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Automated multiple fish tracking in three-Dimension using a Structured Light Sensor

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ABSTRACT

Image-based monitoring using video tracking has been showing potential in aquaculture behavioural studies during the past decade. It provides higher spatial and temporal resolution in comparison to most conventional methods such as hand scoring, tagging or telemetry. It also permits more quantitative environmental data to be collected than do other methods. Studies about trajectory are usually based on tracking in two-Dimensional (2D) environments; however, most aquatic organisms move in a three-Dimensional (3D) environment, which greatly influences ecological interactions. Furthermore, in most 2D image analysis, occlusion of fish is a frequent problem for analysis of tracking and ultimately evaluating their behaviour. Recently, sensors based on 3D single point imaging technology, which can provide geometric information of 3D environment with high-frame rate in real time have been developed. These sensors provide the opportunity to develop a practical and affordable tracking system to study movements of multiple fish in real-time. This study aims to develop a multiple fish tracking system in 3D space based on currently available structured-light sensor. Kinect I as low cost available structured-light sensor was used to record a 10-min video from four Nile tilapia (*Oreochromis niloticus*) which were freely swimming in an aquarium. The video was processed to identify position of each fish in 3D space (x, y, and z) within each frame so as to create a trajectory. The system accurately (98%) tracked multiple tilapia in an aquarium. Another objective of this study was comparing trajectory of introduced system with stereo vision as a conventional method for monitoring in 3D space. This study is contributing to feasibility of new sensor for monitoring fish behaviours in 3D space.

1. Introduction

Aquatic organisms are sensitive to changes in the environment and they respond to these variables with distinctive movement and behaviour (Little and Finger, 1990; Mancera et al., 2008). For example, fish infested with parasites often have increased jumping behaviour (Furevik et al.,1993), have disrupted schooling during feeding (Juell et al., 1993) or show changes in vertical distribution when artificial light is used (Oppedal et al., 2011). Monitoring of fish behaviour, such as individual feeding or swimming speed, can provide useful information for improving production management (Brown et al., 2006; Oppedal et al., 2011) as well as helping farmers to observe fish behaviour as an indicator of relative welfare (Zion, 2012). Fish behaviour analysis can also be used for environmental risk assessment, such as detecting chemical agents in water as an inexpensive and rapid alternative to laboratory analysis (Kane et al., 2004; Masud et al., 2005; Xiao et al., 2015).

1.1. Fish tracking system in 2D

There are different conventional monitoring methods such as direct visual inspection, including hand scoring (Bjerselius et al., 2001; Wibe et al., 2001; Frommen et al., 2009) and computer simulation (Parrish et al., 2002). Bio-logging methods such as telemetry (Bridger and Booth, 2003; Conti et al., 2006; Fore et al., 2011) and marking or tagging (Block et al., 2005; Delcourt et al., 2011) are also conventional monitoring techniques, but all the aforementioned systems cannot provide fast, accurate and real-time information, especially when large volumes of data are collected. In some cases, these methods are also invasive and can modify fish behaviour, which alters natural interactions in fish groups (Dahlbom et al., 2011).

During the past decade, Machine Vision Systems (MVS), as cheaper, easier and more accurate alternative in comparison to

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conventional methods, have been used for near real-time and off-line monitoring of fish behaviour (Delcourt et al., 2012). For instance, MVSs have been applied for monitoring schooling and shoaling (Suzuki et al., 2003; Salierno et al., 2007), novelty behaviours (Stewart et al., 2012), abnormal behaviour (Pinkiewicz et al., 2011; Beyan and Fisher, 2013) and also feeding behaviour (Parsonage and Petrell, 2003; Lee et al., 2013; Atoum et al., 2015) in both tank and sea cages. They also have been used to monitor fish behaviour in response to stress from high stocking density (Papadakis et al., 2012) or hypoxic conditions (Xu et al., 2006). Furthermore, image-based tracking can provide remote automatic measurement and analysis of fish movement without human presence (Dell et al., 2014). For example, Spampinato et al. (2012) recorded fish activities using an under-water camera to understand fish behaviour during typhoon events.

To date, the number of MVSs for studying individual fish behaviour has been expanded. For instance, Kato et al. (2004) developed a system for quantifying individual Zebrafish (*Brachydanio rerio, Cyprinidae*) behaviour such as velocity, swimming distance, trace map and turning directions. Stewart et al. (2012) recorded individual fish behaviour in open field test arenas to understand unusual activity.

Monitoring multiple fish using MVS automatically also have been studied. Pinkiewicz et al. (2011) developed a system to record and analyse movement of multiple fish using Kalman filter and data association techniques based on video footage of salmon in a sea cage. Papadakis et al. (2012) created low-cost MVS to analyse fish behaviour in a tank. They have studied fish interaction with sea cage net under various conditions. Mirat et al. (2013) expanded a program called ZebraZoom to track larval Zebrafish movement. Lee et al. (2014) developed a MVS based on a particle-filter algorithm for tracking multiple fish in a single tank.

