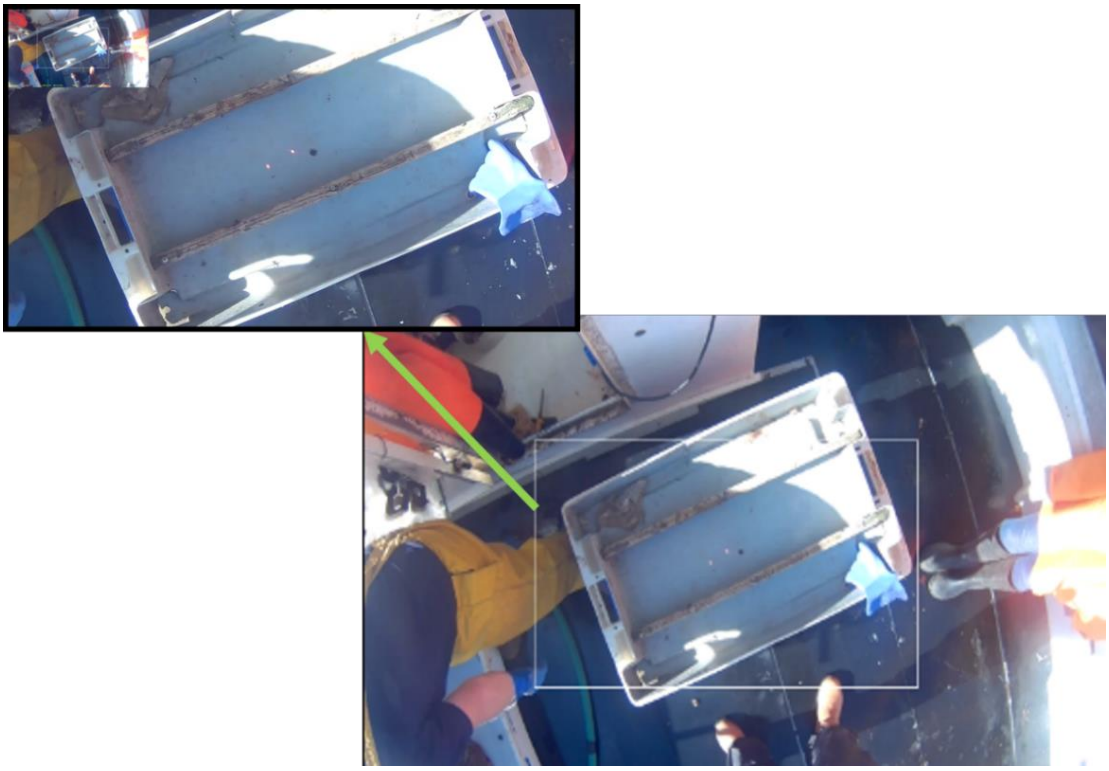

Figure 7: Screenshot (main image) of the calibration footage recorded by Camera 1 being viewed in VLC media player version 2.2.4, with the interactive zoom rectangle focused on the defined surface that the lasers were projected onto. The inset (indicated by the green arrow) shows the still image (still) that was extracted from the footage in the main image.

The snapshot feature in VLC media player was used to extract a minimum of one still for the dorsal and ventral sides of each crab and lobster. More than one still was extracted if a more preferable one was observed in subsequent footage, however only one dorsal and ventral still were analysed for each animal. The ideal still was one in which the trait of interest was perpendicular to the axis of the lasers and one in which both lasers were projected onto and visible on the trait of interest. For both species, it was sometimes hard to distinguish the laser projections from the natural coloration of the animal or soiling of the carapace (Figures 8 to 10).

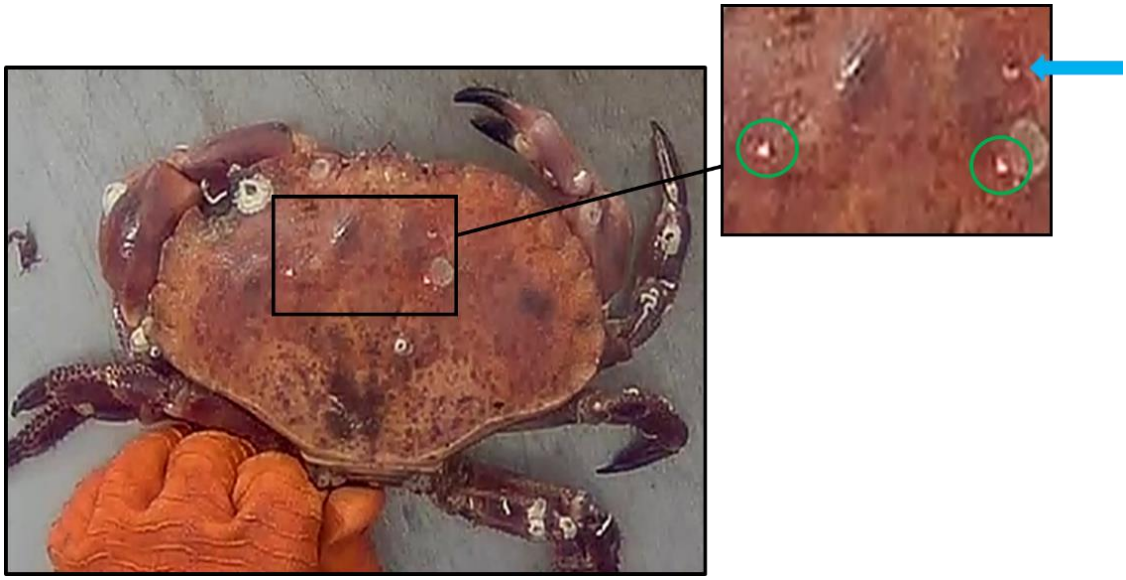

Figure 8: Still image (still) showing how a marking on the carapace of a brown crab (indicated by the blue arrow in the inset) could be mistaken for a red laser projection. The paired lasers are demarcated by green in the inset. The still was extracted from calibration footage recorded by the on-board camera unit: Camera 2.

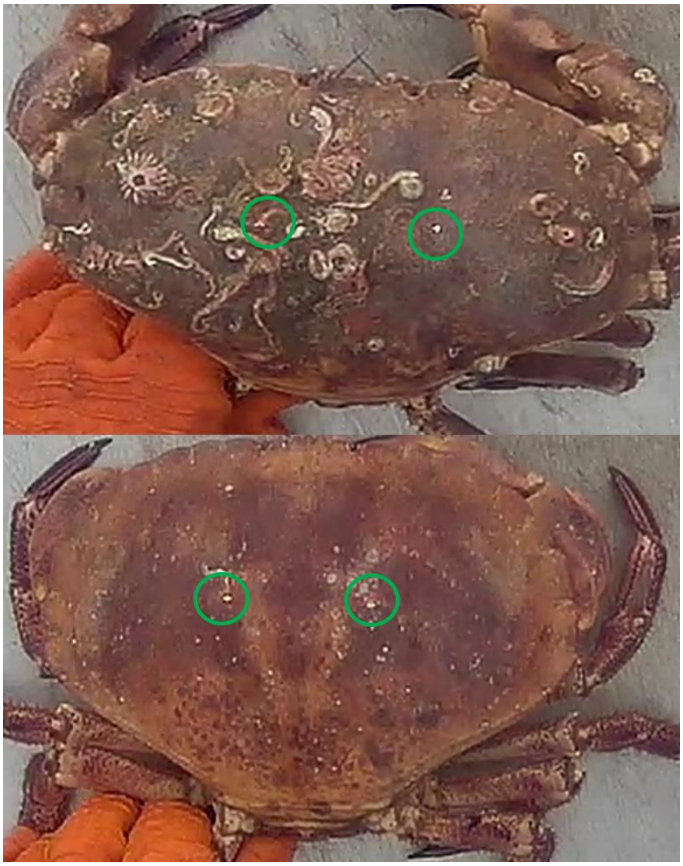

Figure 9:Still images (stills) showing the potential difficulty in distinguishing the paired red laser projections (demarcated by green). from markings on the carapace of brown crab. The stills were extracted from calibration footage taken using the on-board camera unit: Camera 2.

Figure 10: Still image (still) showing the potential difficulty in identifying the paired red laser projections (demarcated by green) on the ventral sides of European lobster, due to the natural colouration of the lobster. The still was extracted from calibration footage taken using the on-board camera unit: Camera 2.

In addition, it was preferable if both laser projections were two well defined points, rather than dispersed points or projections that had split into multiple points (Figures 11 and 12), as an error in determining the centre of the laser projections introduces error into Still measurements made using the laser scale as a reference. Replacement stills were extracted from the footage as required. If it was not possible to measure a trait from the replacement still, the reason for still rejection was coded using the codes in Table 3.

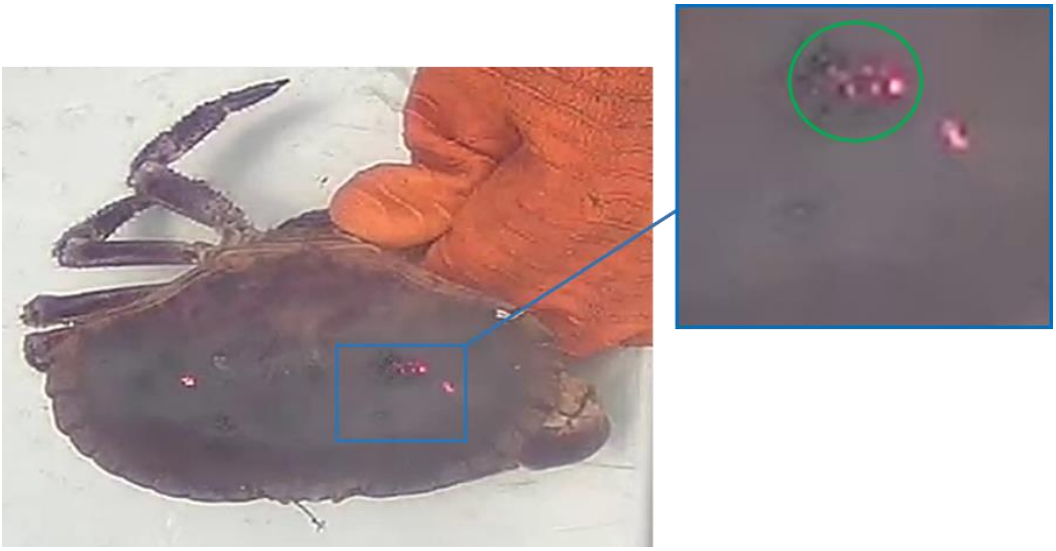

Figure 11: Still image (still) showing the paired red lasers projected onto the carapace of a brown crab. One of the projections (demarcated by blue in the main image) has split on the carapace. The laser speckle (demarcated by green in the inset) could be indicative of irregularity of or damage to the carapace. This still was extracted from calibration footage recorded by the on-board camera unit: Camera 2.

Figure 12: Still image (still) showing the paired lasers dispersing when projected onto the carapace of a brown crab. This still was extracted from calibration footage recorded by the on-board camera unit: Camera 1.

Table 3: Codes assigned to rejected stills (taken during the calibration process and during the fishery-dependent data collection program) to explain the reason for still rejection and as a result the reason why a trait could not be measured for an individual brown crab or European lobster. Species that the codes were assigned to are indicated by the letter in brackets (C:crab, L:lobster). CW: crab carapace width; CL: lobster carapace length; AW: lobster abdomen width.

Code	Description
Con	Start or end of CL (L), edge of AW (L) or edge of CW (C) obscured by condensation in the camera housing (see section 2.7).
ES	Poor definition of the eye socket, used to demarcate the start of CL (L) as a result of sunlight reflecting of the eye socket, soiling of the carapace around the eye socket and poor video resolution.
LNV	One or both lasers not visible on the trait of interest (or anywhere in the still) as a result of bright sunlight or due to difficulty distinguishing the laser projections from the colouration of or markings on the carapace (L & C).
LS	One or both of the laser projections split or dispersed when projected onto the trait of interest (L & C).
NU	Animal not presented to the camera, only one side of the animal presented, or the animal presented so that one or both of the lasers are projected onto the defined surface rather than the trait (L & C).
OB	Start or end of CL (L), edge of AW (L) or edge of CW (C) obscured by shadow or object, such as seaweed or the string.
OH	End of CL (L), edge of AW (L) or edge of CW (C) obscured by the hand of the person presenting the animal to the camera.
OL	Edge of AW obscured by the leg of the animal (L).
PD	Poor definition of the end of the CL (L), edge of AW (L) or edge of CW (C).
TC	Tail fan is curled when the animal is presented to the camera (L).
T	The animal presented at an angle that is not perpendicular to the axis of both lasers (L & C).

Where possible, for each extracted crab and lobster dorsal still and lobster ventral still, the Straight Line function in ImageJ was used to draw a straight line between the centre of the laser projections (Figures 13 and 14). The laser scale for the respective camera system, determined as described in section 2.2, was entered in to the Set Scale function in ImageJ in order to make a pixel to millimetre conversion. Due to non-parallelity of the lasers, it was found to be necessary to set the scale in ImageJ for each dorsal and ventral still individually rather than using the Global option in the Set Scale function to set the scale once for stills taken by the same camera unit.

Where possible, the CW of each crab was measured from the dorsal still by drawing a straight line across the widest part of the carapace, perpendicular to the bottom of the carapace; the CL of each lobster was measured from the dorsal still by drawing a straight line from the eye socket to the distal joint of the carapace and the AW of each lobster was measured from the ventral still by drawing a straight line across the second abdominal segment. The measure function in ImageJ was then used to determine the straight-line length of each trait. The zoom feature in ImageJ was used as required to get a closer view of the anatomical features that demarcated the start and end points of the trait of interest, for example the back of the eye socket in lobsters.

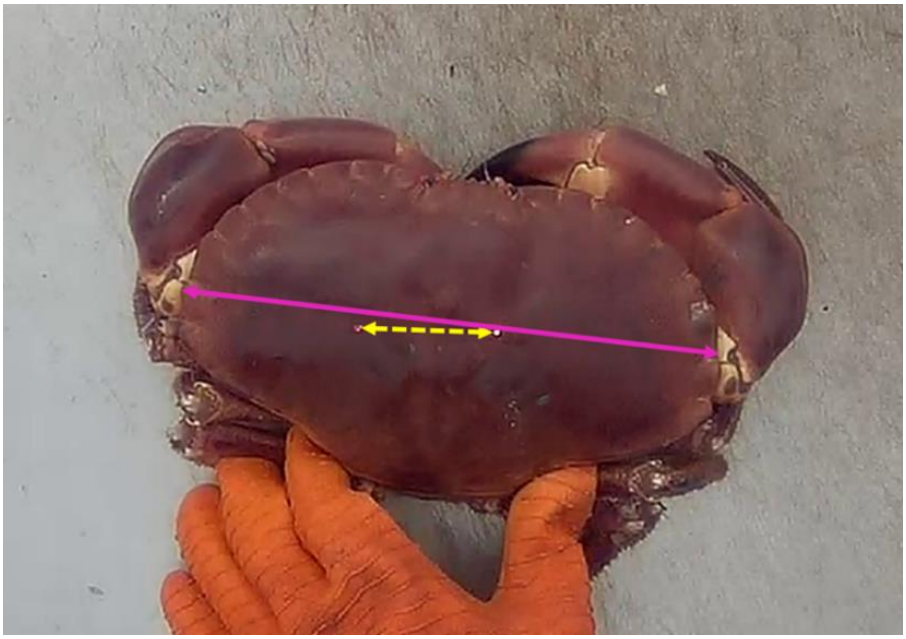

Figure 13: Still image (still) of the dorsal side of a brown crab, presented to a camera so that both lasers were projected across the width of the carapace. The Straight Line function in ImageJ was used to draw a straight line between the centre of the laser projections (the yellow dashed line). The laser scale for the respective camera system, was used to make a pixel to millimetre conversion, which was then used to measure the carapace width (CW: indicated by the purple arrow).

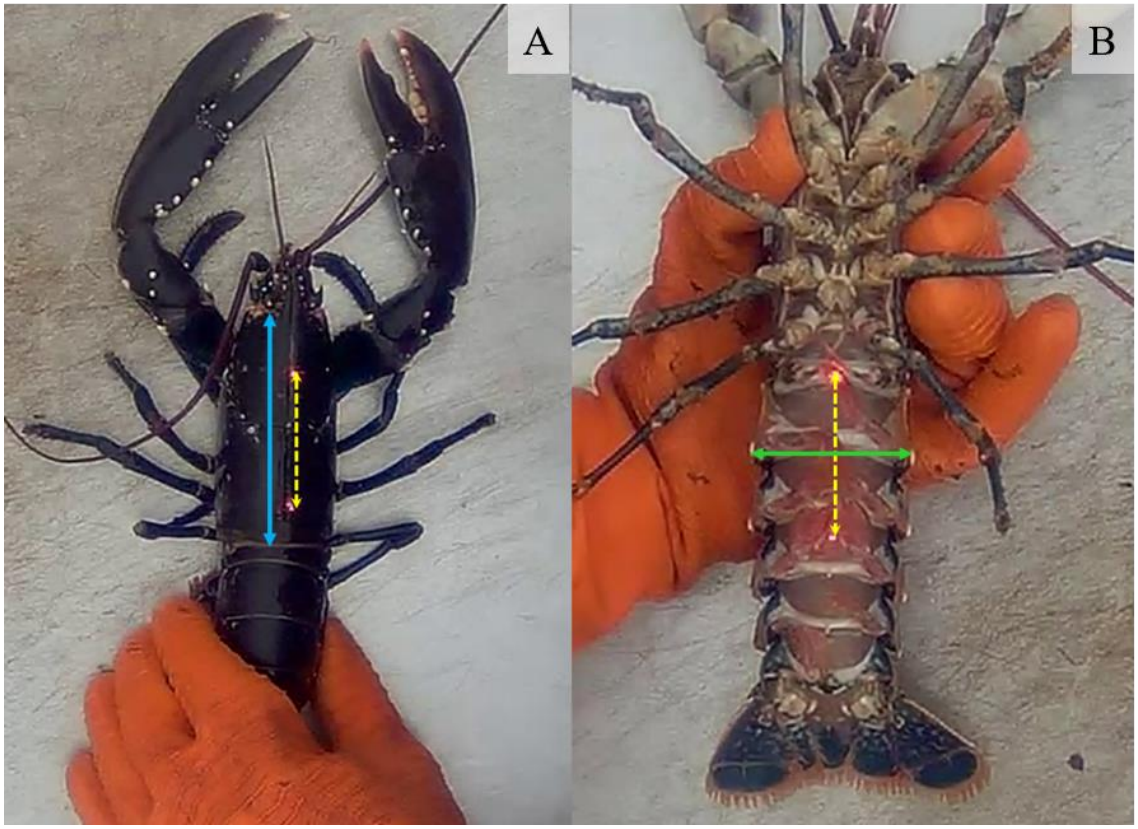

Figure 14: Still images (stills) of the dorsal and ventral sides of a European lobster (A: dorsal; B: ventral), presented to a camera so that both lasers were projected along the length of the carapace or the abdomen, respectively. The Straight Line function in ImageJ was used to draw a straight line between the centre of the laser projections (the yellow dashed lines). The laser scale for the respective camera system, was used to make a pixel to millimetre conversion, which was then used to measure the carapace length (CL: indicated by the blue arrow) or abdomen width (AW: indicated by the green arrow).

The condition of each crab and lobster was assessed from the stills and coded using the codes in Table 4. Soft-shelled crabs were identified by the colouration of the ventral side of the exoskeleton; pale colouration between the joints of the limbs was taken to be indicative that an individual crab was soft-shelled. It was not possible to determine if a lobster was soft-shelled from the extracted stills or raw video footage. Presence of black spot in an individual crab was determined by the presence of at least one black lesion in the dorsal or ventral still: the Still black spot assessment.

*Table 4: Codes assigned to each animal (photographed during the calibration process and during the fishery-dependent data collection program) to describe condition. Species that the codes were assigned to are indicated by the letter in brackets (C:crab, L:lobster). *only assigned to lobsters photographed using Camera 1 during the fishery-dependent data collection program (see section 2.7).*

Code	Definition
A	Absence of black spot (shell disease) (C)
P	Presence of black spot (C)
1-6	Quantifies the number of missing legs (C)
X	One missing claws (L & C)
XX	Two missing claws (L & C)
B	Berried (egg bearing) animal (L & C)
SS	Soft-shelled (L* & C)

To control for analyst identity, a single analyst extracted and analysed all the calibration stills. As recommended by Hold *et al.* (2015), training was provided to the analyst by an experienced researcher (JE) in order to mitigate the subjectivity in identifying the anatomical features used to demarcate the start and end points of the traits.

2.5 Morphometric allocation of sex

Where possible, crabs were sexed from the ventral stills by a visual assessment of the size and shape of the dimorphic abdominal flap. The accuracy of still sex allocations was determined by calculating the percentage of crabs that were allocated the Observed crab sex.

The AW:CL ratio cut off value between male and female lobsters was determined using Real AW and CL measurements taken during the calibration process and as part of an investigation into the SOM of lobster in the Isle of Man (Emmerson, *un published*). In total, the Real AW:CL ratio was calculated for 264 lobsters (151 females and 113 males). Male lobsters were found to have a Real AW:CL ratio of less than 0.52 whilst females were found to have a Real AW:CL ratio of. greater than or equal to 0.52. However, juvenile female lobsters had a similar morphology to males.

Where possible, the Predicted AW and CL were calculated for each calibration lobster from the corresponding Still measurements. The value of the Predicted AW:CL ratio determined the sex that was assigned to each lobster from the stills: the Predicted sex. Sex was assigned

using the ratio cut off value between male and female lobsters, determined as described above.

An error will be introduced into the sex allocation of lobsters as a result of using the Real AW:CL ratio rather than observing the pleopods, due in part to juvenile female lobsters having a similar morphology to males. The accuracy of the Real AW:CL ratio at allocating sex to the calibration lobsters was assessed by calculating the percentage of lobsters that were allocated the Observed lobster sex. Similarly, an error will be introduced in to the sex allocation of lobsters from stills as a result of using the Predicted AW and CL rather than the corresponding Real trait sizes. The accuracy of the Predicted AW:CL ratio was assessed following the same method used to assess the accuracy of the Real AW:CL ratio. Finally, the accuracy of the Real and Predicted ratios were compared.

2.6 Error and variance

2.6.1 Intra-observer effect

In the present study, the accuracy of data obtained using the on-board cameras was assessed using data collected by a single observer *in situ*. However, there will be error in data collected by observers and as a result variance in data collected from the same animal multiple times by a single observer: the intra-observer effect. In order to investigate the intra-observer variability in data collected from crabs, the single observer (JE) performed two repeat non-paired Real CW measurements, sex allocations and black spot assessments on a set of 30 crabs *in situ*.

2.6.2 Inter and intra-analyst effect

In order to investigate the inter-analyst effect for all three traits, defined as the variation amongst repeat measurements of the same trait in the same still by multiple analysts, three analysts (CL, JE and SM) measured the relevant traits in a set of 73 crab calibration stills and a set of 36 lobster calibration stills. For each trait, the effect of camera identity on the inter-analyst effect was controlled for by using stills taken by the same on-board camera unit (crab CW: Camera 2; lobster CL and AW: Camera 3).

So as to investigate the intra-analyst effect for all three traits, defined as the variation amongst repeat measurements of the same trait in the same still by the same analyst, all three analysts

repeated the measurements described above three times. In order to investigate subjectivity in still rejection, each analyst recorded their still rejection rates and coded the reasons for still rejection using the codes in Table 3 (section 2.4). Two more experienced analysts (JE and SM) also assessed the crab stills for the presence of black spot, so as to investigate the inter and intra-analyst variability in Still black spot assessments.

2.6.3 Comparison of the intra-observer and intra-analyst effect

In order to compare the variability of data collected remotely using the camera systems with the variability of data collected *in situ*, the intra-observer variance in two repeat Real CW measurements and black spot assessments (n=30) performed by a single observer (JE) *in situ* (as described in section 2.6.1) was compared with the inter-analyst variance in three repeat Still CW measurements and black spot assessments performed by the same observer/analyst (JE) during the investigation into the inter and intra-analyst effect (as described in section 2.6.2).

2.6.4 Still selection

Still selection from the raw video footage may influence the precision and accuracy of measurements taken directly from stills. For all three traits, the precision and accuracy of measurements taken directly from stills were assessed in a process whereby Still trait measurements were made by a single analyst using three different stills (extracted from the raw calibration footage in a succession of less than five seconds) of the same 42 crabs and the same 36 lobsters.

Further, for 21 lobsters, the mean Predicted AW±CV of the three Still AW measurements was plotted against the mean Predicted CL±CV of the three Still CL measurements, in order to assess the effect of still selection on the accuracy and precision of the Predicted AW:CL ratio. To control for analyst identity, the single analyst who investigated the effect of still selection was the same analyst who determined the predictive models for all three traits (SM).

2.7 Fishery-dependent data

The fishers who participated in the fishery-dependent data collection program target crab and lobster in three different areas in the territorial waters of the Isle of Man (Figure 15). Fishers were asked to pass catch of the target species (brown crab and lobster) into the FOV of the camera, as described in section 2.3, in the order that the traps were hauled. Fishers were not required to keep paper records or modify their behaviour in any other way. It was up to the discretion of the fishers when they used the cameras and how much of the catch they recorded.

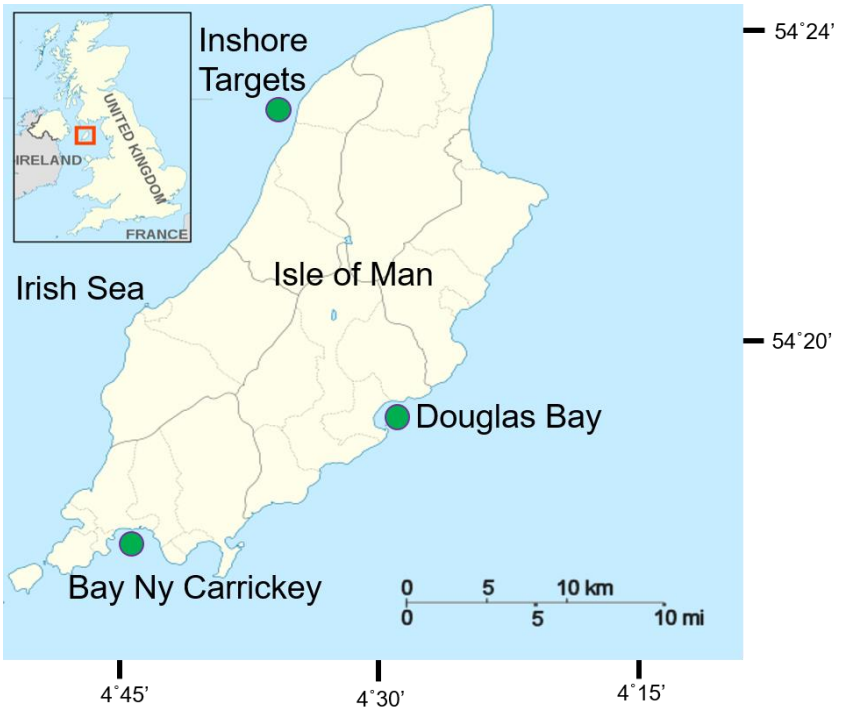

Figure 15: Map showing the three areas in the territorial waters of the Isle of Man (indicated by green) where fishers participating in the present study target brown crab and European lobster. (Credit: adapted from Wikipedia).

Analogous to the calibration footage, the fishery-dependent footage was viewed in VLC media player using the interactive zoom feature. This enabled a close up of the defined surface to be viewed in the centre of the screen whilst activities in the entire FOV of the camera were visible in the inset rectangle in the left-hand corner of the screen (Figure 16). To control for analyst identity, all the fishery-dependent footage and extracted stills: the fishery stills, were analysed by the same trained analyst that analysed the calibration footage (SM).

Before being analysed, random sections of each day's footage from each vessel was previewed to determine what information could be taken from it (Figure 17). For example, when previewed, footage recorded by Camera 3 in June was of poorer quality than footage from previous months. This was found to be a due to condensation in the camera housing as a result of a leak around the screws affixing the window to the box. As a result, the only information that was taken from this footage was the number and fate of crab and lobster in each georeferenced trap.

Figure 16: A: still image (still) extracted from fishery-dependent footage recorded by Camera 1, showing a close up of the defined surface in the centre of the screen whilst activities in the entire field of view (FOV) of the camera are visible in the inset rectangle in the left-hand corner of the screen. B: Zoomed in image of the inset rectangle, showing activities in the entire FOV of the camera. A lobster is being banded (left-hand side of the image) whilst the next trap is being hauled onto the gunwale (right-hand side of image). GPS data has been removed to protect commercial sensitivity.

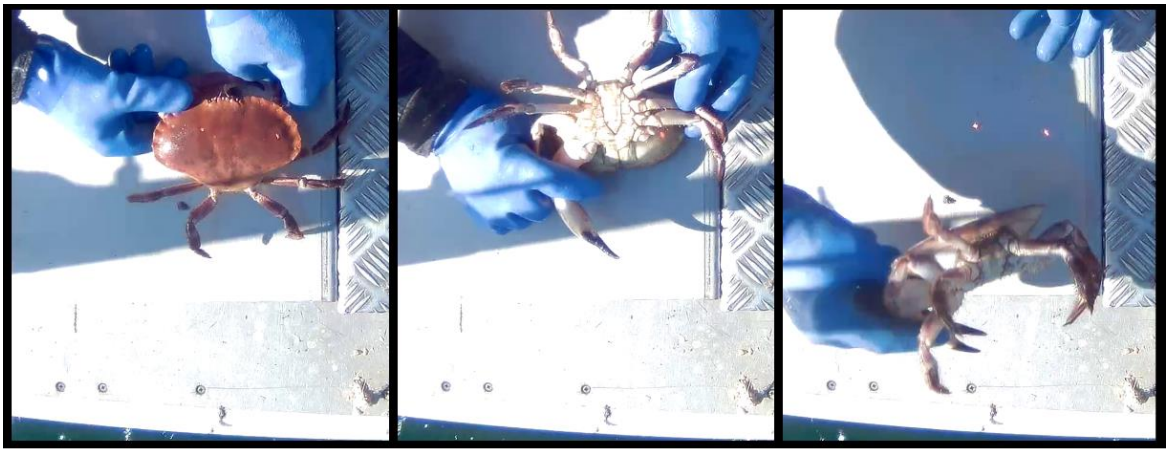

Figure 17: Raw video footage from the on-board camera unit installed on Vessel 3, showing a male brown crab being presented to the camera dorsal then ventral side up before being discarded (left to right). GPS data has been removed to protect commercial sensitivity.

For footage that could be used to measure the size of crabs and lobsters, stills were extracted and measured in ImageJ as described in section 2.4. The video playback speed was decreased as required to allow the best still to be extracted even if the animal had only briefly been passed under the camera by the fisher. The speed was decreased to as slow as 0.06 times the original speed for the fastest footage. For example, to extract stills of lobsters that flexed their tail fans when they were held ventral side up. The video playback speed was increased to as fast as 1.5 times the original playback speed during periods when the catch was not being sorted.

Trial and error found that the most efficient way to extract and analyse the fishery stills was to pause the footage and analyse each still as soon as it had been extracted. If a still was rejected the footage was restarted and a replacement still extracted if possible. If it was not possible to extract a usable replacement still, the reason for the still rejection was coded using the codes in Table 3 section 2.4.

For footage that could be used to investigate the sex ratio of crab and lobster, where possible crabs and lobsters were allocated a sex from the extracted stills as described in section 2.5. In order to quantify the still rejection rate and qualify reasons for still rejection for each of the traits, the AW for each lobster was measured from the ventral still where possible, even if it was not required for sex allocation, i.e. if a lobster was berried or if the dorsal still had been rejected.

Each crab and lobster was assigned an identifying code comprising the code of the vessel it was caught on, the date that it was caught, the string and trap number and the GPS coordinates of the trap that it was caught in. The coordinates at the moment the traps were first visible in the FOV of the camera were taken to be the trap coordinates: on two vessels, this corresponded to the coordinates at the time the trap was hauled onto the vessel, whilst on the third vessel this corresponded to the coordinates at the time the trap was put on the sorting table. The earliest registered GPS coordinates were assigned to all the traps that had been hauled before the GPS receiver had triangulated. The fate of each crab and lobster was determined if possible and coded using the codes in Table 5. The crab and lobster fate unknown codes, CU and LU respectively, were used if an animal was taken permanently outside of the FOV of the camera or if the camera was switched off before the fate of an animal could be determined by the analyst.

Table 5: Codes assigned to each brown crab and European lobster caught during the fishery dependant data collection program in the Isle of Man Crustacean fishery, February to June 2017, to describe the fate of each animal. The crab and lobster fate unknown codes: CU and LU respectively, were used if an animal was taken outside of the field of view of the camera or if the camera was switched off before the analyst could determine the fate of an animal.

Code	Definition
CK	Crab kept
CD	Crab discarded
CU	Crab, fate unknown
LK	Lobster kept
LD	Lobster discarded
LU	Lobster, fate unknown

The video footage was reviewed as necessary for information that could not be determined from the stills, for example in bright sunlight it was sometimes only possible to sex crabs when they were tilted away from the light; at the point of discard or when they were being put into a fish box. If a crab could not be sexed from a dorsal still or the raw footage, the reason was coded using the codes in Table 6.

Table 6: Codes assigned to rejected ventral still images (stills) of brown crab, to explain the reason for still rejection and as a result, the reason why a crab could not be sexed from the still or the raw video footage. The footage was recorded by three on-board cameras during a fishery-dependent data collection program in the Isle of Man Crustacean fishery, February to June 2017

Code	Definition
Con	Abdominal flap obscured by condensation in the camera housing.
L	Abdominal flap obscured by the legs of the crab
NU	Crab not presented to the camera or only the dorsal side of the animal presented to the camera.
OB	Abdominal flap obscured by an object, such as seaweed.
S	Sunlight reflecting of the abdominal flap.

Where possible, the condition of each crab and lobster was assessed from the stills as described in section 2.3. Although it was not possible to determine if a lobster was soft-shelled from the extracted stills or raw video footage, the fisher on one vessel: Vessel 1, developed a hand signal to indicate to the camera that an individual lobster was soft-shelled before discarding it.

Various features In ImageJ were trialled in an attempt to reduce the numbers of stills that were rejected (Appendix II). For example, the Invert function in ImageJ was found to sometimes improve the contrast between the laser projections and the colouration of an animal (Figure 18) or improve the visibility of the projections when sunlight was reflecting of the carapace. However, the utility of all these features were image dependant; none of the features worked consistently to resolve the same issue in multiple stills. The time cost of trying all the different features was found to outweigh the benefit of a minimal reduction in the number of rejected stills.

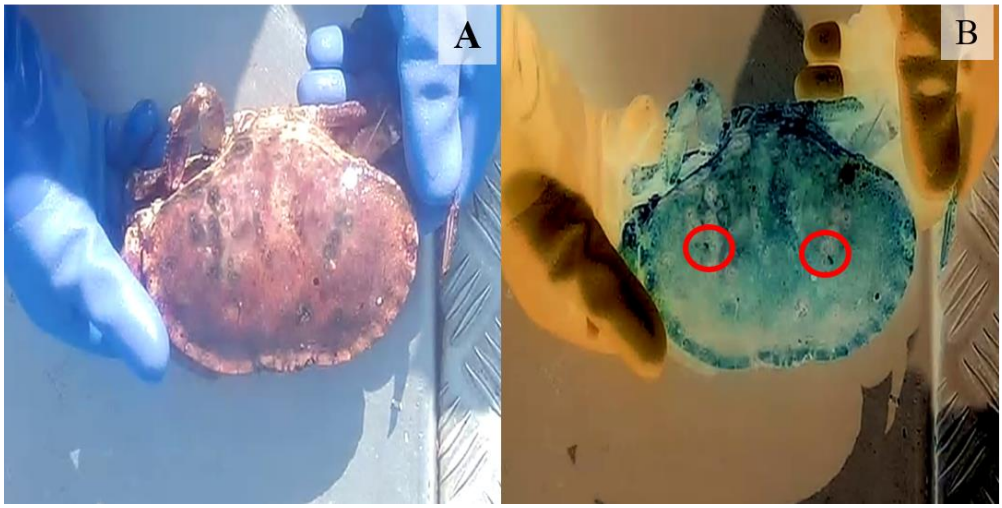

Figure 18: Still images (stills) showing how the Invert function in ImageJ (A: non-inverted image; B: inverted image) could sometimes be used to increases the contrast between the red paired laser projections (circled by red in the inverted image) and the colouration of brown crab.

Although fishers were not asked to pass bycatch into the FOV of the on-board cameras, stills of visible bycatch were extracted from the fishery-dependent footage to give an indication of the quality of image that could be obtained using the cameras.

3.0 Statistical analysis

All statistical analysis was performed in Microsoft Excel and R version i386 3.0.2 (R Core Team, 2013). The significance level was set at 0.05.

3.1 *In situ* calibration of the individual camera units

The relationship between the Real and Still trait measurements was investigated separately throughout for each of the three traits: CW, CL and AW. Prior to statistical modelling, Q-Q plots of the CW, CL and AW data were visually inspected to check for normality. Levene's test (Brown and Forsythe, 1974) was used to test for heteroscedasticity and a Cook's distance plot was used to check for outliers.

In order to determine the effect of camera identity on the error in the Still trait measurements, ANCOVA was used to model the error in the Still trait size as a function of the Real trait size and the camera identity (**Model 1)**.

(Still trait size-Real trait size)~Real trait size*Camera identity **Model 1**

Initial data exploration found that the relationship between the Still trait measurements and the Real trait size was linear for all three traits and indicated that a camera specific predictive model was required for all three traits. The starting predictive model for each trait included all the terms (**Model 2**). Any non-significant terms were dropped in a process of model simplification. Anova for model selection was used to test if the simpler model explained significantly less of the variation in the Real trait size. The most parsimonious model was chosen as the preferred predictive model for each trait.

Real trait size ~ Still trait size*Camera identity **Model 2**

3.1.1 Real and Predicted size frequencies

The camera specific predictive models were applied to the respective Still CW, CL and AW measurements to produce the Predicted trait sizes. The Predicted CW, CL and AW datasets for all three cameras were combined, as were the Real CW, CL and AW datasets. Linear regression analysis was used to model the relationship between the Predicted trait datasets

and the corresponding Real trait datasets. The goodness-of-fit of each predictive model was assessed by inspecting the diagnostics plots and the residual error structure.

A non-parametric Kolmogorov–Smirnov test was used to test for significant differences between the Real and Predicted size frequencies of the calibration lobsters and crabs. The mean size, median size, size range, and number of undersized individuals were calculated for the Real crab and lobster size frequencies and the corresponding Predicted size frequencies.

3.1.2 Condition assessment

For all three cameras combined, three calibration crabs were assessed as soft-shelled, 38 as infected with black spot and 37 assessed as damaged by the observer *in situ*. 11 calibration lobsters were assessed as being berried and five assessed as damaged by the observer *in situ*. These low sample sizes excluded the possibility of using statistical analysis to compare the results of the Still and *in situ* condition assessments, however some descriptive results are presented in section 4.1.1. Finally, the still rejection rates and reasons for still rejection were compared descriptively for both crab and lobster.

3.2 Morphometric allocation of sex

Due to the small numbers of large and small lobsters used to calibrate the camera systems lobsters smaller than 80mm CL were binned together, as were lobsters larger than 100mm CL. Lobsters in between 80mm and 100mm CL were binned into 5mm size classes. This size class was chosen to enable a direct comparison to be made between results obtained in the present study and results obtained by Hold *et al.* (2015) using a background reference scale rather than a laser scale. The accuracy of the Real AW:CL ratio at allocating sex to male and female lobsters was assessed by calculating the percentage of lobsters in each bin class that were allocated the Observed lobster sex.

The accuracy of the Predicted AW:CL ratio at allocating sex to lobsters from stills was assessed using the Observed lobster sex, following the same method as described above for the Real AW:CL ratio. The accuracy of the Real and Predicted sex allocations were compared graphically for each sex. With regards crabs, the accuracy of still sex allocations was determined by calculating the percentage of crabs that were allocated the Observed crab sex, for all size classes combined.

3.3 Error and variance

3.3.1 Intra-observer effect

A non-parametric Kolmogorov–Smirnov test was used to test for significant differences between the two Real crab size frequencies measured by the single observer (JE) *in situ*. The intra-observer variability in the two non-paired repeat black spot assessments and sex allocations were compared descriptively.

3.3.2 Inter and intra-analyst effect

For all three traits, the intra-analyst effect was investigated by calculating the mean error in the three repeat Still measurements performed by each of the three analysts. The inter and intra-analyst effect in Still black spot assessments were investigated by calculating the mean percentage (±CV) of crabs correctly and incorrectly assessed as having black spot, in the three repeat assessments performed by the two analysts.

So as to investigate the inter-analyst effect, ANCOVA was used to model the Real trait size as a function of the Still trait size and the analyst identity. The starting predictive model for each trait included all the terms (**Model 4**). Non-significant terms were dropped in a process of model simplification. and anova for model selection was used to test if the simpler model explained significantly less of the variation in the Real trait size.

Real trait size ~ Still trait size*Analyst identity **Model 4**

3.3.3 Comparison of intra-observer and intra-analyst effect

The observer who collected the data used to investigate the intra-observer effect was one of the analysts who participated in the investigation into the intra-analyst effect (JE). In order to compare the intra-observer and intra-analyst effect, Kolmogorov-Smirnov tests were performed on all possible combinations of the three Still crab size frequencies obtained by the observer (JE) during the investigation into the intra-analyst effect. The results were compared with the result of the Kolmogorov-Smirnov test used to determine the intra-observer effect in Real crab size frequencies (section 3.3.1). The intra-observer effect in the two *in situ* repeat black spot assessments was compared descriptively with the intra-analyst effect in the three Still black spot assessments carried out by the same observer/analyst.

3.3.4 Still selection

The effect of still selection on the accuracy and precision of Still measurements was assessed for all three traits in a process whereby Still trait measurements were made by a single analyst using three different stills of the same 42 crabs and same 36 lobsters. For all three traits, the Real trait size was plotted against the mean Still measurement (±CV), alongside the ideal relationship: Real trait size equals Still trait size. The effect of still selection on the accuracy of the Still measurements was graphically assessed. For each trait, the effect of still selection on the precision of Still measurements was assessed by calculating the mean coefficient of variation of the three Still measurements.

For 21 lobsters, the predictive models were used to calculate and plot the mean Predicted AW±CV of the three Still AW measurements against the mean Predicted CL±CV of the three Still CL measurements. The Observed lobster sex was included as a categorical variable so that the effect of still selection on the accuracy and precision of the Predicted AW:CL ratio could be graphically assessed for each individual lobster.

3.4 Fishery-dependent data

3.4.1 Fishery still rejection

In order to investigate why traits could not be measured from the fishery-dependent stills, percentage histograms were created for the codes assigned to rejected stills (Table 3, section 2.4) taken by all three camera units combined. The still rejection codes were grouped according to human error and error as a result of the photogrammetric apparatus. The code for condensation was not included in the analysis.

3.4.2 Fishery-dependent data applications

In order to demonstrate possible future applications of data acquired from the camera systems the trap coordinates taken from the footage were plotted in ArcGIS version 10.3. The points to line tool was used to join the traps together and plot the strings. A heat map was created to show the observations of the target species collected throughout the fishery-dependent data collection program. Pre-existing environmental data layers: bathymetry, median particle size and benthic infauna biomass were mapped to explore any habitat interactions of the fishery.

descriptively for both crab and lobster. The utility of the cameras in investigating the spatial and temporal variations in the sex ratio of crab was demonstrated by creating pie charts for each month and each Port Erin grid-square within which fished traps fell. Pie charts were only created for a particular month and grid square if the number of observations of crab was greater than 10. Due to the high lobster still rejection rate, it was not possible to use the fishery-dependent footage to investigate the spatial and temporal variations in the sex ratio of lobsters.

The camera specific predictive models were applied to the crab and lobster size measurements taken directly from the fishery-dependent stills. Size frequency histograms were plotted to investigate the spatial and temporal variations in the size frequencies of both species, in each port Erin grid square. Histograms were only created for a particular month and grid square if the number of observations of crab or lobster was greater than 10.

4.0 Results

4.1 *In situ* calibration of the individual camera units

The size and condition of animals used to perform the *in situ* calibration of the three camera systems varied depending on the composition of the respective vessels catch on the day the cameras were calibrated. For all three cameras combined, a total of 195 and 155 sets of dorsal and ventral stills of crabs and lobsters were extracted respectively. The Real and Still CW and CL datasets failed to meet the assumption of homogeneity of variance (Levene's test: both $p<0.05$). Therefore, there was an increase in the possibility of type one errors when comparing the relationships between the Still and corresponding Real trait sizes, between the three camera systems. Non-equality of variance was likely a consequence of the different size ranges of each species used to calibrate each individual camera system.

For all three traits, ANCOVA showed that there was a significant effect of the camera identity on the error in Still trait size (**Model 1**; Figure 19). Measurements taken directly from stills could under or overestimate all three trait sizes if the stills were extracted from footage taken by Cameras 2 or 3. Whereas measurements taken directly from stills consistently underestimated all three trait sizes if the stills were extracted from footage taken by Camera 1. The magnitude of the error in all three Still trait sizes also tended to be greater for this camera than for the other two cameras, for similar Real trait sizes.