Occlusion has been the most common technical difficulty that researchers have encountered during the study of multiple individual fish in the same area using optical sensors. Occlusion occurs, when several fish move simultaneously, or some individuals swim close to each other, or in several time units in succession. It can also be defined as the phenomenon of two or more tracked objects merging during a short time period (Delcourt et al., 2012). Typically there are two types of occlusion: (I) when two fish swim so close that they appear as a single, longer fish and (II) when two trajectories cross and the two fish are perceived as a single T- or X-shaped image (Dolado et al., 2014).

Some researchers have studied occlusion, and tracking individuals during and after occlusion in 2D space. For example, Kato et al. (2004) suggested using an erosion and dilatation system for solving occlusion problems when more than one fish is being tracked. Miller and Gerlai (2012) recommended the application of a user-defined threshold to recognize pixels which belong to different targets and assign them to a clump. Pérez-Escudero et al. (2014) expanded an algorithm by identifying individual fish, using fingerprints from occlusion-free portions of video and then using the signature to resolve the occlusion and identify switches. Dolado et al. (2014) introduced an image-processing method to detect occlusion in a video and separate individuals involved in 2D space. Baum et al. (2013) created an algorithm for overcoming occlusion by employing a hybrid filter and using game-theory related reinforcement. Recently, Fukunaga et al. (2015) built a video tracking system called GroupTracker by adopting a Guassian mixture model-based for tracking multiple fish, even under severe overlapping positions. Most of the above-mentioned methods are still far from optimal, in spite of improvements during the past decades. For example, most algorithms need to record data from fish swimming in tank with water depth less than 5 cm, which may be acceptable for small fish like Zebrafish, but would not be applicable for bigger fish, where fish might be swimming in tanks of 3–4 m depth and 15–20 m in width. In other words, this will limit the applicability of behavioural studies in small environments and would not permit researchers to study fish activities in bigger tanks.

1.2. Fish tracking system in 3D

Studies about trajectory are mostly based on tracking in 2D environment; however, most organisms live in three-Dimensional (3D) environments, which extensively influence ecological interactions (Pawar et al., 2012; Dell et al., 2014). For instance, it would be difficult to recognize some behaviour that include vertical movement using 2D tracking (Horodysky et al., 2007). Also, as described above, occlusion is a common problem for analysis of fish tracking and ultimately their behaviour where 2D images are used. Therefore, tracking animal in 3D is more desirable in animal behaviour studies.

Tracking systems in 3D have been studied using different approaches such as light field video cameras in which, composite optics simultaneously capture images which are focused at different distances from lens, therefore, allowing the reconstruction of a scene in 3D (Matsumoto et al., 2013). Three-Dimensional (3D) tracking systems also have been expanded based on a single reflected image or shadows from surface of a 3D object such as spherical mirror (Kanbara et al., 2006; Chen et al., 2011). Another approach has been 3D tracking based on intensity of reflected light when images are captured using NIR camera (Pautsina et al., 2015). Nevertheless, multiple cameras are usually employed to reconstruct 3D scene for tracking objects. For example, Spitzen et al. (2013) used two monochrome Couple-Charged Device (CCD) video cameras to study 3D in-flight behaviour of individual malaria mosquitos in response to human odour and heat. Cachat et al. (2011) reconstruct 3D environments using images from two video cameras, and manually recording the positions of individual Zebrafish so as to understand neurophenotyping of adult Zebrafish in 3D environment. Viscido et al. (2004) employed stereo vision system to track 4–6 groups of giant danios (*Danio aequipinnatus*). Veeraraghavan et al. (2006) proposed a method based on motion information to track multiple bees using two video cameras. Wu et al. (2011) developed an algorithm by solving three linear assignment problems for tracking multiple fruit-fly using two video cameras automatically. Synchronizing multiple cameras usually requires different hardware and complicated software; also more handling and complicated manual procedures such as calibration is required, which may affect animal behaviour (Dell et al., 2014). Further, image spatial resolution dramatically drops when objects move away from the sensors (Gokturk et al., 2004).

Recently, a new hardware based on single-point 3D imaging technology (e.g. Microsoft Kinect I and II or Asus's Xtion Pro) has been introduced, which can provide 3D single points in real-time based on two range sensing principals namely (I) Time-of-Flight (ToF) and (II) Structured Light (SL) emission. Time-of-Flight (ToF) sensors generate a map of distances from the measurement of the phase difference between the emitted and the received modulated signals (Lefloch et al., 2013). In other hand, SL sensors operate on a completely different principle. They provide 3D geometric information to obtain depth information from objects of interest by using a colour video camera, simultaneously combining an Infrared (IR) video camera with an IR projector to create a defined IR laser light pattern. These new hardware provide a practical capability to develop an affordable tracking system for the study of multiple fish in real-time. Consequently, the main objective of this study was to develop a multiple fish tracking system in 3D space based on SL sensor. To the best of our knowledge, no studies have been done on this technology to track fish. The introduced system was able to resolve the occlusion problem and track several fish separately in real-time and 3D space. Moreover, an output