(Still trait size-Real trait size) ~ Real trait size*Camera identity **Model 1**

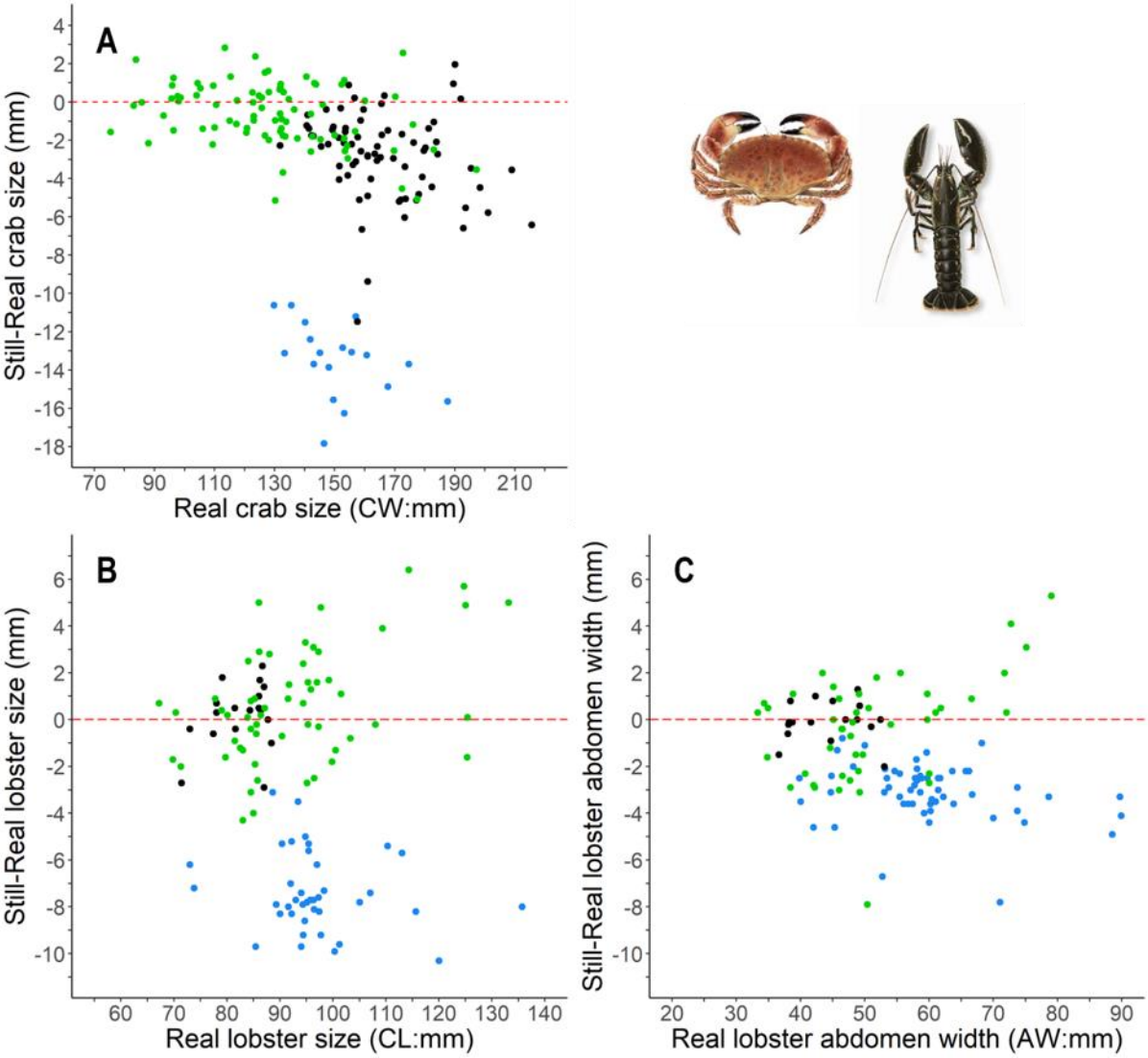

Figure 19: The relationship between the error in the Still trait size (Still-Real trait size) measured remotely using paired lasers as a reference scale (A: brown crab CW, B: European lobster CL, C: European lobster AW) with the corresponding Real trait size, measured in situ, for the animals used in the calibration of all three camera units combined (blue: Camera 1, black: Camera 2, green: Camera 3). The red dotted line represents the ideal relationship between the Still and Real trait sizes, i.e. no difference.

With regard to lobster CL and AW, the error in Still trait measurements changed with the Real trait size if the stills were taken by Cameras 1 and 3, as indicated by a gradient significantly different from zero (Camera 1: $p<0.05$; Camera 3: $p < 0.01$). For camera 3, the error in both Still lobster trait sizes increased with increasing Real trait size, whilst for Camera 1 the error in both Still trait sizes decreased with increasing Real trait size. The error in Still CL measurements changed non-significantly with the Real CL size if stills were taken using Camera 2 ($p = 0.23$), even though the rate of change of the error in Still CL with Real CL was the same for Camera 2 as for Camera 3, as indicated by identical gradients (gradient = 0.08). This could be indicative that an insufficient sample size and size range of lobster

were used to calibrate Camera 2 compared to Camera 3 (Camera 2: n= 15, CW range: 71.4-88.4mm; Camera 3: n=55; CW range: 67.2- 133.1mm) resulting in insufficient statistical power to detect a significant change in error with Real trait size even if there was one.

For crab, the error in Still CW measurements decreased with the Real CW size for stills taken using all three cameras, as indicated by a gradient significantly different from zero for Camera 3 ($p < 0.005$) and near significantly different from zero for Cameras 1 and 2 ($p=0.07$ and $p=0.05$ respectively).

Initial data exploration found that the relationship between trait measurements taken directly from stills and the corresponding Real trait sizes was linear for all three traits (Appendix III). ANCOVA showed that there was a significant effect of the camera identity on the linear relationship between the Real and Still trait measurements for all three traits, indicating that it was necessary to apply a camera specific predictive model to measurements taken directly from stills. Anova for model selection determined that the preferred predictive model for lobster CL and AW was the starting model; **Model 2** (Table 7; Figures 20 and 21). The preferred predictive model for crab CW was the simpler model; **Model 3.** However, due to heterogeneity of variance in the data, it is possible that the starting CW predictive model failed to detect a significant interaction of the camera identity and the Still CW size.

Real trait size ~ Still trait size*Camera identity **Model 2**

Real trait size ~ Still trait size + Camera identity **Model 3**

*Table 7: The results of the ANCOVAs and anova for model selection, used to determine the trait (brown crab CW, European lobster CL and AW) and camera specific preferred predictive models adopted to calibrate the corresponding trait measurements made from still images: the Still trait sizes (Still $_{CW}$, Still $_{CL}$, and Still $_{AW}$). > indicates a significant difference in model parameters between on-board camera units (gradient or intercept), where 1>3 in the Model gradient column would indicate that the gradient for Camera 1 is greater than the corresponding model gradient for Camera 2. N indicates an intercept that is near significant at the 0.05 significance level (p=0.08). *** p-value ≤ 0.05; ** p-value < 0.01; * p-value < 0.001.*

			Differences in model parameters	
Preferred predictive model	**F statistic**	**p-value**	**Model gradient**	**Model intercept**
Real $_{CL}$~Still $_{CL}$* Camera	$F_{5,112}$=1104	<0.001*	1>3 *	1>2^{N}
Real $_{AW}$~Still $_{AW}$ * Camera	$F_{5,110}$=1494	<0.001*	3<1 *	3>1*
Real $_{CW}$~Still $_{CW}$ + Camera	$F_{3,169}$=11560	<0.001*	*3<1>2 *	NA

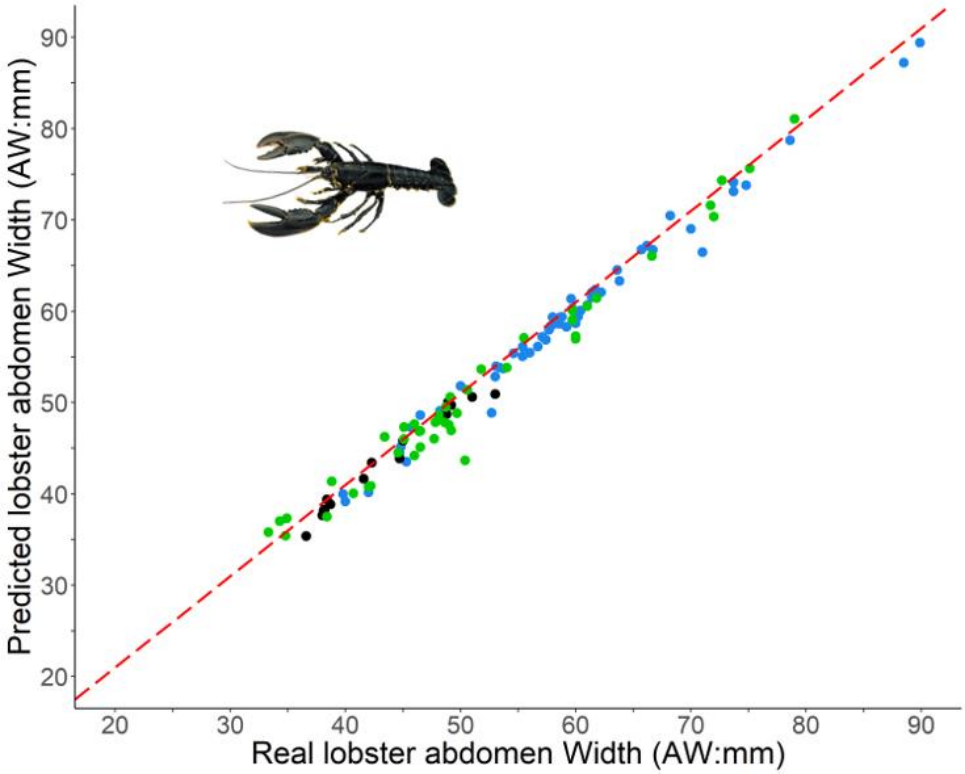

Figure 20: The relationship between the Predicted European lobster AW, derived from measurements made from still images using parallel lasers as a reference scale and the Real lobster AW measured in situ, for the animals used in the calibration of all three camera units combined (blue: Camera 1, black: Camera 2, green: Camera 3). The red dotted line represents the perfect relationship between the Predicted and corresponding Real AW size, i.e. Predicted AW equals Real AW.

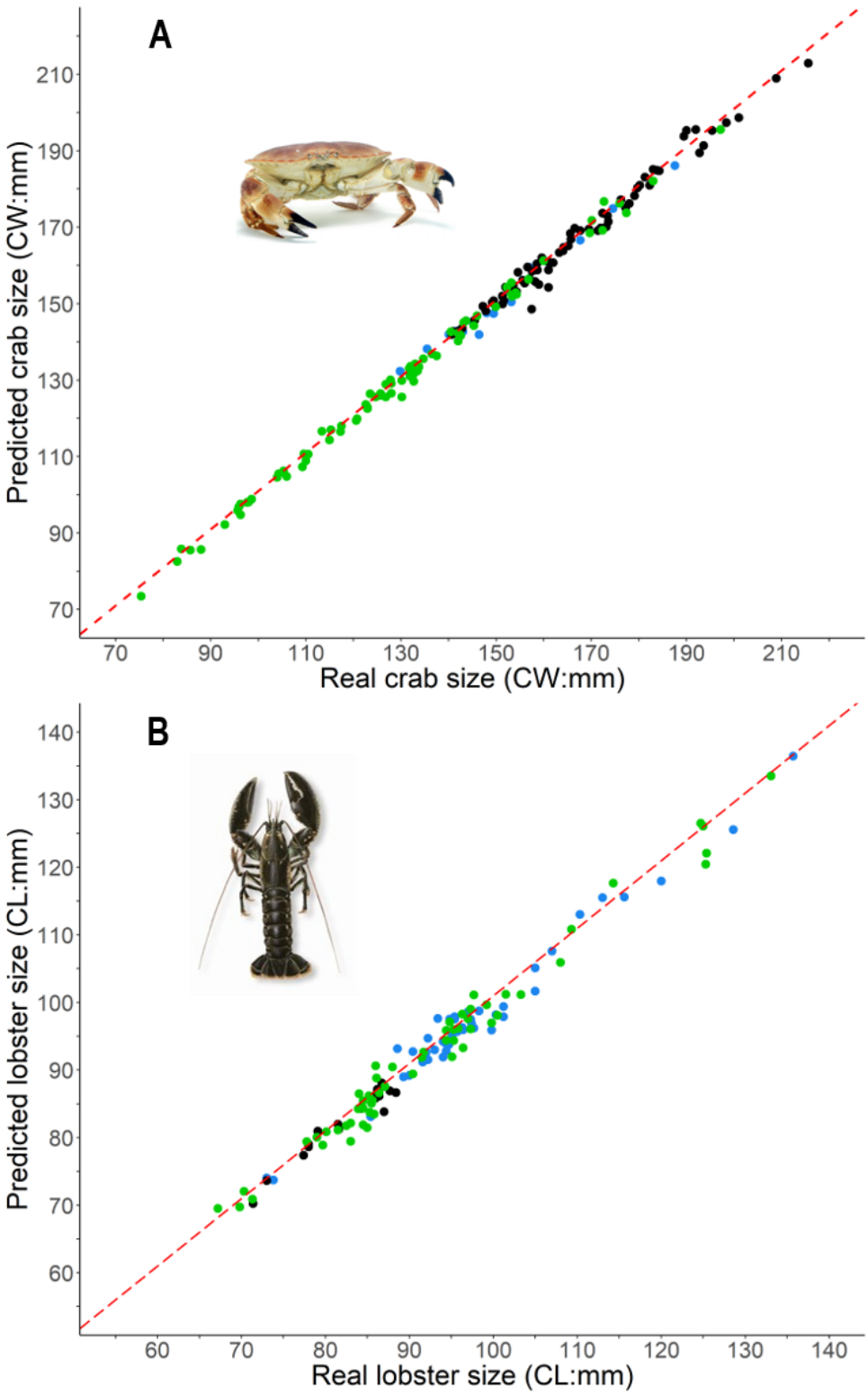

Figure 21: The relationship between the Predicted trait size (A: brown crab CW and B: European lobster CL) derived from measurements made from still images using parallel lasers as a reference scale and the Real trait size, for animals used in the calibration of all three camera units combined (blue: Camera 1, black: Camera 2, green: Camera 3). The red dotted line represents the perfect relationship between the Predicted and corresponding Real trait size, i.e. Predicted trait size equals Real trait size.

For all three traits, the respective predictive models explained 98% of the variance in the Predicted trait size. Due to outliers in the Predicted datasets, the median residual error was calculated for each dataset instead of the mean residual error (Table 8). The preferred predictive model tended to overestimate the Real CW and Real AW slightly, as indicated by a negative median residual error. Whilst the preferred predictive CL model tended to underestimate the Real CL slightly. The CL predictive model had the smallest residual error structure (Figure 22). For all the traits, 50% of the Predicted trait sizes were within ±1.2 mm of the corresponding Real trait sizes.

Table 8: The results of the linear regression analysis on the Predicted brown crab and European lobster trait sizes (crab: Predicted $_{CW}$; lobster: Predicted $_{CL,}$ and Predicted $_{AW}$) against the corresponding Real trait size (crab: Real $_{CW,}$ lobster: Real $_{CL,}$ and Real $_{AW}$). The median, range and inter quartile range (IQR) of the residual error are shown for each of the preferred predictive models. The residual error in the predictive models are shown graphically in Figure 22.

		Residual error		
Preferred Predictive model	**R^2**	**Median (mm)**	**Range (mm)**	**IQR (mm)**
Predicted $_{CL}$~Real $_{CL}$*Camera	0.98	0.05	-4-5	-1.1-1.2
Predicted $_{AW}$~Real $_{AW}$*Camera	0.98	-0.07	-3-7	±0.8
Predicted $_{CW}$~Real $_{CW}$+Camera	0.98	-0.13	-5-9	±1.1

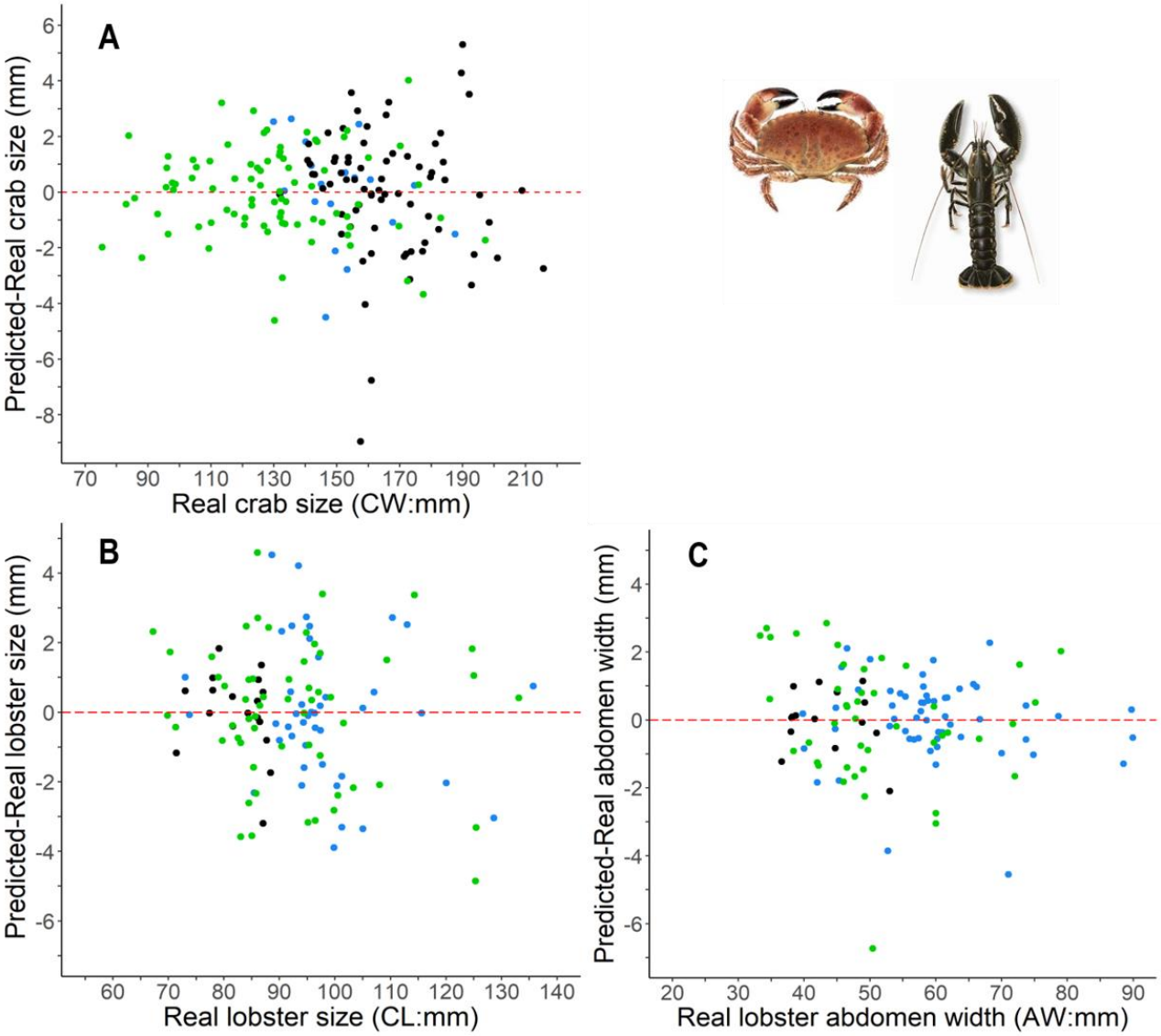

Figure 22: The relationship between the residual error (Predicted-Real trait size) in the Predicted brown crab and European lobster trait sizes (A: brown crab CW, B: European lobster CL, C: European lobster AW) derived from measurements made from still images using paired lasers as a reference scale and the corresponding Real trait size measured in situ, for the animals used in the calibration of all three camera units combined (blue: Camera 1, black: Camera 2, green: Camera 3). The red dotted line represents the ideal relationship between the Predicted and Real trait sizes, i.e. no difference.

Outliers in the residual error of the predicted CW model, characterised by a magnitude greater than 6mm, were investigated and found to be associated with errors in the CW measurements taken from the stills rather than inaccuracy in the real measurement value recorded *in situ* (see Appendix IV for methods).

4.1.1 Condition assessment

The calibration still analysis was 100% accurate at determining if an individual lobster was berried (n=11) and 100% accurate at assessing damage to lobsters when it was quantified by the number of missing claws (n=5). However, it was noted that a non-berried lobster could potentially be assessed as berried as a result of shadow falling on the tail fan (Figure 23).

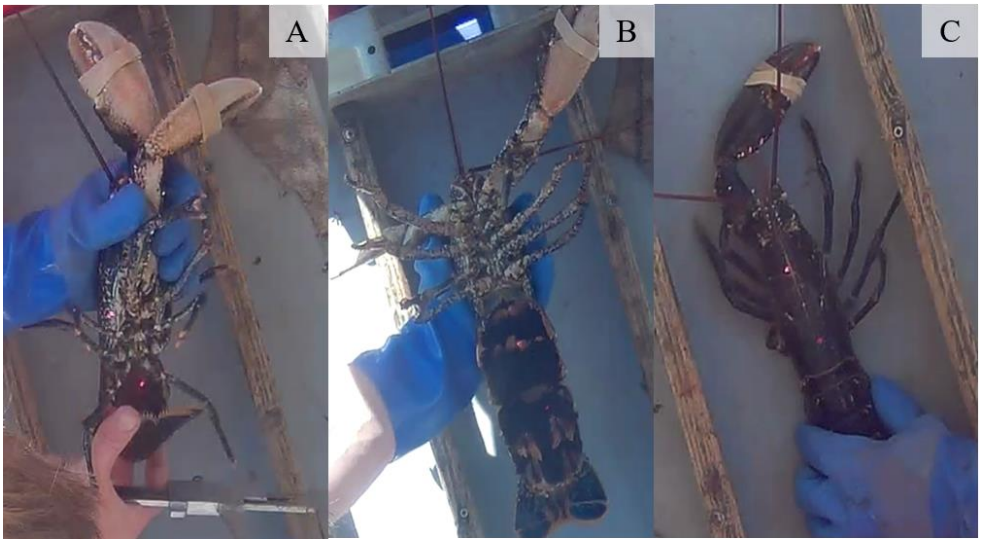

Figure 23: Still images (stills) showing the various conditions of the calibration lobsters (A: a lobster that appears to be berried (egg bearing) due to shadow from a curled tail fan; B: a lobster that is berried; C: a lobster that is missing one claw). For all three lobsters, the condition assessments made remotely from stills were in agreement with the condition assessments made in situ by the observer. All the stills were extracted from calibration footage taken by the on-board camera unit: Camera 1.

Still analysis was found to be an inaccurate method for assessing if a crab was soft-shelled. For all three cameras combined, analysis of the stills only accurately determined that one crab was soft-shelled (n=3) whilst two individuals were wrongly determined to be soft-shelled. 19% (n=195) of the crabs were assessed as damaged by the observer *in situ*, quantified by the loss of claws and legs and damage to the exoskeleton. Still damage assessments of the same crabs determined that 22% (n=195) individuals were damaged (Figure 24). Indicating that damage assessments from stills could potential overestimate the damaged component of the catch slightly.

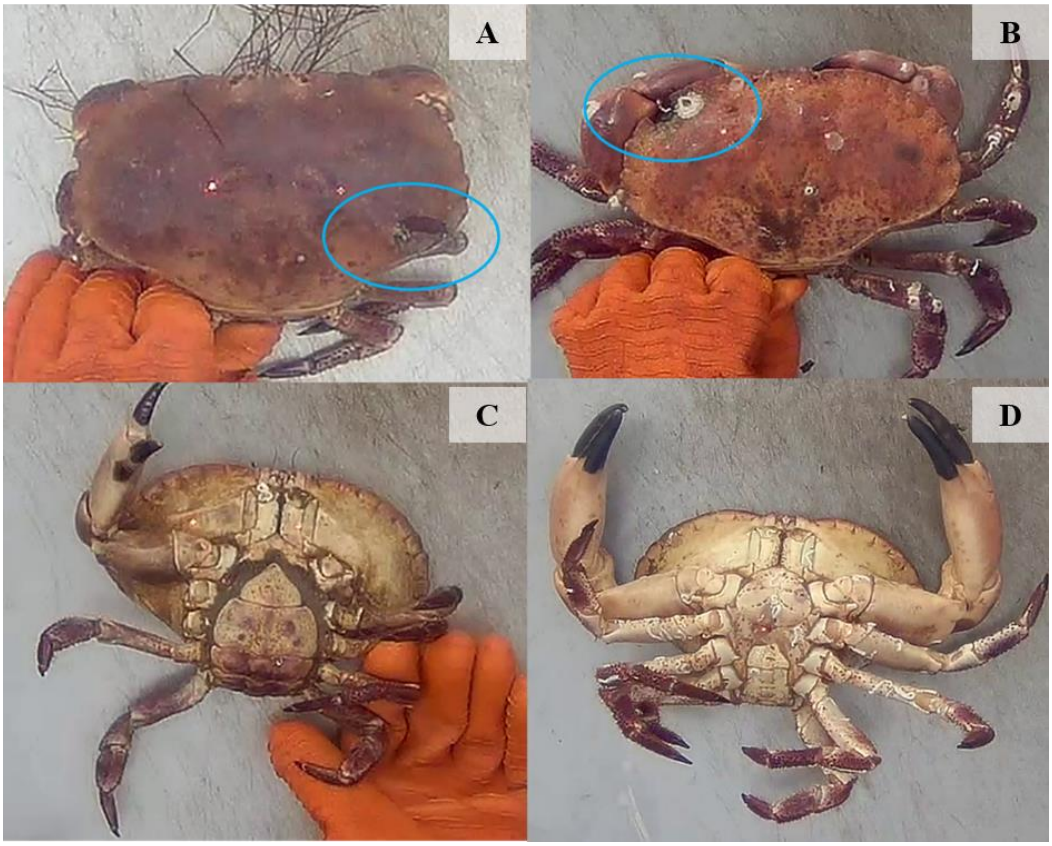

Figure 24: Still images (stills) of non-paired dorsal and ventral sides of damaged brown crabs (A and B: damaged carapace: circled in blue; C: one missing claw and two missing legs; D: damaged abdomen). For all four crabs, the condition assessments made remotely from stills were in agreement with the condition assessments made in situ by the observer. The stills were extracted from calibration footage taken by the on-board camera unit: Camera 2.

Still analysis was found be an inaccurate method for assessing the presence of black spot on an individual crab and was found to overestimate the percentage of the catch that was infected. 19% (n=195) of crabs were determined to be infected with black spot according to a visual assessment by the observer *in situ*, whilst 32% (n=195) of crabs were determined be infected with black spot from analysis of the stills. The still analyst failed to detect the presence of black spot on 34% (n=38) of the crabs that were assessed as having black spot *in situ* (Figure 25).

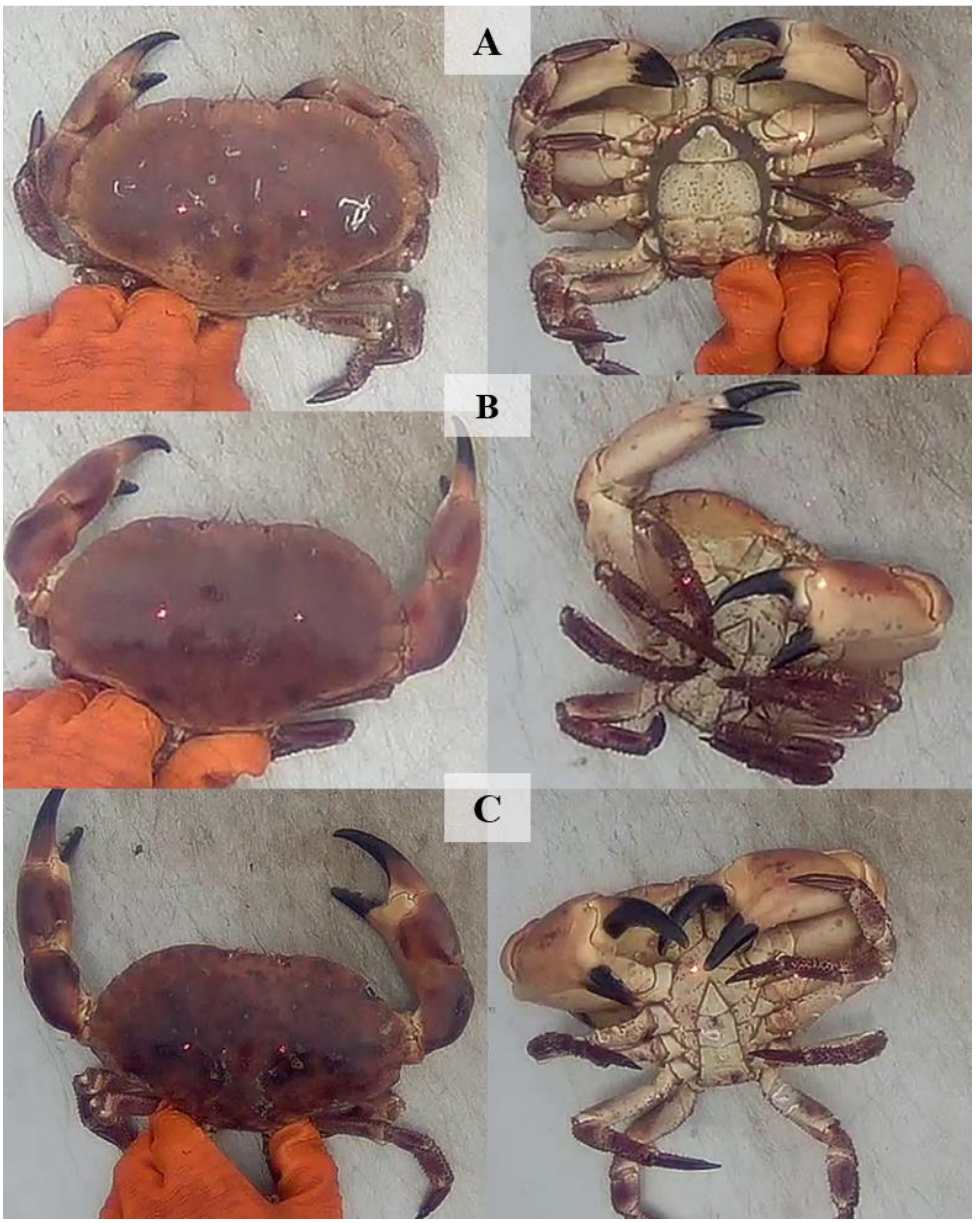

Figure 25: Still images (stills) of the dorsal and ventral sides (left: dorsal; right: ventral) of three crabs that were assessed for the presence of black spot (shell disease) by a still analyst. All three crabs were also assessed for the presence of black spot by an observer in situ. For two of the crabs, the still analyst's black spot assessment disagreed with the observer's assessments (A: assessed as having black spot by the still analyst but not the observer; B: assessed as having black spot by the observer but not the still analyst). For the third crab, the still analyst's black spot assessment was in agreement with the observer's assessment (C: assessed as having black spot by both the still analyst and the observer). The stills were extracted from calibration footage taken by the on-board camera unit: Camera 2.

4.1.3 Real and Predicted size frequencies

Kolmogorov–Smirnov tests showed that there was no significant difference between the Real and Predicted size frequencies of both species (crabs: D = 0.033, p =1; lobsters: D =0.069, p =0.91; Figure 26)

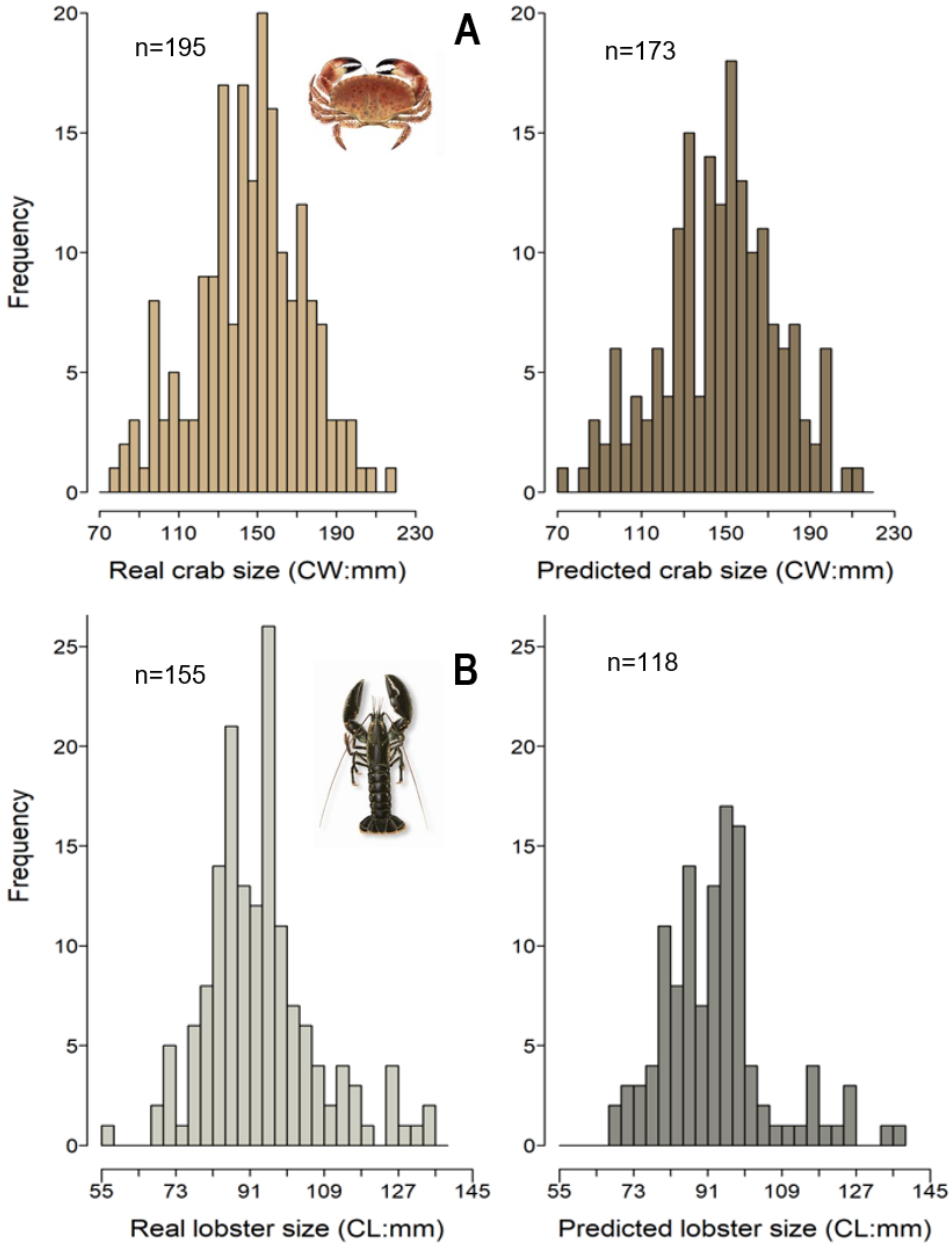

Figure 26: Real and Predicted size frequencies of: A: brown crab CW (5mm bin widths); B: European lobster CL (3mm bin widths). Predicted size frequencies were derived from measurements made from still images using paired lasers as a reference scale. The corresponding Real trait sizes were measured in situ, for the animals used in the calibration of all three camera units combined. Sample sizes are shown above the respective histograms. Differences in the sample sizes of the Real and the corresponding Predicted datasets are as a result of the rejection of dorsal stills for both species.

Differences in the sample size of the Real and corresponding Predicted dataset was due to still rejection for both species. The predicted number of crabs under the MLS, was four and six less than in the Real datasets for the 130mm and 135mm MLS respectively (Table 9). Whilst the difference in the predicted number of lobsters under the MLS was 11 and 17 less than in the Real datasets for the 87mm and 90mm MLS respectively. However, when the numbers of lobsters under the MLS was compared for only the animals that had been measured using both the Real and Predicted methods, the difference between the Predicted and Real lobster datasets decreased to one less for both the 87mm and 90mm MLS.

Table 9: Summary statistics for the Real and Predicted brown crab and European lobster datasets, for animals used in the calibration of all three on-board cameras combined. Real dataset (crab: n=195; lobster n=155) Predicted dataset (crab n= 173, lobster n= 118). MLS is the minimum landing size in most of the territorial waters of the Isle of Man. BNC MLS is the minimum landing size in Bay Ny Carrickey. Subscripts indicate the species that the minimum landing size relates to (C: crab, L: lobster). Differences in the sample sizes of the Real and corresponding Predicted datasets are as a result of the rejection of dorsal stills for both species.

	Crab		**Lobster**	
Statistic	**Real CW**	**Predicted CW**	**Real CL**	**Predicted CL**
Mean	146.3	146.9	93.5	93.1
SD	27.2	27.5	13.3	13.2
Median	148.8	149.3	92.2	92.7
Range CL	75.4-215.6	73.4-212.9	58.0-135.7	69.5-136.5
No. under MLS (87^{L},130^{C})	47	43	53	42
No. under BNC MLS (90^{L},135^{C})	64	58	67	50

4.1.2 Calibration still rejection

For all three cameras combined, the CL of 24% of the calibration lobsters and the AW of 23% of the lobsters could not be measured remotely (both n=155). With regard crab, the CW of 11% of the calibration crabs could not be measured remotely (n=195).

For calibration lobsters that were presented to the cameras both dorsal and ventral side up, the predominant reason for the rejection of lobster dorsal stills was poor definition of the eye socket (17%, n=155), whilst the predominant reason for the rejection of lobster ventral stills was poor definition of the edge of the abdomen width (5%, n=155). The crab dorsal calibration stills were only rejected due to poor definition of the carapace edges (11%, n=195; Figure 27).

Camera 1 had the highest dorsal and ventral still rejection rate, with 35% (n=75) and 18% (n=22) of lobster and crab dorsal stills rejected respectively, as a result of poor definition of the eye socket or carapace. Whilst 11% (n=75) of the lobster ventral stills were rejected as a result of poor definition of the abdomen width (Figure 28)

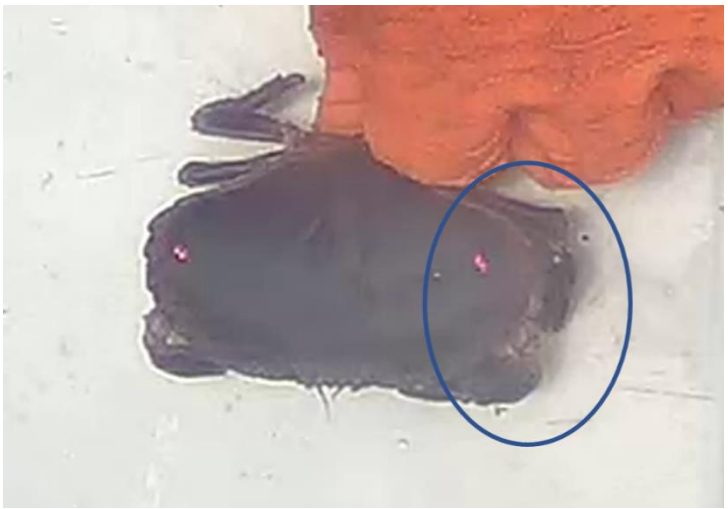

Figure 27: Dorsal still image (still) of a crab extracted from calibration footage taken using the on-board camera unit: Camera 2. The still was rejected, i.e. the carapace width was not measured from the still, due to poor definition of the carapace edge (demarcated by blue).

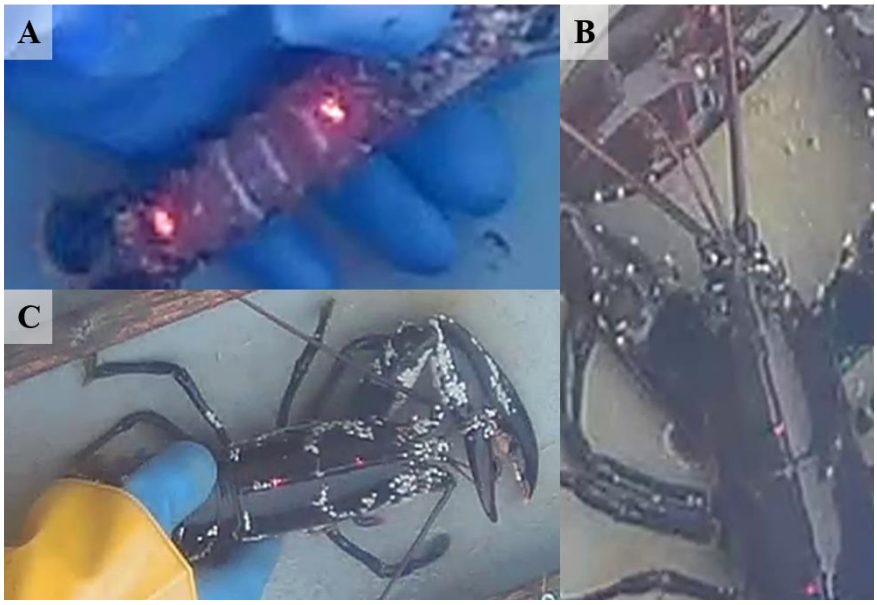

Figure 28:Dorsal and ventral still images (stills) of European lobster extracted from calibration footage taken using the on-board camera unit: Camera 1. The still was rejected, i.e. the carapace length (CL) or abdomen width (AW) were not measured from the stills, due to poor definition of A: the edge of the abdomen width; B and C: the eye socket of the lobster, which is used to demarcate the start of the CL.

4.2 Morphometric allocation of sex

Male lobsters were found to have a Real AW:CL ratio of less than 0.52 whilst females were found to have a Real AW:CL ratio of. greater than or equal to 0.52. However, juvenile female lobsters had a similar morphology to males (Figure 29). The Real AW:CL ratio was 100% accurate at allocating sex to female lobsters that had a Real CL greater than 95mm and 100% accurate at allocating sex to male lobsters in all size classes except the 85-90mm size class.

Due to the rejection of dorsal, ventral or both dorsal and ventral stills only 62% (n=154) of the calibration lobsters could be sexed using both the Real and Predicted AW:CL ratios, restricting the sample sizes available to compare the accuracy of both ratios at allocating sex. The Predicted AW:CL ratio was 100% accurate at allocating sex to female lobsters in three more size classes than the Real ratio and less or equally accurate at allocating sex to males in all size classes. However, this could be due to anomalies skewing the relatively small sample size of males that could be sexed using both ratios.

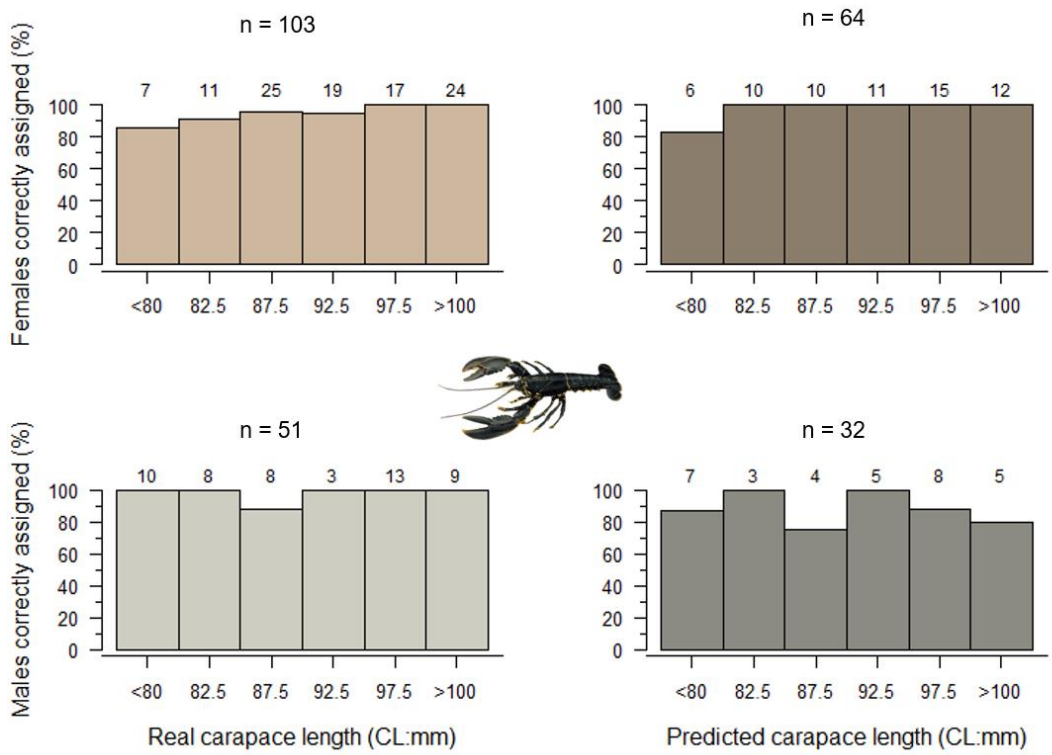

Figure 29: Histograms showing the results of the sex allocation of lobsters based on the Real and Predicted AW:CL ratio (female: purple; male: blue). The Real ratio was determined using the Real trait sizes measured in situ by an observer. The Predicted ratio was determined by applying the respective predictive models to the CL and AW trait sizes measured directly from still images. The accuracy of both the Real and Predicted ratios at allocating sex was determined by comparing the Real and Predicted sex allocations to the Observed lobster sex, determined by a visual assessment of the first of the dimorphic pleopods in situ Sample sizes are shown above the respective histograms. Differences in the sample sizes between the Real and Predicted datasets are due to the rejection of dorsal and ventral stills precluding the use of the Predicted AW:CL ratio to allocate sex.

4.3 Error and variability

4.3.1 Intra-observer effect

The Kolmogorov–Smirnov test showed that there was no significant difference between the two Real crab size frequencies (Kolmogorov–Smirnov: n =30 D=0.07, p=1; Figure 30), indicating that there was no significant intra-observer effect in repeat CW measurements made by the single observer (JE) *in situ*.

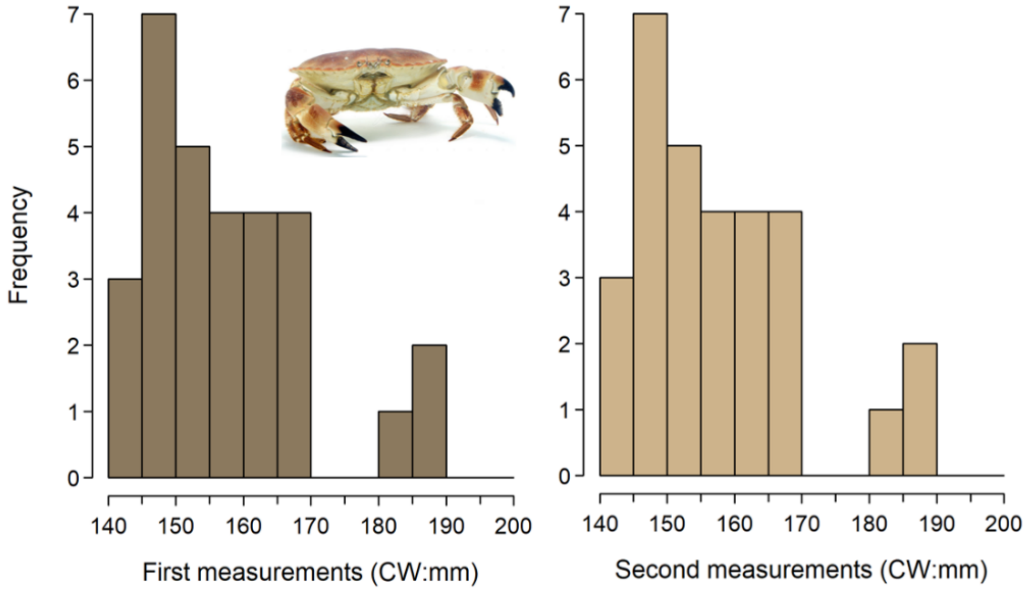

Figure 30: Size frequencies resulting from two sets of repeat Real brown crab size measurements (CW; n=30), measured in situ by a single observer (JE).

No intra-observer effect was observed between the two repeat crab sex allocations and black spot assessments made by the single observer *in situ*. The percentage of crabs allocated as male and female in the first set of assessments was in agreement with the percentage of crabs allocated as male and female in the second assessment (Female=40%, Male=60%, n=30). As were the percentage of crabs assessed as having black spot (first assessment:30%, second assessment:30%, n=30).

4.3.2 Inter and intra-analyst effect

An inter and intra-analyst effect was observed in the still rejection rate; with the choice of whether or not to reject a still changing between repeat analyses of the same set of stills by the same analyst, as well as differing between analysts. The mean error in the Still trait measurements (±SD) are shown for each analyst, for all the stills that were measured three times by all three analysts (Figures 31 to 32).

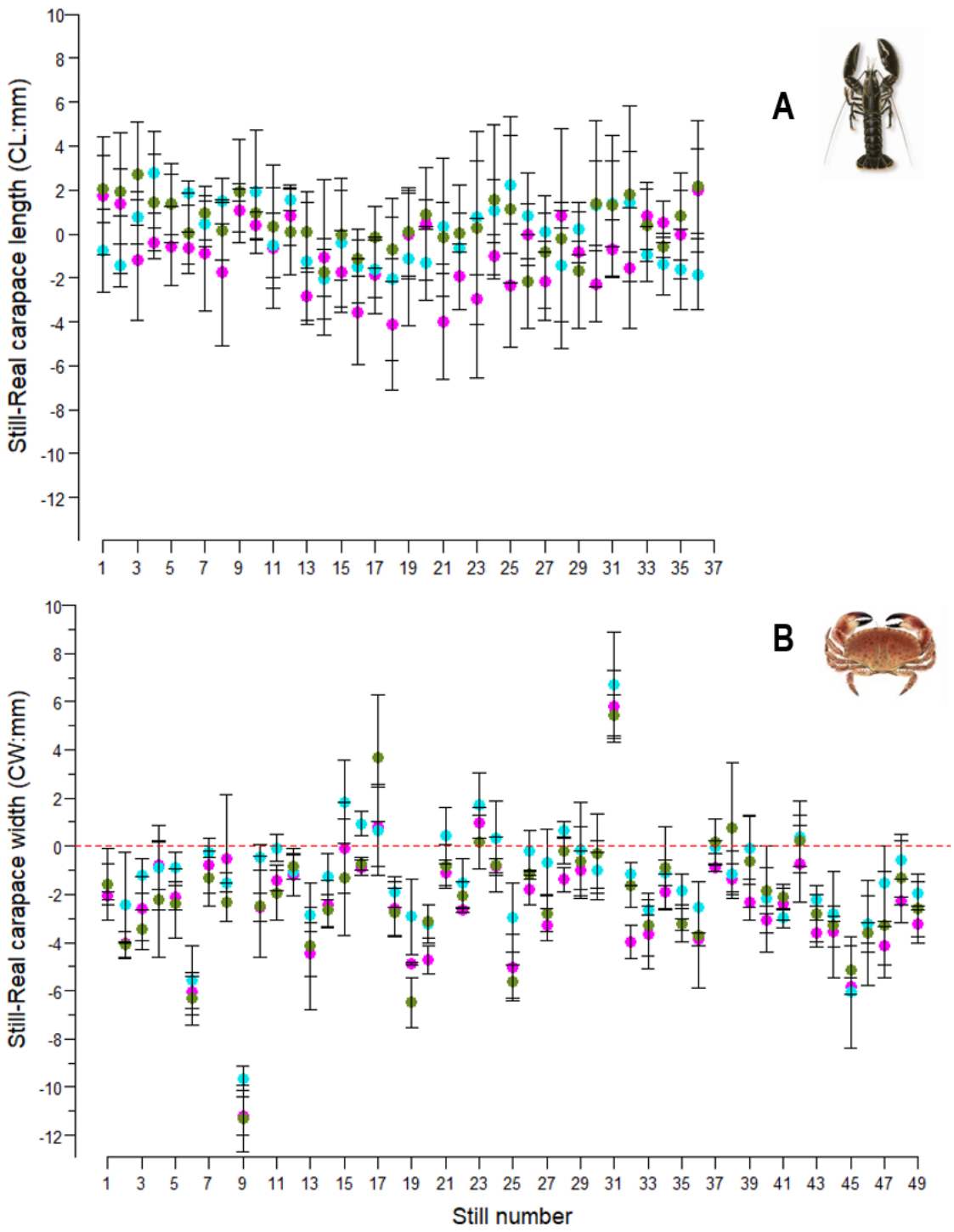

Figure 31. The mean error in three repeat Still trait measurements ((Still-Real trait size) ± SD) performed by three analysts using parallel lasers as a reference sale, during an investigation into the intra-analyst effect in Still trait measurements (A: European lobster CL± SD; B: brown crab CW± SD). Analyst identity is indicated by colour (pink: CL, blue: JE and dark green: SM). The corresponding Real trait size was measured by an observer in situ (European lobster: n=36, brown crab: n=49). The red dotted line represents the perfect relationship, i.e. no difference between the Real and Still trait measurements.

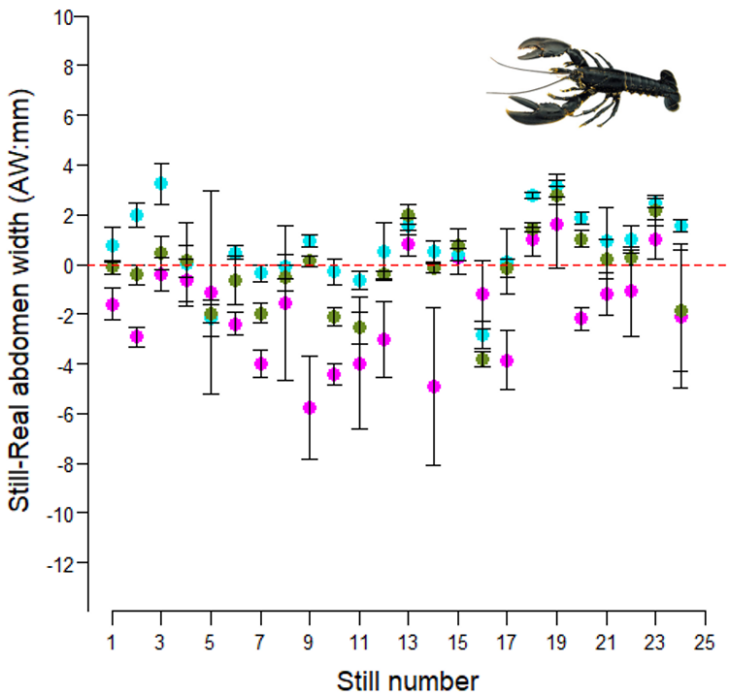

Figure 32: The mean error in three repeat Still abdomen width measurements ((Still AW-Real AW) ± SD) performed by three analysts using parallel lasers as a reference sale, during an investigation into the intra-analyst effect in European lobster Still AW measurements. Analyst identity is indicated by colour (pink: CL, blue: JE and dark green: SM).). The corresponding Real AW size was measured by an observer in situ (n=24). The red dotted line represents the perfect relationship, i.e. no difference between the Real and Still AW measurements.

The intra-analyst effect for all three analysts (CL, JE and SM), was greatest for the crab CW, as indicated by a mean Still measurement error of between -1.3 and -2.4. The trait with the smallest intra-analyst effect varied depending on the analyst identity: for CL and SM it was the carapace length of lobster, whilst for JE it was the abdomen width of lobster. Although this suggests that the intra-analyst subjectivity in determining the start and end of the three traits was greatest for the CW of crab, it should be noted that the set of crab stills and the set of lobster stills were extracted from footage recorded by different camera units (lobster: Camera 2; crab: Camera 3). Subjectivity in the identification of anatomical features can be influenced by properties of the individual camera sensors (Butler *et al.*, 1998; Galbany *et al.*, 2016).

For all three traits, ANCOVA showed that there was a significant effect of the analyst identity on the linear relationship between the Real and Still trait size, suggesting that all analysts need to collect data to validate their own linear predictive models before undertaking analysis of stills taken using the on-board cameras. Anova for model selection determined

that the preferred predictive model with the highest power to explain the inter-analyst effect in the variance in the Real trait size was **Model 4** for CL (R^2=0.72, $F=_{(3,212)}$=1875, p<0.001) and the simpler model **Model 5** for AW (ANCOVA: R^2=0.96, $F=_{(3,212)}$=1875, p<0.001) and CW (ANCOVA: R^2= 0.98, $F_{(3,497)}$=7716, p<0.001)

Real trait size ~ Still trait size * Analyst identity **Model 4**

Real trait size ~ Still trait size + Analyst identity **Model 5**

36% of the crabs (n=73) used to investigate the inter and intra-analyst effect were assessed as having black spot by the observer *in situ*. For both analysts (JE and SM), none of the repeat Still black spot assessments were in complete agreement with each other. There was considerable intra-analyst variability in the results of repeat assessments made by SM (Figure 33).

There was also considerable inter-analyst variability in the number of crabs incorrectly assessed as having black spot in repeat Still assessments, (JE: mean (±CV) = 1.0±1.7%; SM: mean (±CV) =14±1.0%, n=73) and less inter-analyst variability in the number of crabs correctly assessed as having black spot (JE: mean (±CV) = 7±0.2%; SM: mean (±CV) =10±0.6%, n=73). In any particular assessment, both analysts were likely to underestimate the total percentage of the catch that was infected, by between 13% and 32% (n=73).

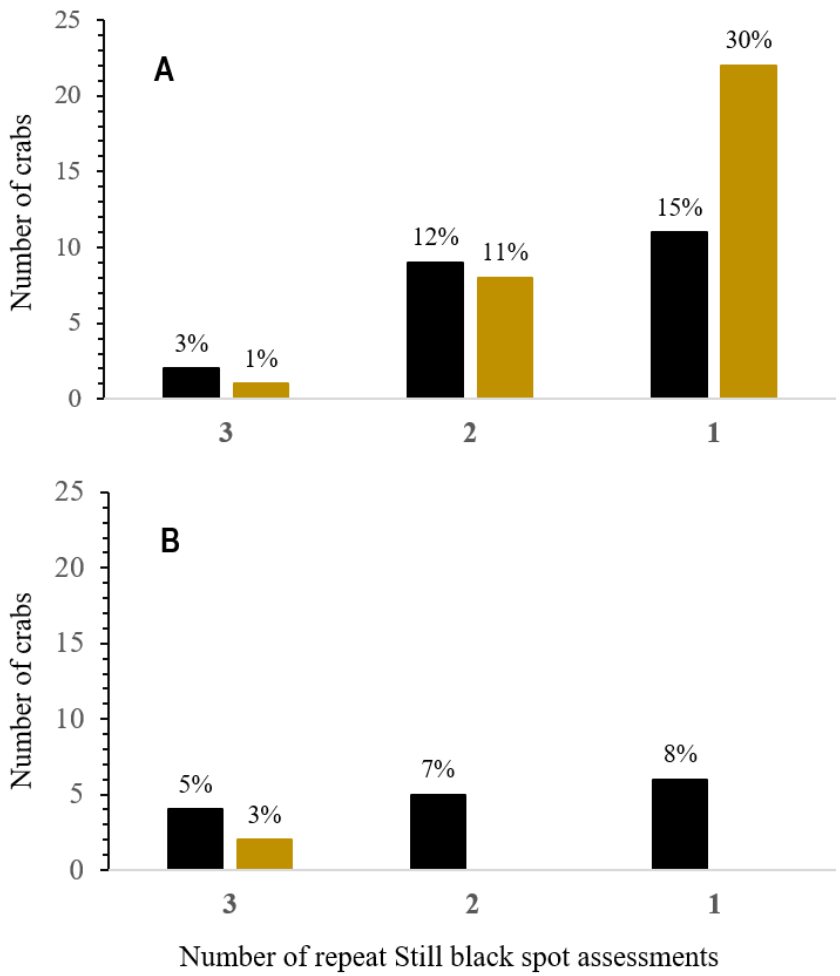

Figure 33: The number of brown crabs correctly (black bars) and incorrectly (brown bars) assessed as having black spot (shell disease) in all three (3), two out of three (2) and one out of three (1) repeat black spot assessments made from dorsal and ventral still images (Still black spot assessments) of 73 crabs, during an investigation into the intra-analyst effect in Still black spot assessments. Analyst identity is indicated by the letters (A: SM, B: JE). The accuracy of the Still assessments were assessed against black spot assessments of the same individuals made by an observer (JE) *in situ*. Percentages above the bars are the percentages of the total catch correctly (percentages above the black bars) and incorrectly (percentages above the brown bars) assessed as having black spot, in each repeat assessment. The total percentage of the catch assessed as having black spot in each repeat assessment can be calculating by adding the numbers above the black and brown bars. 36% of the catch was assessed as having black spot by the observer *in situ.*

4.3.3 Comparison of intra-observer and intra-analyst variability

The observer who collected the data used to investigate the intra-observer effect was one of the analysts who participated in the investigation into the intra-analyst effect (JE). In order to compare the intra-observer and intra-analyst effect, Kolmogorov-Smirnov tests were performed on all possible combinations of the three Still crab size frequencies obtained by the observer (JE) during the investigation into the intra-analyst effect. The results of these tests are presented in Table 10 alongside the result of the Kolmogorov-Smirnov test used to

determine the intra-observer effect in the set of two repeat Real crab size frequencies (section 4.3.1).

Table 10: The results of the non-parametric Kolmogorov-Smirnov test between the two sets of Real brown crab size (CW) frequencies measured by a single observer (JE) in situ. Also presented are the results of Kolmogorov-Smirnov tests between all possible combinations of the three sets of Still CW frequencies measured from still images (stills) by the same observer (JE) using paired lasers as a reference scale, during an investigation into the intra-analyst effect in Still CW measurements.

Species	Measurement set numbers	Kolmogorov-Smirnov test		
	Real sets	**n**	**D**	**p-value**
Brown crab	1&2	30	0.07	1.00
	Still sets	**n**	**D**	**p-value**
	1&2	49	0.06	1.00
	1&3	49	0.07	1.00
	2&3	49	0.06	1.00

Comparison of the Kolmogorov-Smirnov test results indicated that there was no significant intra-observer or intra-analyst effect for repeat Real and Still crab size frequencies measured by the same observer/analyst.

There was a small amount of intra-analyst variability in the total percentage of the catch that was assessed as having black spot in the three repeat Still black spot assessments (mean ±CV = 8.0±0.1%, n=73) compared to no intra-observer variability in the percentage of the catch that was assessed as having black spot in the two repeat *in situ* black spot assessments performed by the same observer/analyst (first assessment:30%, second assessment:30%, n=30).

4.3.4 Still selection

The effect of still selection on the precision of Still trait measurements was on average least for the CW of crabs, as indicated by the smallest mean coefficient of variation (CW: mean CV=1.4). Likewise, the effect of still selection on the precision of Still trait measurements was on average the greatest for lobster AW, as indicated by the largest mean coefficient of variation (AW: mean CV=2.9).

Still selection had the greatest effect on the accuracy of the Still AW measurements and the smallest effect on the accuracy of the Still CW measurements, as indicated by the variance of the respective Still trait measurements about the ideal relationship between the Real and Still trait size (Figures 34 and 35).

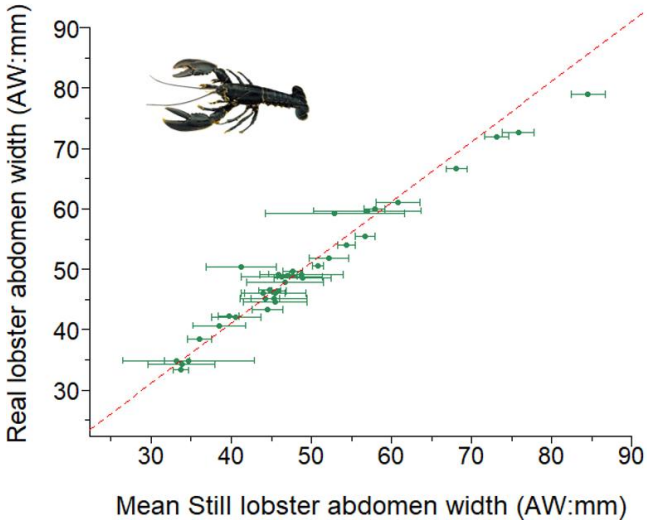

Figure 34: The mean European lobster abdomen width (AW±CV) of three measurements made from three different still images of the same animal (the mean Still lobster AW) using parallel lasers as a reference scale, plotted against the corresponding Real AW measured by an observer in situ (n=36). The red dotted line represents the perfect relationship between the Real and Still measurements, i.e. Real AW equals Still AW.

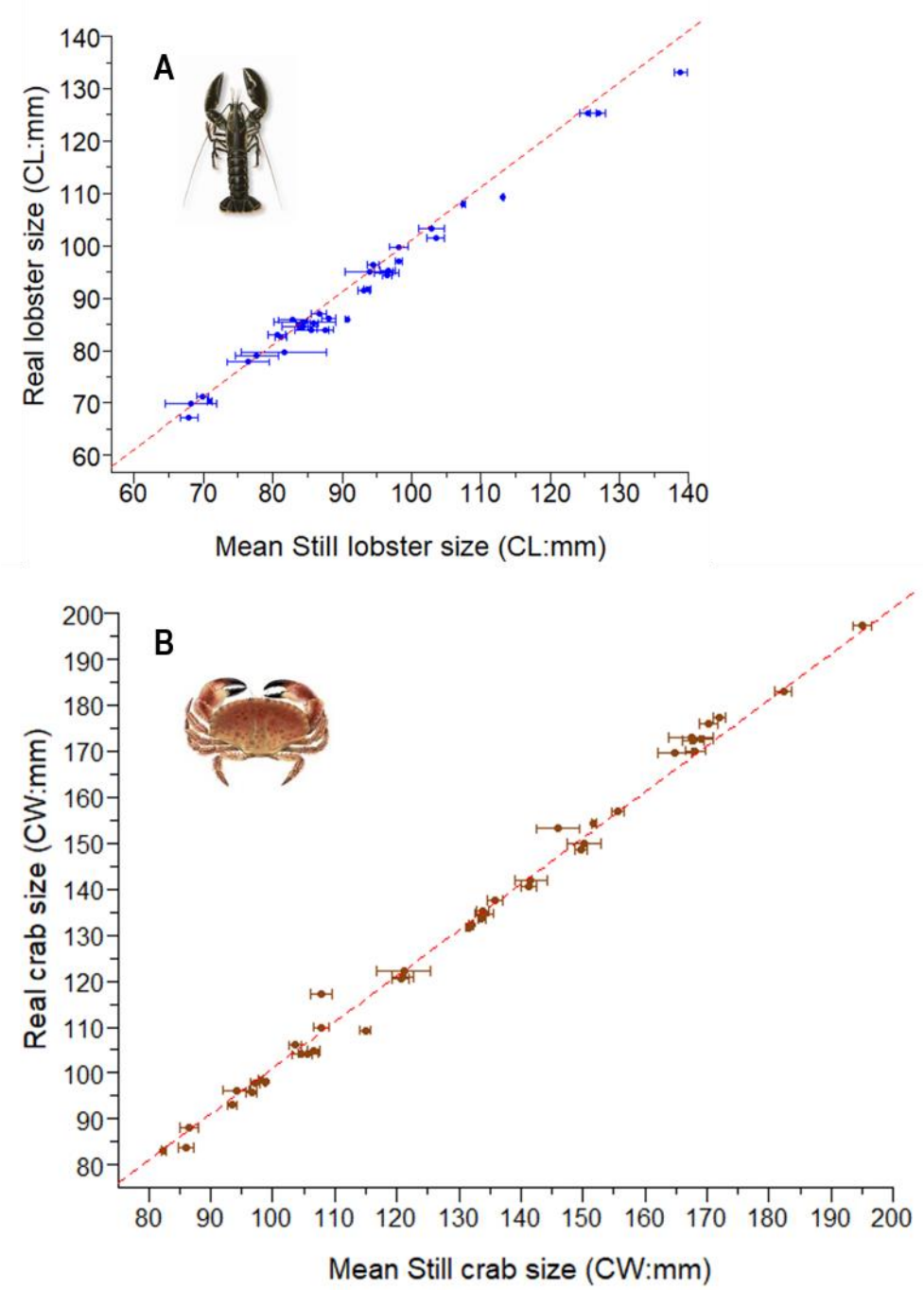

Figure 35:The mean European lobster carapace length (A: CL±CV) and mean brown crab carapace width (B: CW±CV) of three measurements made from three different still images (stills) of the same animals (the mean Still crab size and mean Still lobster size respectively) using parallel lasers as a reference scale, plotted against the corresponding Real trait size measured by an observer in situ (crab: n=42; lobster: n=36), The red dotted line represents the perfect relationship between the Real and Still measurements, i.e. Real size equals Still size.

Dependent on still selection and as a result the accuracy and precision of the Predicted AW and CL, the sex of an individual lobster could be misallocated (Figure 36), as indicated by the variance of the Predicted AW and CW trait sizes about the line that represents the ideal ratio

cut-off between male and female lobsters ($AW = 0.52 * CL$). However, based on the ratio of the mean Predicted AW and CL measurements, lobsters were assigned the correct sex 86% of the time (n=21).

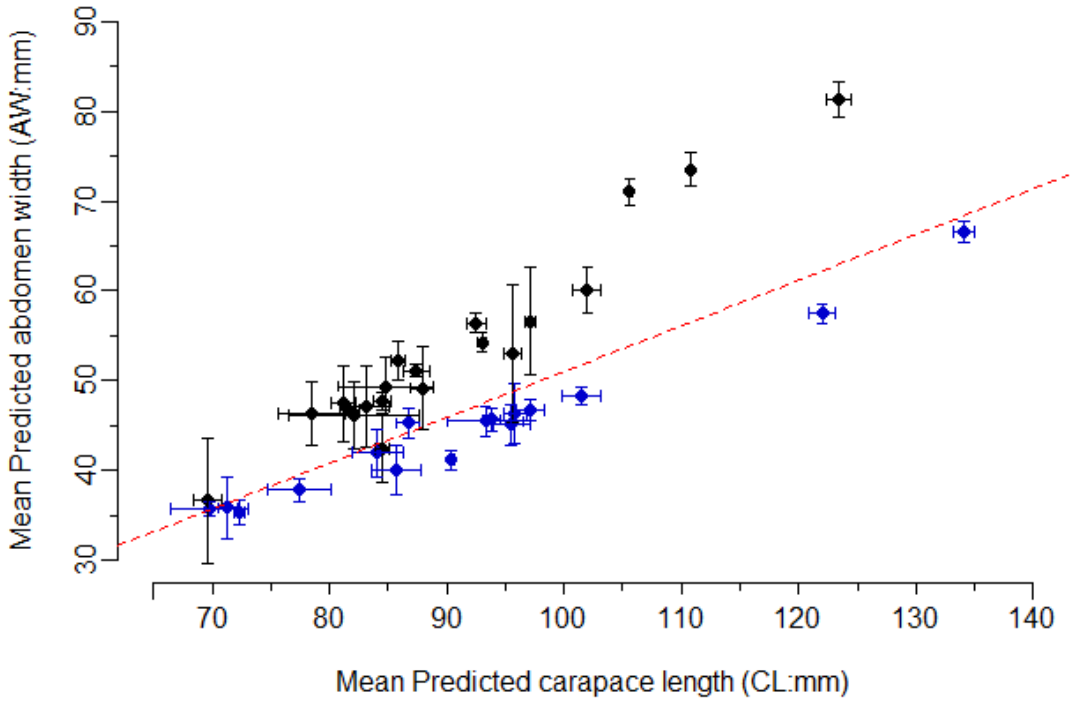

Figure 36: Mean Predicted AW(±CV) plotted against mean Predicted CL (±CV) for 21 lobsters measured three times, from three different sets of dorsal and ventral still images (stills) All the still measurements were performed by a single analyst, using lasers as a reference scale. during an investigation into the effect of still selection on the accuracy of the Predicted AW:CL ratio at allocating sex to lobsters. The colour indicates the Observed sex of each lobster, determined by a visual assessment of the dimorphic pleopod pairs made by a single observer in situ (blue: male, black: female). The red dotted line represents the ideal ratio cut-off value between male and female lobsters ($AW = 0.52 * CL$) determined from in situ measurements taken during the calibration process of all three on-board cameras and as part of an investigation into the size of maturity (SOM) of lobster in the Isle of Man (Emmerson, unpublished data). Error bars or points above the dotted line represent lobsters that were determined to be female according to the Predicted AW:CL ratio, whilst error bars or points below the dotted line represent lobsters that were determined to be male according to the Predicted AW:CL ratio.

4.4 Fishery-dependent data

4.4.1 Fishery still rejection

During the fishery-dependent data collection period of February to June 2017, a total of 3061 individuals were presented to the camera comprising 2230 crabs and 831 lobsters. On Vessels 1 and 2, the same fisher passed the animals under the camera, whilst on Vessel 3, apart from a few animals during periods of large catch, the same fisher passed the animals under the camera. As a result, fisher identity was excluded as a factor in the number of rejected fishery stills.

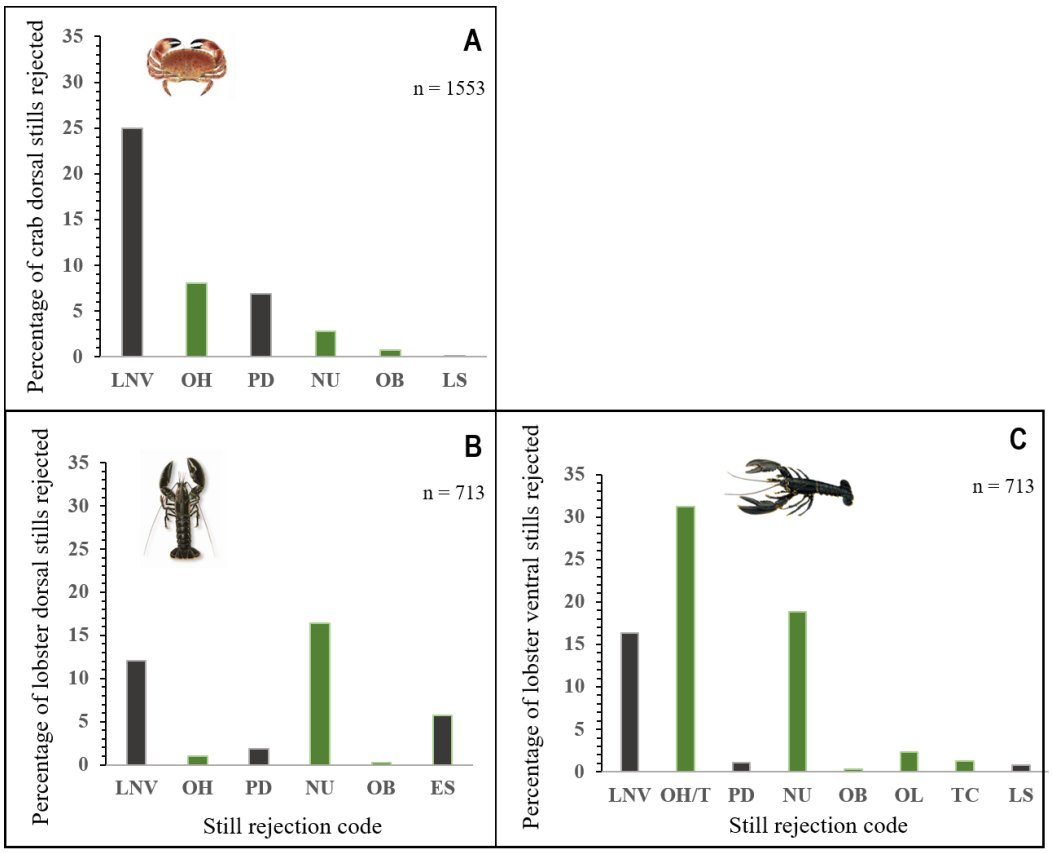

Figure 37: Percentage histograms of the codes assigned to still images (stills) taken by the three on-board camera units during the fishery-dependent data collection program, to explain the reason for still rejection and as a result the reason why a trait (A: brown crab CW, B: European lobster CL and C: European lobster AW) could not be measured for an individual animal. **LNV:** one or both lasers not visible on the trait of interest or anywhere in the still; **OH:** edge of the CW, end of the CL or edge of the AW obscured by fishers' hand; **OH/T:** the edge of the AW obscured by the fisher's hand whilst the lobster is held at an angle that is not perpendicular to the axis of one or both of the lasers; **PD:** poor definition of the CW edge, end of the CL or the AW edge; **NU**: animal not presented to the camera; only one side of the animal presented, or the animal presented so that one or both of the lasers are projected onto the defined surface rather than the trait; **OB:** edge of the CW, start or end of the CL or edge of the AW obscured by shadow or inanimate object, such as seaweed or the string; **LS:** one or both of the laser projections split or dispersed when projected onto the trait of interest; **ES:** poor definition of the eye socket, used to demarcate the start of the CL; **OL:**:edge of the abdomen obscured by the leg of the animal; **TC:** tail fan is curled when the lobster is presented to the camera. The still rejection codes are grouped according to human error and error as a result of the photogrammetric apparatus (green: human error, dark grey: apparatus).

When all the cameras were operating without condensation in the camera housing, the lobster fishery stills were primarily rejected due to human error. Lobster not being presented to the camera properly was the predominant reason why CL could not be measured from the dorsal stills (Figure 37 and 38), i.e. the dorsal side was presented so that one or both of the lasers were projected onto the defined surface rather than the trait, only the ventral side was presented or the individual was not presented at all. With regard lobster AW, the majority of lobster ventral stills were rejected because the edge of the abdomen was obscured by the fisher's hand whilst the lobster was held at an angle that was not perpendicular to the axis of one or both of the lasers. Whilst crab dorsal stills were predominantly rejected as a result of one or both lasers not being visible on the carapace of the crab as a result of bright sunlight or difficulty distinguishing the laser projections from the colouration of, or markings on the carapace (Figure 38). However, for all three traits, there was a degree of subjectivity in coding the reason for still rejection; there were multiple reasons why some stills could have been rejected.

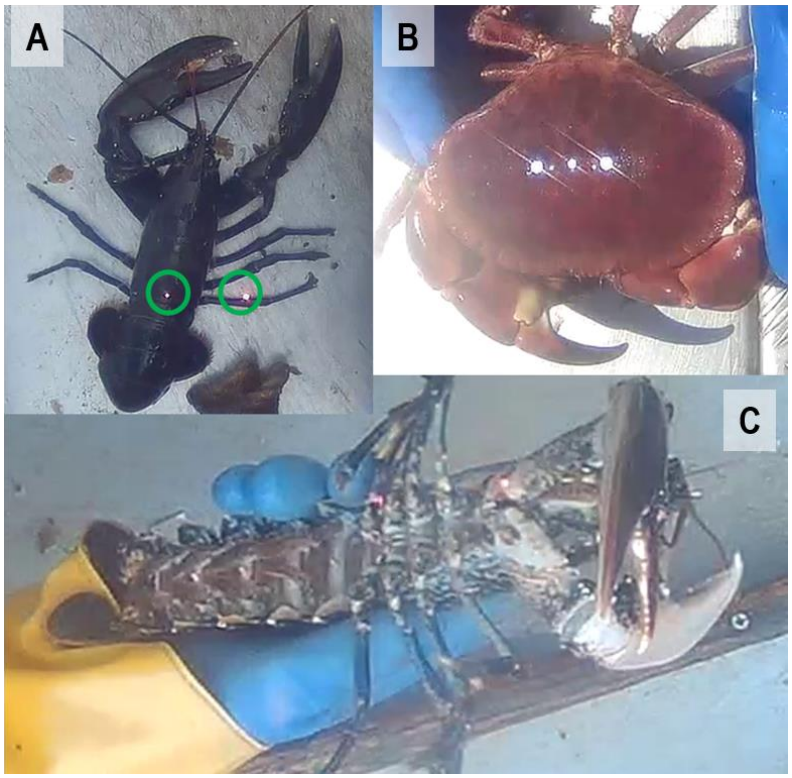

Figure 38:Still images (stills) showing the predominant reasons for the rejection of dorsal and ventral stills taken by the three on-board cameras during the fishery-dependent data collection program in the Isle of Man Crustacean Fishery, February to June 2017, and as a result the reason why a trait (A: European lobster: CL, B: brown crab CW and C: European lobster AW) could not be measured remotely using parallel lasers as a reference scale. A a European lobster dorsal still rejected due to the individual not being presented to the camera correctly, i.e. one of the laser projections (circled in green) was projected onto the defined surface rather than the CL; B: a brown crab dorsal still, rejected due to the red laser projections not being visible on the carapace, as a result of bright sunlight and/or difficulty distinguishing the projections from the colouration of the crab; C: a lobster ventral still rejected because the fisher's hand was obscuring the edge of the AW whilst the lobster was held at an angle that was not perpendicular to the axis the lasers.

When all the cameras were operating without condensation, 1% (n=1586) of crabs could not be sexed from the fishery stills or video footage. Whilst 80% (n=718) of lobsters could not be sexed from the fishery stills: 4% as a result of dorsal still rejection; 31% as a result of ventral still rejection and 33% as a result of the rejection of both dorsal and ventral stills. The predominant reason that a crab could not be sexed from the ventral still was due to sunlight reflecting of the abdominal flap:<1% (n=1586; Figure 39).

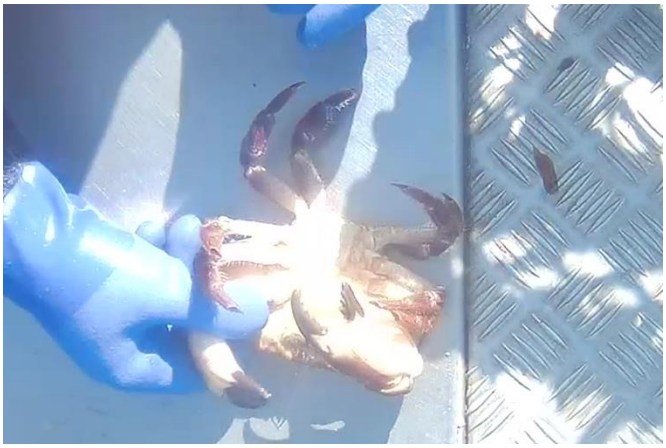

Figure 39: Ventral still image (still) of a brown crab showing the difficulty sexing a crab if sunlight is reflecting of the abdomen. This still was extracted from footage taken by the on-board camera unit: Camera 3 during the fishery-dependent data collection program in the Isle of Man Crustacean fishery, February to June 2017.

4.4.2 Data applications

During the fishery-dependent data collection program it was up to the discretion of the fishers when they used the cameras and how much of the catch they recorded. The number of strings and traps recorded by the analyst during the fishery-dependent footage analysis are presented in Table 11, along with the information that the analyst estimated could be taken from each day's footage. For example, the fate of both crabs and lobsters was always decided in the FOV of only one camera: Camera 1. As a result, the analyst determined that size frequencies of landed crab and lobster could only be obtained from footage taken by this camera. Observer trips may be needed to verify the accuracy of fishery-dependent footage analysis at determining the information in Table 11

.

Table 11: The number of strings and traps recorded by the analyst during analysis of footage recorded by the three on-board camera units during the fishery-dependent data collection program in the Isle of Man Crustacean Fishery, February to June 2017. Green crosses indicate information that the analyst estimated could be taken from a day's footage, whilst red indicates information that the analyst estimated could not could be taken from each day's footage. Size freq is an abbreviation for size frequency. Observer trips may be needed to verify the accuracy of fishery-dependent footage analysis at determining the information in the table. Subscripts explain why less information could be taken from a particular day's footage (R: High lobster dorsal still rejection rate; S: bright sunlight; C: condensation in the camera housing)

Vessel Code	Date (day/month)	No. strings	No. traps	Crab and lobster		Crab			Lobster		
				Habitat associations	Damage	Size freq caught	Size freq landed	Sex ratio	Size freq caught	Size freq landed	Sex ratio
1	07/04	2	20	X	X	X	X	X	X	X	X
1	25/04	2	20	X	X	X	X	X	X	X	X
1	27/04	5	7-20	X	X	X	X	X	X	X	X
1	04/06	3	13-19	X	X	X	X	X	X	X	X
1	25/06	1	25	X	X	X	X	X	X	X	X
1	29/06	6	13-23	X	X	X	X	X	X	X	X
1	30/06	5	13-25	X	X	X	X	X	X	X	X
2	05/02[R]	14	15-12	X	X	X	X	X	X	X	X
2	26/04[R]	4	7-10	X	X	X	X	X	X	X	X
2	28/05	5	4-10	X	X	X	X	X	X	X	X
3	09/03	3	14-20	X	X	X	X	X	X	X	X
3	28/04[S]	4	7-23	X	X	X	X	X	X	X	X
3	09/05	4	16-20	X	X	X	X	X	X	X	X
3	10/05	3	14-20	X	X	X	X	X	X	X	X
3	12/05	7	12-24	X	X	X	X	X	X	X	X
3	25/05[C]	4	6-18	X	X	X	X	X	X	X	X
3	26/06[C]	4	16-20	X	X	X	X	X	X	X	X

ArcGIS was used to create a heat map of the observations of the target species collected throughout the fishery-dependent data collection program (Figure 40). For each Port Erin grid square, the environmental variables associated with the observations are summarised in Table 12.

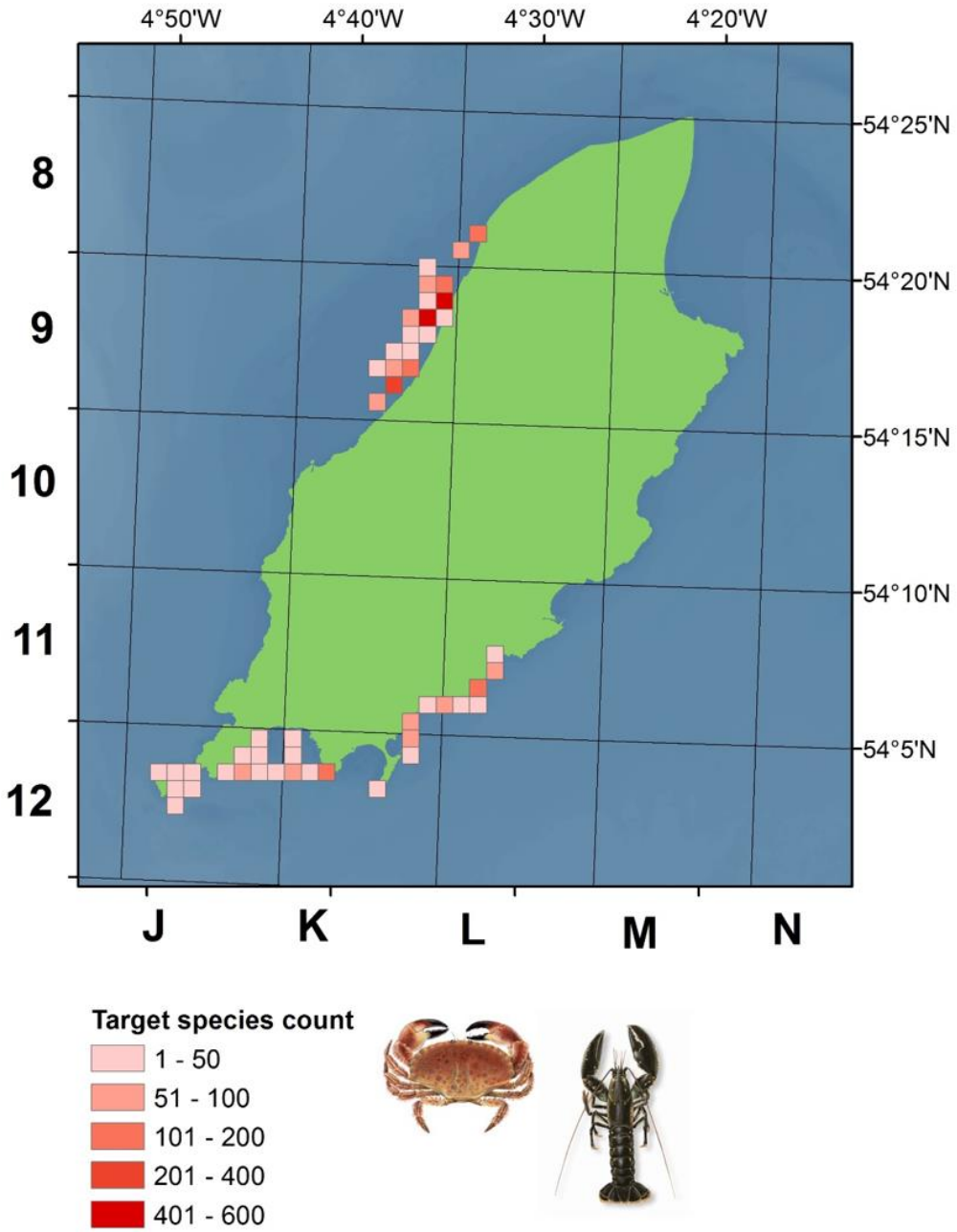

Figure 40: A heat map showing the observations of the target species (brown crab and European lobster) in each Port Erin grid square, observed in footage collected by three on-board cameras during the fishery-dependent data collection program in the Isle of Man Crustacean Fishery, February to June 2017. N.b. target species count is not representative of catch per unit effort.

Table 12: Table summarising the environmental variables associated with observations of the target species (European lobster and brown crab) in each Port Erin grid square. The observations were recorded by three on-board cameras during a fishery-dependent data collection program in the Isle of Man Crustacean Fishery, February to June 2017.

Port Erin grid square	**Environmental variables**		
	Mean bathymetry (m)	**Range of median particle sizes (mm)**	**Mean benthic production (g WM m^{-2})**
K12	-7.8	0.6-1.6	0.0
L9	-9.0	1.2-2.0	71.0
L11	-8.0	1.6-1.8	0.0
L12	-8.2	1.6-1.7	11.1
M8	-14.9	1.3-1.9	113.7
M11	-7.4	1.0-2.0	0.0

The utility of the cameras in investigating the spatial and temporal variations in the sex ratio of crab around the Isle of Man was demonstrated by creating pie charts for each month and each Port Erin grid-square within which fished traps fell. Pie charts were only created for a particular month and grid square if the number of observations of crab was greater than 10. The number of female crabs caught in traps was greatest in April which, agrees with fishers' observations. (Figure 41).

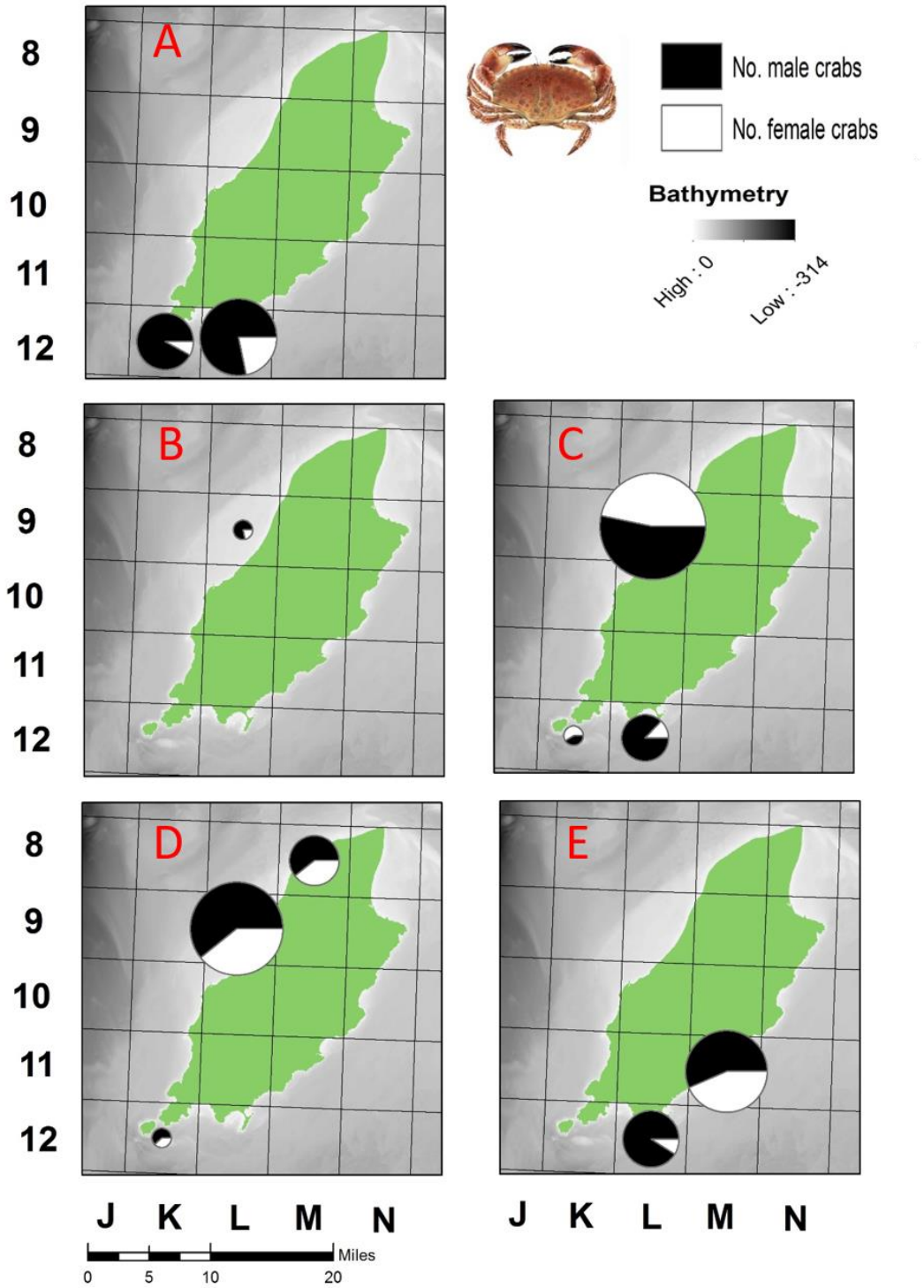

Figure 41: Seasonal and temporal variation in the sex ratio of brown crab around the Isle of Man. Sex ratio data was collected using three on-board cameras during a fishery-dependent data collection program in the Isle of Man Crustacean Fishery, February to June 2017. Pie charts were only created for a particular month and Port Erin grid square if the number of observations of crab was greater than 10 (A: February; B: March; C: April; D: May; E: June). The pie chart size is proportional to the number of observed crab.

The temporal variation in the crab and lobster size frequencies for one Port Erin grid square are presented as an example of the outputs that could be produced using size measurements obtained utilising parallel-paired lasers in on-board camera systems (Figures 42 and 43).

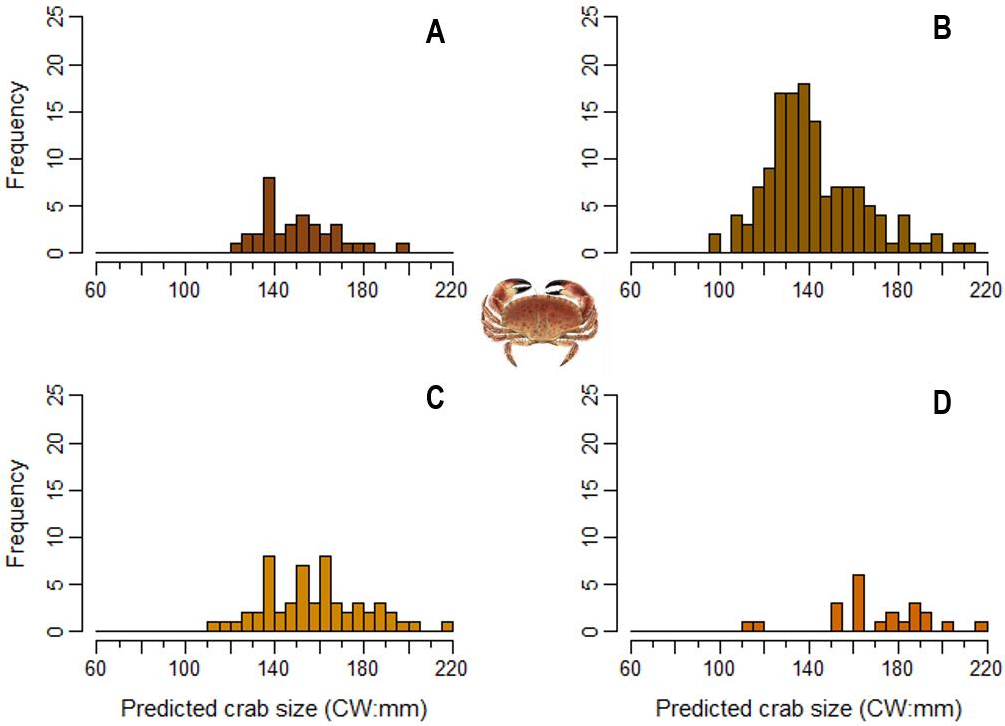

Figure 42: The temporal variation in the size frequency of brown crab in one Port Erin grid square: L9. (A: February; B: April; C: May; D: June) measured remotely using paired lasers as a reference scale. The size frequency data was collected by three on-board cameras during a fishery-dependent data collection program in the Isle of Man Crustacean Fishery, February to June 2017. Histograms are only shown for months when there were more than 10 observations.

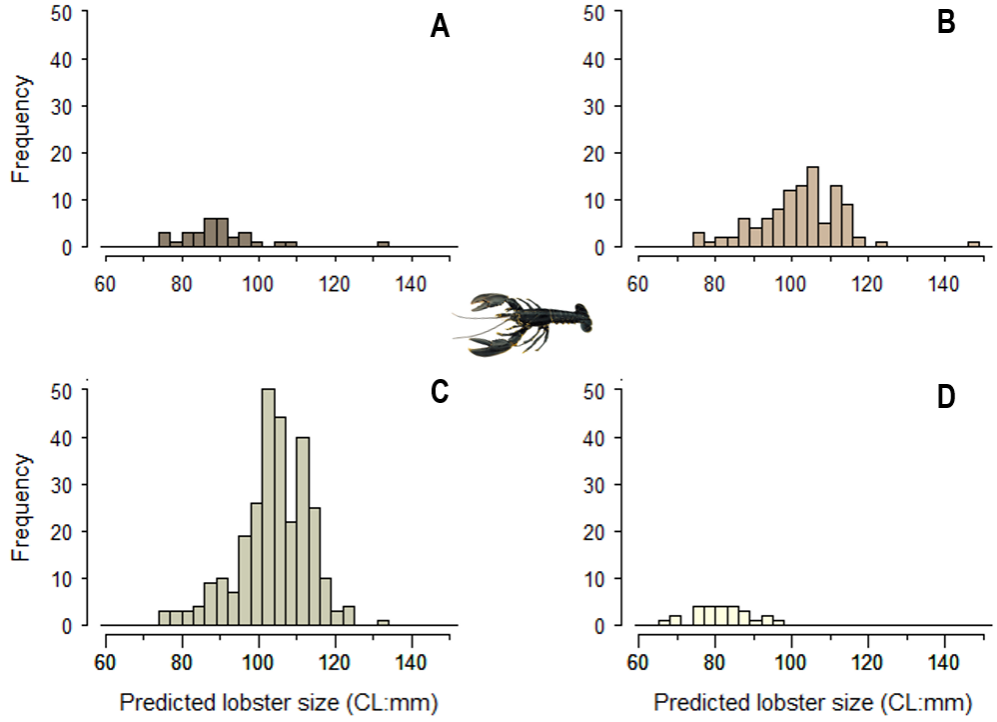

Figure 43: The temporal variation in the size frequency of European lobster in one Port Erin grid square: L9. (A: February; B: March; C: April; D: June) measured remotely using paired lasers as a reference scale. The size frequency data was collected using three on-board cameras during a fishery-dependent data collection program in the Isle of Man Crustacean Fishery, February to June 2017. Histograms are only shown for months when there were more than 10 observations.

Although fishers were not asked to pass bycatch into the FOV of the cameras, examples of bycatch that was recorded by one of the on-board cameras: Camera 1, are presented (Figure 44). Species names are not given as the accuracy of species identification from footage taken by the on-board cameras needs to be verified.

Figure 44: Examples of bycatch that was recorded by one of the three on-board cameras: Camera 1, during the fishery-dependent data collection program in the Isle of Man Crustacean Fishery, February to June 2017. Species names are not given as the accuracy of species identification from footage taken by the on-board cameras needs to be verified.

5.0 Discussion

5.1 *In situ* calibration of the individual camera units

The present study utilised the third generation of on-board cameras trialled by Bangor University, the second generation to utilise parallel laser photogrammetry. An error is introduced when a trait is measured remotely from a still. Unlike in Cambiè *et al.* (2016) the present study found that it was necessary to include the camera identity as a factor when modelling the relationships between Still trait measurements and the corresponding Real trait measurements. This could be due to inter and intra-study differences between the camera units and installations. The three cameras utilised in the present study were mounted at approximately 100cm (Cameras 2 and 3) and 140cm (Camera 1), whereas the two cameras utilised by Cambiè *et al.* (2016) were both mounted at approximately 80cm.

For all the traits, the error in Still measurements tended to be greatest for the camera with the greatest mounting height: Camera 1, for similar Real trait sizes. This could be due to the fact that larger camera mounting heights require greater camera resolution to produce the same image quality as cameras mounted at smaller heights (Cambiè *et al.*, 2016). Poor video resolution can be associated with error in Still measurements (Hold *et al.*, 2015). Stills taken by Camera 1 were of poorer resolution than stills from the other two cameras, evidenced by the largest number of calibration stills rejected due to poor definition of all three traits. In the present study, the camera identity and as a result the mounting height by proxy, was treated as a factor. The optimal trade-off between video resolution and the camera mounting height could be established by investigating the effect of height as an independent variable.

For crab, a significant or near significant negative relationship between the error in the Still CW and the Real CW was observed for all the cameras. Contrastingly, the error in lobster traits decreased or increased significantly with the Real trait size if stills were taken by Cameras 1 and 3 respectively. For all the traits, changes in the magnitude of the error in Still measurements with Real trait size could be due to non-parallelity of the lasers. A change in the laser separation distance with the height of the trait above the defined surface results in an error being introduced into the laser scale. This error changes with the height of the trait and introduces an error into Still trait measurements made using the laser scale as a reference. The height of the

trait above the defined surface was determined by the varying height at which each animal was passed into the FOV of the camera and the body depth of each individual, which increased with increasing CL or CW (Cambiè *et al.* 2016; Hold *et al.* 2015). In addition, measurements of the largest trait sizes required large extrapolations beyond the laser scale, which could have resulted in a magnification of any measurement error in the laser scale (Galbany *et al.*, 2016).

A non-significant change in the error in Still CL with Real CL size was observed for Camera 2. This could be indicative that an insufficient sample size and size range of lobster were used to calibrate this camera, resulting in insufficient statistical power to detect a significant change in the error in Still CL with Real CL. To accurately determine the predictive model for all the traits it would have been preferable to calibrate each camera using stratified sampling per 5mm size class of both crab and lobster, spanning the size range of animals that are caught in traps. It would also have been preferable to use an equal number of each species to ensure that the ANCOVA for each trait was balanced, so that there was sufficient power to detect significant effects of any terms before they were dropped during the process of predictive model simplification.

The preferred predictive model tended to overestimate the Real CW and Real AW slightly. Whilst the preferred predictive CL model tended to underestimate the Real CL slightly. Once the respective predictive models were applied to measurements taken directly from the stills, the residual error structure was greatest for the Predicted crab CW dataset. Like Cambiè *et al.* (2015), outliers in the CW residual error structure, characterised by a magnitude greater than 5mm, were attributed to the error associated with measurements taken directly from the stills rather than inaccuracy in the Real trait size recorded *in situ*. The magnitude of the error attributable to measuring an individual remotely rather than directly was less than 5 mm for lobster CL and less than 9mm for crab CW, which is sufficient to detect growth increments in both species, as hypothesised (Bennett, 1973; Agnalt *et al.*, 2007).

5.1.1 Condition assessment

The present study validated the potential of using the cameras to assess damage to the target species. Discarded healthy shellfish are thought to have high survivability, whereas the survivability of damaged individuals is thought to be much lower (Course *et al.*, 2015). When damage was quantified by the number of missing claws, the calibration still analysis was 100% accurate at assessing damage to lobsters. However, the sample size of damaged

lobsters was small (n=5). When damage was quantified by the number of lost claws and legs and damage to the exoskeleton, still analysis was found to slightly overestimate the number of damaged crabs; 22% were assessed as damaged during the calibration still analysis process compared to 19% *in situ* (n=195). Indicating that footage from the on-board cameras could be used quantify the damaged and undamaged components of the crab catch, as hypothesised. Quantification of the undamaged component can provide an indication of recruitment and the health of the stock., whilst quantification of the damaged component can be considered an index of mortality rather than recruitment (Course *et al.*, 2015).

The present study found that Still black spot assessments were not an accurate method for remotely assessing the presence of black spot in crabs. The investigation into the inter and intra-analyst effect found that the percentage of infected animals was likely to be underestimated, by between 13% and 32% (n= 73). There was subjectivity in distinguishing black spot lesions from the natural colouration of the carapace in both the Still black spot assessments and assessments made by the observer *in situ*. In the Still assessment, there was the added difficulty of not being able to view potential lesions at different angles and in different lights. Analyst training could help mitigate some of this subjectivity. Alternatively, fishers could be asked to indicate to the camera that an individual is infected before it is held in position under the camera.

Analysis of the fishery-dependent footage highlighted the potential for the cameras to be used to monitor the presence of shell disease in lobster (Figure 45). Still assessments for lobsters would need to be validated using a method similar to the one used in the present study for crabs.

Figure 45: Dorsal (left) and ventral (right) still images (stills) of a European lobster thought to be infected with shell disease. The lobster was recorded by the on-board camera unit: Camera 1, during the fishery-dependant data collection program in the Isle of Man Crustacean Fishery, February to June 2017.

5.1.2 The still extraction process

The still extraction process was the most time-consuming part of the calibration and fishery-dependent video analysis process. The time taken varied depending on the vessels specific fishing activities, the time that each individual animal was held under the camera and the number of animals in the traps, which varied seasonally. Precisely parallel lasers would reduce the still analysis time by enabling the Global option to be selected in the Set Scale function in ImageJ, in order to set the scale once for stills taken by the same camera unit. When the Global option was selected, the time taken to analyse a pair of dorsal and ventral stills decreased from approximately 20s and 35s to 10s and 15s for crab and lobster respectively. Once the cameras are rolled out on a sentinel fleet, only a sub sample of the footage for each catch will be analysed, rather than all the recorded strings as in the present study (Kaiser, 2017, pers. comm.). Work is currently in progress to automate the image extraction and measurement process.

The video analysis process could be sped up further if size frequency and sex ratio data could be automatically stored and linked to CPUE and spatial data. Course *et al.* (2015) successfully trialled the use of EM systems to provide catch estimates in Scottish inshore fisheries. The systems comprised on-board cameras and sensors to automatically collect effort data with little or no detriment to catch-handling procedures:

- hydraulic pressure sensors that recorded the location of every string that was shot or hauled;
- data storage tags that recorded soak time at the string level and provided temperature at depth data; and
- a radio frequency identification (RFID) tag system that recorded soak time at the trap and string level.

Archipelago Marine Research (AMR) analysis software (EMIPro) was used to automatically store and graph remote crab and lobster size estimations and link the estimations to the sensor data and mapped strings(Course et al., 2015, fig. 19).

5.2 Morphometric allocation of sex and size at maturity

As hypothesized, still analysis was 100% accurate at allocating sex to male and female crabs in all size classes and the Predicted AW:CL ratio was 100% accurate at allocating sex to female lobsters in all size classes over 80mm CL. Contrastingly, the AW:CL ratio was found to be an inaccurate method for allocating sex to male lobsters in most size classes

Hold *et al.* (2015) found that the Predicted AW:CL ratio was 100% accurate at allocating sex to male lobsters in all size classes and 100% accurate at allocating sex to female lobsters larger than 86mm CL (Hold et al., 2015, fig. 4). The observed differences in the accuracy of the Predicted AW:CL ratio between Hold *et al.* (2016) and the present study could be due to differences in the still measurement protocol. In addition to using a background reference scale instead of a laser scale, Hold *et al.* (2016) measured both the CL and AW from the dorsal stills. This meant that the same reference laser scale was used to measure both the CL and AW. As a result, any error introduced in to measurements of the CL and AW due to an error in the scale would have been the same for both traits, so would not have influenced the result of the calculated ratio. Whereas in the present study, different stills, and therefore different laser scales were used to measure each of the traits. As a result, different errors in the laser scales could have resulted in an error being introduced to the calculated ratio. In addition, observed difference could be due to anomalies skewing the relatively small sample sizes of males and females that could be sexed using the Predicted ratio in the present study compared to Hold *et al*. (2015): 68 and 32 males and 122 and 64 females in Hold *et al*. (2015) and the present study respectively.

Further, the present study found that the high fishery still rejection rate precluded the use of the Predicted AW:CL ratio for determining the lobster sex ratio and the SOM of female lobsters from the fishery-dependent footage. The accuracy of still analysis at determining if a lobster was berried was 100% (n=11). However, a larger sample of berried lobsters would need to be used to verify the potential of using the cameras to determine SOM by using the incidence of berried females in size-stratified samples to construct the maturity ogive. Berried crabs rarely enter traps (Ondes, 2015); only one was recorded during the fishery-dependent data collection program, in February (Figure 46). As a result, the cameras are not a useful tool for investigating functional maturity in crab, which is typically determined by the presence of eggs on females (Haig *et al.*, 2016).

Figure 46: Still image (still) of a berried (egg bearing) brown crab. The crab was recorded by the on-board camera unit: Camera 2 in February 2017, during the fishery-dependant data collection program in the Isle of Man Crustacean Fishery, February to June 2017.

As an alternative to the use of the AW:CL ratio, a system could be put in place whereby fishers sex each lobster *in situ* by a visual assessment of the pleopods and indicate the sex to the camera. For example, a set of two discs with a symbol for male and female could be put in the FOV of the camera. The disc that corresponds to the sex of each lobster could be covered by the fisher before the lobster is held in position under the camera.

5.3 Error and variability

5.3.1 Inter and intra-observer and analyst effect

For all the analysts, the greatest intra-analyst effect in Still measurements was observed for crab CW. The trait with the smallest intra-analyst effect varied depending on the analyst identity. Although this suggests that the intra-analyst subjectivity in determining the start and end of the three traits was greatest for the CW of crab, the set of crab stills and the set of lobster stills were taken using different camera units. Subjectivity in the identification of anatomical features can be influenced by properties of the individual camera sensors, including resolution (Butler *et al.*, 1998; Galbany *et al.*, 2016). For example, a "Halo effect"; a region of high intensity pixels was observed around the edges of some animals in the stills. This effect is caused by pixels on the camera sensor receiving too much light (Chen, 2015) and may increase the subjectivity in measuring lobster AW from stills, since the edges of the abdomen are often delineated by white markings (Figure 47). As a result, to compare subjectivity between the traits, all the crab and lobster stills should ideally be taken using the same camera unit.

Figure 47: Zoomed in still image (still) of the tail fan of a lobster showing two regions of high intensity pixels: a "Halo effect" (demarcated by yellow). This still was extracted from calibration footage taken by the on-board camera unit: Camera 3.

For all three traits, there was a significant effect of the analyst identity on the linear relationship between the Real and Still trait sizes. This suggests that all analysts need to

collect data to validate their own linear predictive model for each trait, before undertaking still analysis. For each trait, the effect of camera identity on the inter-analyst effect was controlled for by using stills taken by the same on-board camera unit (crab CW: Camera 2; lobster CL and AW: Camera 3). If analysts measure stills from multiple camera units, the predictive models for each trait may need to include both the analyst identity and the camera identity as factors.

5.3.2 Still selection

Similar to Jeffreys *et al.* (2013) who used laser photogrammetry to measure multiple *Rhincodon typus* (whale shark) traits, the present study found that the coefficient of variation of measurements of the same trait in different stills was on average greatest for the trait measurements that were most affected by the body angle and movement of the subject: the CL and AW of lobsters.

Variation in Still measurements as a result of still selection is influenced by differences in parallax distortion of the laser projections in each still. Two main potential sources of parallax were identified in the present study (pers. obs. Morgan): parallax as a result of the lasers being projected onto a curved or bumpy surface and parallax caused by the projection of the lasers on to a surface that was not perpendicular to the axis of one or both laser beams. The former source of parallax could have been caused by the natural curvature of the carapace of both the target species, the lasers being projected on to the tops of the legs of a lobster when the ventral side was being presented to the camera and as a result of the lasers being projected onto the flexed or moving tail fan of a lobster, when held both dorsal and ventral side up (Figures 48). Rothman *et al.* (2008) argued that if a target surface is curved or bumpy the known distance between the laser projections may be altered with no reliable correction factor. Whilst Jeffreys *et al.* (2013) found that variability caused by lateral flexion of a whale shark tail bending towards or away from the camera unit, could result in either an increase or decrease in Still measurements of the total length of the subject.

The latter source of parallax could have been caused by a combination of human error: the positioning of the animal under the camera (Figure 49) and a divergence or convergence of the lasers from the source, resulting in the lasers being projected onto the trait at an angle. As well as being a potential source of parallax, non- parallelity of the lasers makes the effect of

parallax harder to quantify, as it may vary with the height of the trait above the defined surface.

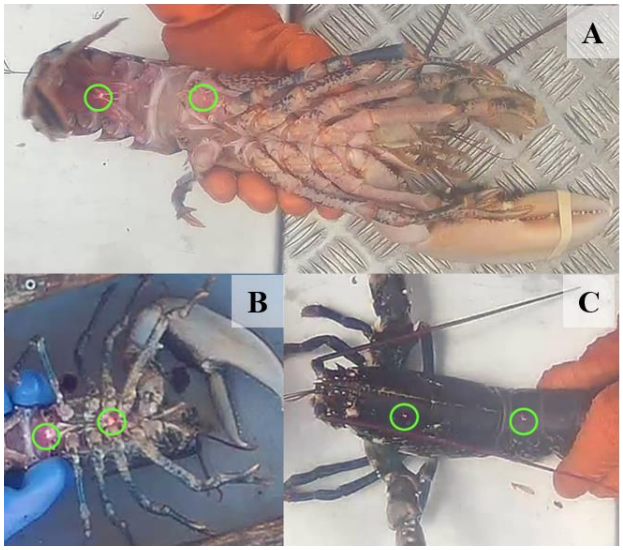

Figure 48:Still images (stills) showing potential sources of parallax distortion of the laser projections, as a result of the lasers being projected onto a curved or bumpy surface when the dorsal or ventral sides of European lobster were presented to the on-board cameras. (A: parallax due to one laser being projected onto the flexed or moving tail fan of a lobster when it is presented ventral side up; B: parallax as a result of lasers being projected on to the top of the legs of a lobster when it is presented ventral side up; C: parallax due to one laser being projected onto the arched carapace of a lobster whilst the other laser is projected onto the flexed or tail fan of the lobster, when it is presented dorsal side up).

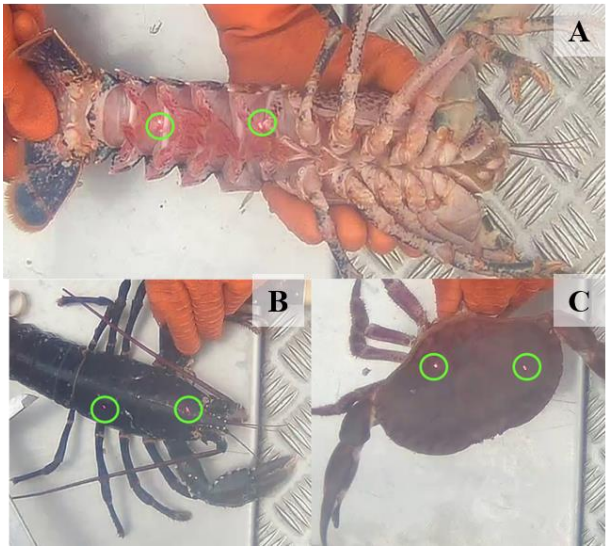

Figure 49: Still images (stills) showing potential sources of parallax distortion of the laser projections, caused by the projection of the lasers on to the trait of interest when it was not perpendicular to the axis of one or both lasers. (A: parallax as a result of the abdomen width of a European lobster being tilted away from the horizontal when the lobster was presented ventral side up; B: parallax due to the lasers being projected on to the carapace length of a European lobster when it was tilted away from the vertical, when the lobster was presented dorsal side up; C: parallax as a result of the lasers being projected on to the carapace width of a brown crab when it was tilted away from the vertical, when the crab was presented dorsal side up).

Footage collected from the on-board cameras could provide training datasets that can be used to mitigate all the sources of subjectivity in the video and still analysis process, including subjectivity in determining which stills to reject due to parallax. Such a dataset could also be used to verify standards amongst analysts (Rycroft *et al.*, 2013). An automated image extraction process would mitigate subjectivity in the still selection process, whilst an automated measurement process would remove the inter and intra-analyst effect in Still trait measurements.

5.4 Protocol for the use of the on-board camera

A protocol may need to be put into place to standardize the way that animals are presented to the cameras, in order to reduce the still rejection rate due to human error and improve the accuracy and precision of the predicted trait sizes. So as to minimize parallax error both lasers should be projected on to, and photographed on the trait of interest when it is perpendicular to the axis of both lasers. Error due to parallax caused by the body angle and movement of lobsters could be reduced if they are restrained flat against the defined surface with the maximum extension. This could be achieved using dorsal and ventral lobster restraint boards per Rycroft *et al.* (2013). Such a restraint could have the additional benefit of increasing the accuracy the Predicted AW:CL ratio at allocating sex to lobsters. However, any increase in the accuracy of Still measurements and the number of lobsters correctly sexed from the stills, would have to be balanced against the increased time cost to the fishers of using such a device. Alternatively, lobsters could be pinned on the defined surface with the tail fan extended using banding tongs. With regards a protocol for presenting crabs to the camera, fishers may need further training to ensure their hands are not obscuring the edges of the carapace when crabs are presented dorsal side up, as indicated by the high still rejection rate for this reason (8%, n=1553). Fishers may need to be asked to pass alternate sides of the animals under the camera in a specified order, such as dorsal then ventral side, in order to facilitate the pairing of the extracted dorsal and ventral stills for each animal. A gap between successive stills taken from the same trap may indicate that the footage needs to be referred to in order to determine if a still has been missed.

Fishers may need to be asked to wipe the camera window before and after each use to ensure that it is not dirty and to prevent an accumulation of salt spray, both of which may affect the image quality. When not in use, the cameras should be stored in such a way so as to minimise

the chance that they are knocked, which could affect the parallelity of the lasers. The cameras should be calibrated before and after each sample of catch is passed under them, by placing a ruler in between the laser projections on the defined surface. If the laser separation distance changes (outside an acceptable tolerance) any catch that has been presented to the camera since the last successful calibration would need to be rejected, due to error in the laser scale for at least some of the catch.

5.5 Limitations of data collected using the on-board cameras

Fishery-dependent data collected using on-board cameras, as in the present study, has its limitations. The catchability of crab and lobster is determined by a complex interaction between physiological, behavioural, environmental factors and fishery-related processes (Addison, 1995; Miller, 1990; Lizárraga-Cubedo *et al.*, 2015). Studies have found evidence of a phenomenon known as trap saturation whereby the presence of a lobster in a trap deters the entry of crabs or additional lobsters. Conversely, the presence of a crab only deters the entry of additional crabs (Bell *et al.*, 2001). Ondes (2015) observed a significant negative relationship between the number of lobsters and brown crabs caught in traps in the Isle of Man Crustacean Fishery. Trap saturation may result in an aggregated distribution of animals on the seafloor appearing as a uniform distribution in a string (Addison, 1995). As a result, CPUE recorded from fishery-dependent footage may not be linearly related to stock abundance and density, or representative of the population of either species around the Isle of Man (Addison, 1995). Data collected by a sentinel fleet can only track what is happening in the fishery and should ideally be supplemented by fisheries independent research.

The presence of on-board cameras may influence the behaviour of fishers and a deployment effect may be observed due to the fact that data can only be collected by the vessels that have cameras installed on them. The deployment effect could be mitigated by installing cameras on a larger selection of vessels, which would have the additional benefit of providing greater spatial coverage (Hold *et al.*, 2015). Similar to self-sampling, data collected using the cameras could be more readily accepted by the fleet, compared to data collected by other fishery-dependent data collection methods, such as observer programs. In the present study, it is not known if the fishers' choice of when to use the cameras was completely random or was influenced by unknown factors. For example, in July the skipper on Vessel 2 said that he did not have time to pass catch under the camera because a large number of crabs were being

caught in each trap. The Isle of Man Crustacean Fishery is year-round so the sentinel fleet could potentially collect data 12 months of the year. However, the amount of footage that can be collected in winter months will be limited by the availability of daylight.

Depending on the information required from the footage, fishers may need to be requested to modify their normal fishing activities. For example, if the fate of animals needs to be known fishers may need to ensure that all the animals are kept in the FOV of the camera until the point of discard or point at which they are being put in a fish box. However, data requirements cannot be at the expense of health and safety and operational considerations; in the present study, on two of the vessels it would not have been possible to have both the crab and lobster fish boxes in the FOV of the camera without them posing a trip hazard. In these instances, an additional camera could be used as an alternative to fishers modifying their behaviour.

In the present study, the video analyst evaluated what information could be taken from footage from each vessel. However, observer trips may be needed to validate that the information is accurate For example, it can be difficult to accurately determine fine-scale effort parameters: the number of traps and soak time, from an EM installation (Course et al., 2015). Depending on the data requirements of a fishery-dependent data collection program, fishers may need to provide information that is not ascertainable from footage; by keeping paper records or by indicating information to the camera. For example, a hand signal could be used to indicate that a crab or lobster is soft-shelled. Training may need to be provided and standards verified for each vessel participating in the sentinel fleet, to ensure that data is accurate to within an acceptable tolerance and analytically useful to scientists and fishery managers.

Unlike in Cambiè *et al.* (2016) and Hold *et al.* (2015), the defined surface that the fishers passed the animals over was not altered for the purpose of this study. During the consultation process with the fishers it was decided that the green and magenta chequered wooden board, used by Cambiè *et al.* (2016) would hinder and be badly damaged as a result of the fisher's normal activities over the prolonged study period (Emmerson, 2016, pers. comm.). For example, on Vessel 2 the defined surface in the FOV of the camera was the surface that the traps were hauled onto. The still rejection rate due to poor definition of the edges of crab CW and lobster AW could be improved by increasing the contrast between the animal and the

background. Good contrast is also essential in order to automate the still extraction process (Cambiè *et al.*, 2016). If this is achieved using the wooden board per Cambiè *et al.* (2016) the distance between consecutive 1cm squares could be used to calibrate the cameras and used as an alternative scale with which to measure traits if the laser scale is not visible in a still or if both lasers are not projected onto the trait of interest. For example, if the animal is smaller than the laser scale. The background reference scale could help extend the application of the cameras to collect data on more size classes of the target species and bycatch species whose colouration may preclude the use of the laser scale. In addition, less variation in the laser scale between the camera units would enable a more accurate comparison of size between geographically distinct regions fished by vessels in the sentinel fleet.

5.6 Wider and future applications of the on-board camera systems

The present study was a proof of concept and demonstrated possible applications for data collected using the on-board camera systems in the Isle of Man Crustacean Fishery (Figure 50).

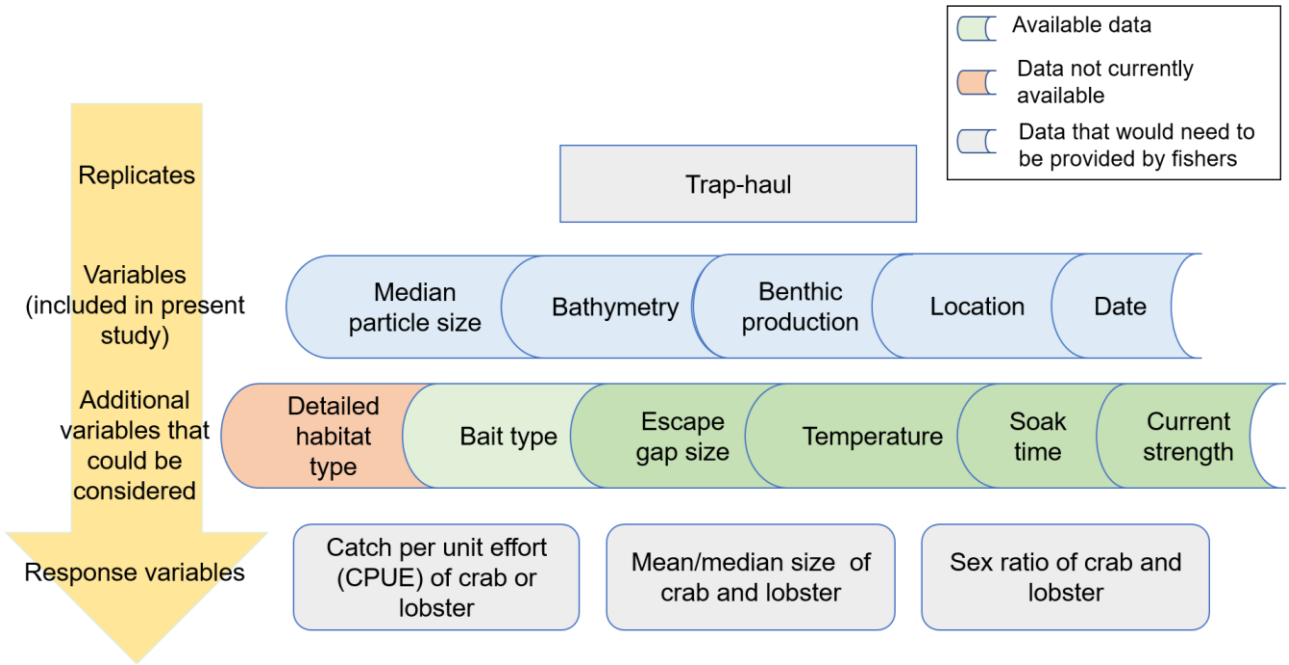

Figure 50: Flow diagram showing how fishery-dependent data collected by the three on-board cameras was combined with pre-existing environmental layers in the present study and how it can be combined with additional data (both available and not currently available) to investigate the effect on response variables such as catch per unit effort.

When the trap coordinates were plotted in ArcGIS the strings were found to be between approximately 130m and 400m for a five and 20 trap string respectively. However, the maximum length of a string fished in the fishery is approximately 100m. The discrepancy between the real and the plotted string lengths was due to the drift of the vessels during the time taken to haul and sort each trap and is indicative that trap haul coordinates taken from the footage maps fishing activity on the surface rather than the fishing footprint on the seafloor. The coordinates of traps taken at the point of deployment may be more accurate at mapping the fishing footprint, however for all the vessels participating in this study this would require the installation of an additional camera, as none of the trap deployment areas were in the FOV of the cameras. Spatial and temporal variations in fishing activity and catch composition could be investigated at a higher resolution by using the cameras to record consecutive catches fished by the same strings. Flying array underwater video systems or drop-down cameras could be used to obtain more detailed habitat data for the areas fished by the string. Habitat associations of the target species, the fishing footprint and fishers' behaviour could be investigated by plotting the coordinates of the strings as they move.

Application of the on-board cameras used in the present study extends beyond the recording of size, sex and condition of the target species. Photographic methods have been successfully used to discriminate morphologically amongst *Homarus americanus* (American lobster) stocks (e.g. Rycroft *et al.* 2013; Cadrin 1995). Preliminary work would be required to determine which trait or traits discriminate geographically between lobsters around the Isle of Man. Cadrin (1995) employed video analysis software to measure carapace, abdomen and chela landmarks, such as CL and AW and found that inshore male American lobsters could be discriminated from offshore males on the basis of larger relative chela size alone. Whilst Rycroft *et al.* (2013) determined that it was necessary to measure multiple traits to identify the ones that could be used for discriminative analysis between American lobster populations from three different sites in the Gulf of Maine.

On-board cameras could be used to demonstrate that bycatch of non-target species is alive and healthy at the point of discard, so as to convince the European Commission to grant exemptions to the landings obligation, due to come into effect for crustacean fisheries in 2019 (Fisheries and Conservation Science Group, 2015). Bycatch species identification and damage assessments from stills would need to be validated. EM in the form of Closed Circuit

Television (CCTV) cameras has already been successfully trialled to monitor bycatch in several fisheries, including the Alaskan Rockfish Fishery (National Marine Fisheries Service., 2011) and the Northern Australian Prawn Fishery (Piasente *et al.*, 2012). Camera resolution and configuration have been identified as limitations to using cameras as bycatch monitoring tools (Ames, 2005). Sufficient frame rates and image clarity are required to provide a high probability of capturing an image that contains unique characteristics of a species, in order to differentiate between similar species (Ames *et al.*, 2007). The cameras used in the present study had frame rates that were over three times greater than the cameras used by Ames *et al.*, (2007) to provide bycatch composition estimates comparable to those recorded by on-board observers, in the Alaskan longline fishery for Pacific halibut. Fishery-dependent footage from the on-board cameras could be used determine the time between the bycatch being hauled onto the vessel and the point of discard, as an index of survivability.

Adequate spatial and temporal coverage of the cameras could be used to collect crab sex ratio data during the months of April to Autumn, to map the north-south migration of female crabs (Ondes, 2015). Such a dataset would be useful for observing changes in migration patterns around the Isle of Man, for example as a response to ocean warming or acidification. Increases in sea water temperatures has already been attributed to an expanded distribution of some crustacean species in the northeast Atlantic (Ices, 2015).

5.7 Cost implications

The camera units used in the present study had a simple design and were inexpensive to construct and install: approximately £400 per unit. The accuracy and precision of each camera unit has to be balanced against the financial cost of its construction and installation. Camera units comprising precisely parallel lasers are required in order to automate the image extraction and measurement process. However, the construction of such units would require costly precision engineering. Other recommendations made in this report could incur minimal or no cost, for example asking fishers to extend the tails of lobsters with banding tongs, a standard piece of equipment already carried on vessels that target lobster.

6.0 Conclusion

Data derived from footage recorded by the on-board cameras was found to provide information on the damaged component of the *crab* catch, the sex ratio of *crabs* and the size frequencies of both *crab and lobster*, comparable in accuracy to that collected by an observer *in situ*, indicating that the cameras can be used to monitor these aspects of the Isle of Man Crustacean Fishery. The magnitude of error attributable to measuring the size of *both species* remotely from stills rather than *in situ* was within an acceptable tolerance, sufficient to detect growth increments in both species. An accurate method is required to allocate sex to lobsters from stills, so as to utilise the cameras to monitor the sex ratio of the lobster catch. The five month fishery-dependent data collection program showed that a protocol may need to be put into place to standardise the way that animals are presented to the cameras; in order to reduce the still rejection rate due to human error and improve the accuracy and precision of the predicted trait sizes by minimising parallax error. Camera units comprising precisely parallel lasers are required in order to automate the still extraction process and facilitate the rolling out of the cameras on to a sentinel fleet in the Isle of Man Crustacean Fishery. Once the cameras are rolled out, all still analysts may need to collect data to validate their own predictive models before measuring traits from stills. Depending on the properties of, and vessel specific installations of each camera unit, the predictive models for each trait may need to also include the camera identity. Application of the on-board cameras extends beyond the recording of size, sex and condition of the target species. The cameras could be used to demonstrate that bycatch is alive and healthy at the point of discard, so as to convince the European Commission to grant exemptions to the landings obligation.

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Grey literature

Map of Isle of Man: Wikipedia

Graph pictures: http://seafish.org/

Appendices

Appendix I

Computer program	Change to default setting	Reason
VLC media player version 2.2.4 *Weatherwax*.	Snapshot hot key interchanged with stop hotkey i.e. snapshot hot key changed from Shift+S to S. Tools>Preferences>Hotkeys	Reduces the number of key strokes and therefore the video analysis time. Reduces the chance that the video is accidently restarted instead of extracting a still.
	The pause on last frame option checked. Tools>Interface	Prevents video closing after the last frame, so that a still can be extracted from the last frame if necessary.
Microsoft Excel (2016)	The Enable AutoComplete for cell values option was unchecked. File>Options>Advanced	To reduce the chance of data being entered incorrectly.
ImageJ	A short cut was created to open the Set Scale dialog box. Plugins>Shortcuts>Add Shortcut by Name	To reduce the number of key strokes and therefore time needed to analyse the stills

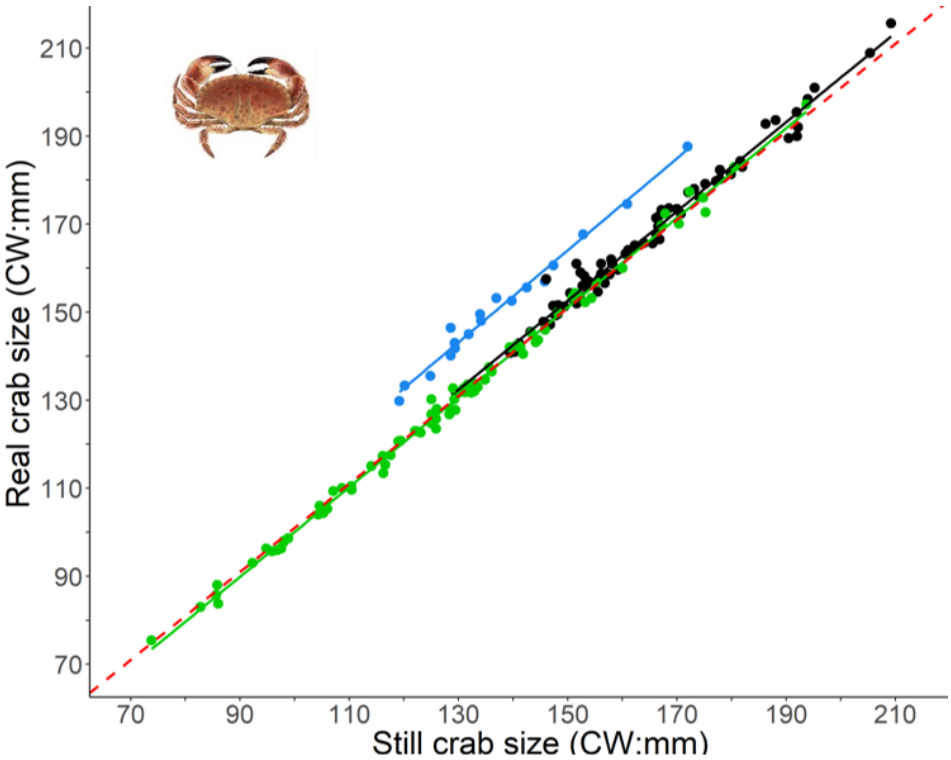
Table detailing changes made to the default settings of computer programs used to carry out the calibration and fishery-dependent footage and still analysis process.

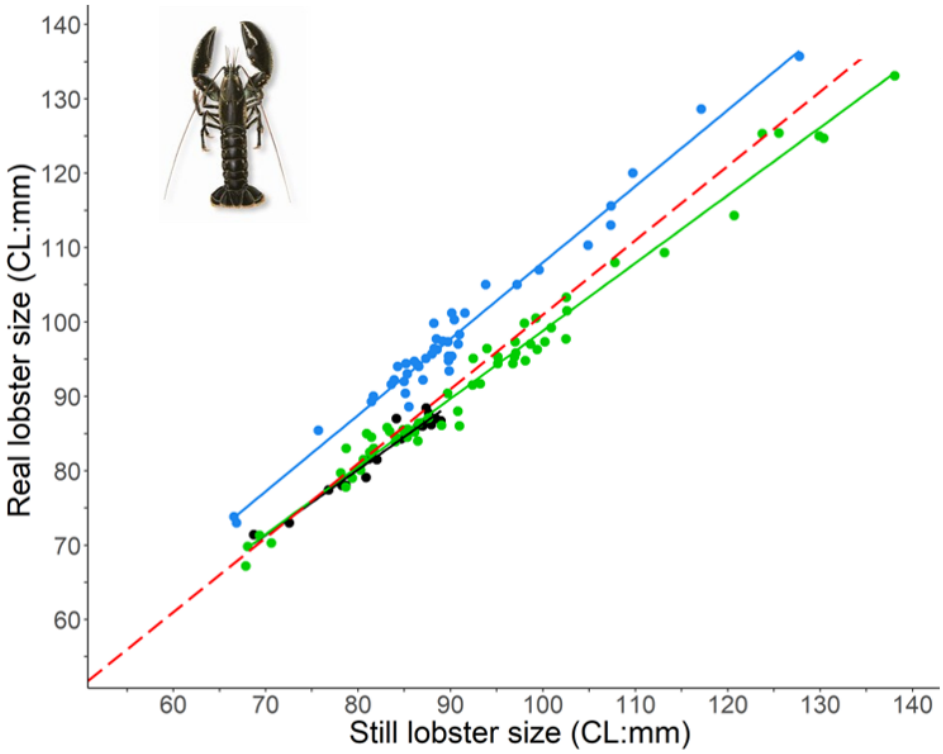
Appendix II

Feature and location (short cut)	Description	Use
Invert function Edit>Invert (Ctrl+Shift+I)	Creates a reversed image, analogous to a photographic negative.	Improved the contrast between the laser projections and the colouration of an animal or improved the visibility of the projections when sunlight was reflecting of the carapace.
Light background Process>Sharpen>Light background	Allows the processing of images with bright background and dark objects.	Helped distinguish between the pale surface and the animal.
Separate colours Process>Sharpen>Separate colours	Adjusts the brightness, leaving the hue and saturation untouched.	Used to locate the laser projections or increase the contrast between the animal and the pale background.
Sharpen Process>Sharpen	Increases contrast and emphasises detail in the still image.	Improves definition of crab carapace edge or end carapace or the back of the eye socket of lobster. However, it may also accentuate noise in the still image.
Find edges Process>Find Edges	Uses an edge detector to highlight sharp changes in intensity within the still image	Used to correct poor definition of the edges of lobster AW and crab CW.

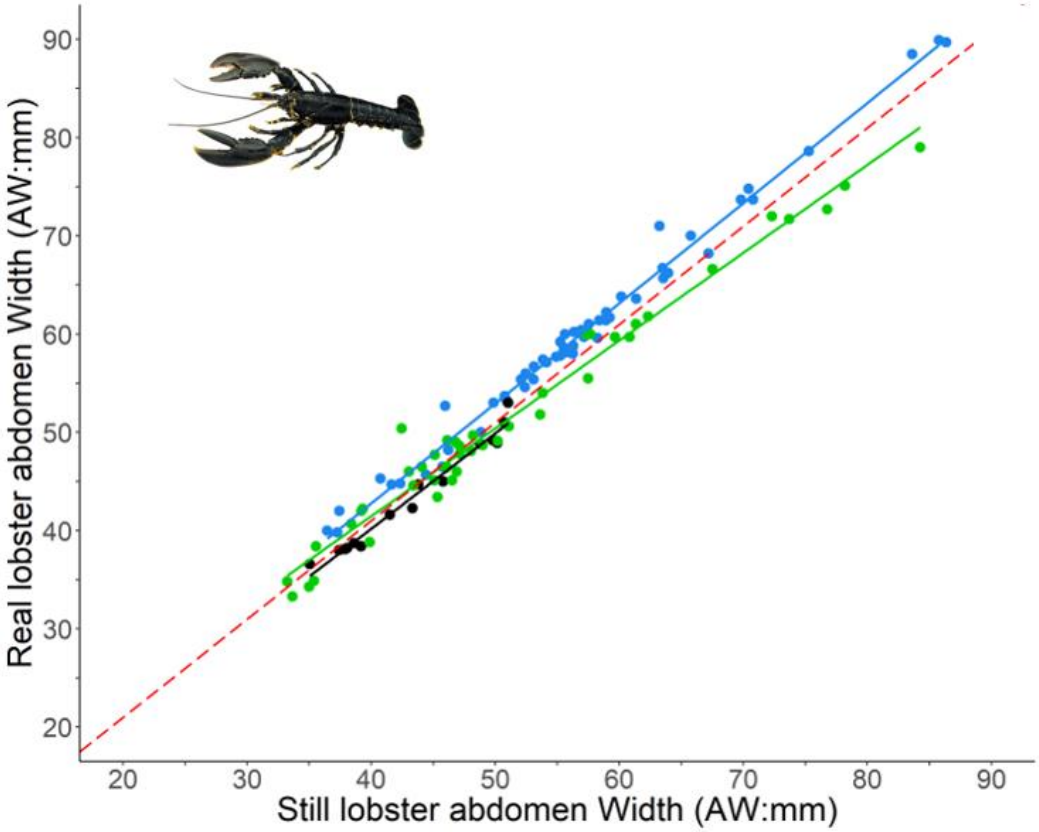
Table detailing the various features In ImageJ that were trialled in an attempt to reduce the numbers of stills that were rejected.

Appendix III





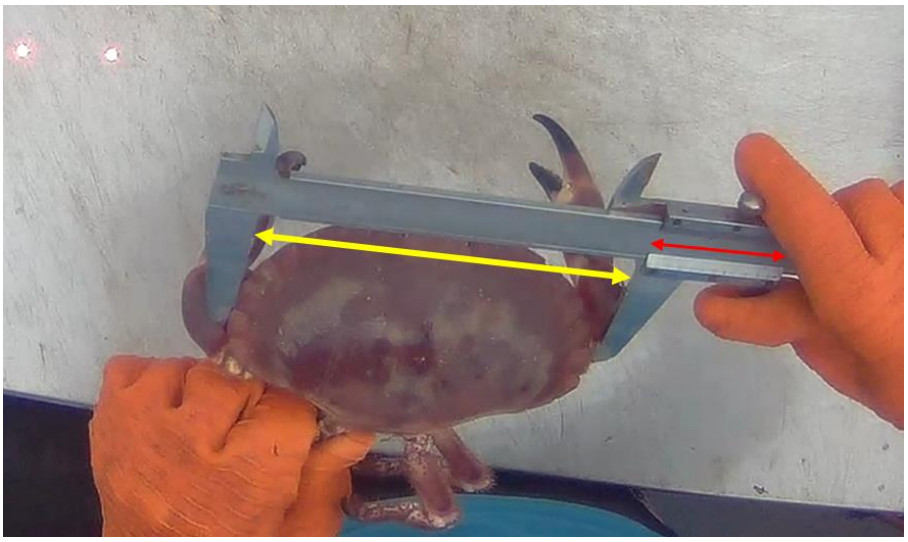
Relationship between brown crab and European lobster size (A: crab CW; B: lobster CL) measured directly from the stills (the Still size) and the corresponding measurement of the same individual made by the observer *in situ* (the Real size), for all three camera units combined (blue: Camera 1, black: Camera 2, green: Camera 3). The red dotted line represents the perfect relationship between the Real and corresponding Still animal size, i.e. no difference.



Relationship between European lobster abdomen width (AW) measured directly from the stills (the Still size) and the corresponding measurement of the same individual made by the observer *in situ* (the Real size), for all three camera units combined (blue: Camera 1, black: Camera 2, green: Camera 3). The red dotted line represents the perfect relationship between the Real and corresponding Still AW, i.e. no difference.

Appendix IV

Outliers in the residual error of the predicted CW model (Predicted size -Real size), characterised by a magnitude greater than 6mm, were checked by extracting stills of individual crabs alongside the callipers that were used to take the Real measurement of the CW. The known length of the Vernier scale was used to measure the distance on the main calliper scale.



Still image (still) used to check an outlier in the residual error of the predicted CW model (Predicted size -Real size), characterised by a magnitude greater than 6mm. The known length of the Vernier scale (indicated by the red arrow) was used to measure the distance on the main calliper scale (indicated by the yellow arrow) in order to check for an error in the Real carapace width recorded in situ.