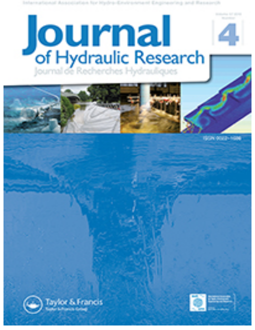

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Technical Note

A computer-based vision method to automatically determine the 2-dimensional flow-field preference of fish

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ABSTRACT
Ecohydraulics research is just beginning to have all the tools needed to examine the 2-dimensional velocity preference of fish in flow fields. We developed an experimental system with a gradient flow field in a test channel to observe flow-field preference of juvenile silver carp, *Hypophthalmichthys molitris*. We used automatic methods, which acquire fish swimming tracks using computer vision (video). We examined the flow field using hydrodynamic software simulation; then, using the fuzzy c-means clustering algorithm, each frame of the flow field was divided into areas of different velocity. Finally, the automatic fish trajectory tracking was coupled with hydraulic simulation of the flow field to compute an estimate of the time fish spent in each velocity area. To validate results from the automatic method, we used manual examination of videos of swimming juvenile silver carp to analyse their preferred velocity fields. Results show the automatic method greatly reduces processing time compared to the manual method.

Keywords: Automatic tracking; computer vision; fish trajectories; flow–fish interface; fuzzy c-means clustering

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1 Introduction

It is difficult to couple fish movements and flow-field dynamics in an efficient way. In laboratory studies, most researchers count fish tracks manually or use behavioural analysis software, and separately calculate flow-field characteristics (Goettel, Atkinson, & Bennett, 2015). Analysis of fish choice of flow fields then follows to complete the process using time-consuming manual methods.

Presently, the main methods used to determine fish movements include video software analysis, marker positioning based on radio and acoustics, accelerator trajectory analysis, or manual counting (Castro-Santos & Haro, 2010; Watanabe, Wei, Du, Li, & Miyazaki, 2013). Each method has its merits and among them, video software analysis is relatively efficient in the laboratory with many video processing software programs available (e.g. SwisTrack, Noldus, Logger Pro and ToxTrac (Delcourt, Denoël, Ylieff, & Poncin, 2013; Rodriguez, Zhang, Klaminder, Brodin, & Andersson, 2017; Stewart et al., 2015).

Most automatic fish tracking algorithms are in principle analogous to the object tracking techniques using a computer vision field. After pre-processing steps, such as extracting video frames, converting colour frames to grey, and filtering out noise, the fish tracking method employs inter-frame video differences to determine fish locations and obtain the fish swimming trajectory (Boussarie, Teichert, Lagarde, & Ponton, 2016). The principles for acquiring tracks of moving animals are well developed (Stewart et al., 2015). Recently, new fish tracking algorithms, such as those used for edge, region and multi-tracking analyses, were investigated in a more complex environment using multiple video camera systems in fishways (Pérez-Escudero, Vicente-Page, Hinz, Arganda, & de Polavieja, 2014; Rodríguez, Bermúdez, Rabuñal, & Puertas, 2015). However, these studies provide techniques to analyse fish behaviour without automatically relating fish movements to environmental factors, like water flow. Thus, these methods leave a gap in technique automation. For example, hydraulic preference of fish was usually acquired by a "separate coupling" of video tracking and flow-field analysis, which is time consuming (Goettel et al., 2015).

Ecohydraulic researchers wish to obtain the 2-dimensional (2-D) position of a fish using video processing methods, couple fish locations with flow fields (calculated by fluid dynamics software), and conduct time–space fusing by computer science in the most efficient way to acquire fish swimming trajectories in flow fields. We used a gradient flow-field channel system and automatic computer-video-hydraulic methods to examine the flow-field preference of juvenile silver carp, *Hypophthalmichthys molitris*.

2 Materials and methods

2.1 *Experimental flow-field channel system*

We used a water channel system composed of a submersible pump (rated flow: 0.05 m^3 s^{-1}), a polyvinyl chloride (PVC) water pipe, two large water tanks (diameter: 1.5 m; height: 1.8 m), a 190 mm diameter swing pipe, a flow straightener, a gradient water channel, and support frames (1). The entire system was set up on one side of a large sump tank with a submerged pump that sent sump water into tank I. The PVC inlet water pipe was 320 mm diameter; the diameters of connecting pipes were 200 mm or 110 mm. University water was used in the system.

The swing pipe installed at one side of water tank II was adjusted to control velocity in the test channel. During tests, flow velocity in the test channel was 0.22–0.5 m s^{-1} (0.22 m s^{-1} at the inlet; 0.5 m s^{-1} at the outlet).

To record fish swimming movements in 2-D (x and y axes), we placed a video camera (ZLD-8880RCB-3, Xianchuangan-fang Corporation, Dongguan city, China; 640 × 480 pixels, 25 frames per second (fps)) 2 m over the test channel.

2.2 *Handling and testing of fish*

Test fish consisted of 30 juvenile *H. molitris* from the Yidu Fishing Farm. Mean total length of fish was 9.4 ± 1.1 cm; mean body weight was 9.5 ± 3.0 g. After transport to the Ecohydraulics Laboratory, China Three Gorges University, we held fish for three days in a 1.8 m diameter × 0.3 m height circular tank with 0.2 m water depth. We used aerated university water maintained at a temperature of 20°C for holding and testing. We changed about 25% of the water volume every day.

Testing began after fish were held for three days and were feeding and swimming around in the holding tank. For each test, we randomly selected one fish, removed it from the holding tank by dip net, and placed it in the inlet area of the test channel. The

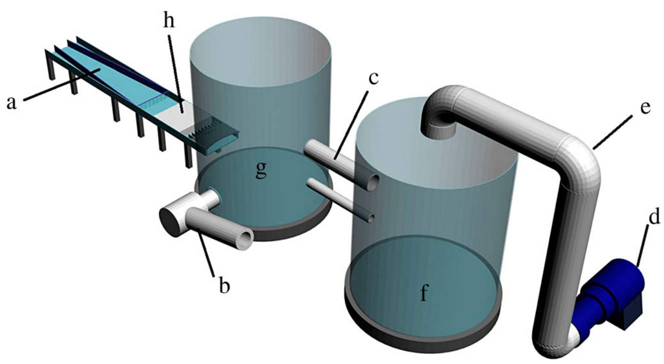

Figure 1 Model layout of the experimental channel apparatus. (a) Gradient water channel; (b) swing pipe; (c) PVC connecting pipe; (d) submersible pump; (e) inlet water pipe; (f) water tank I; (g) water tank II; (h) flow straightener

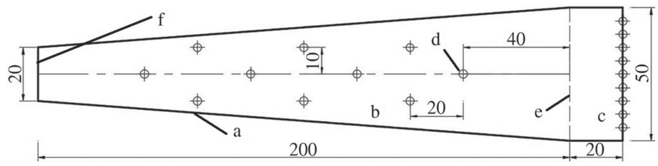

Figure 2 Plan view of the experimental water channel showing velocity sampling stations (⌖) in the inlet and in the experimental channel. Distances measured are cm. Letters indicate the following features: (a) water channel; (b) fish test area; (c) water inlet with 10 stations across inlet where velocity was measured; (d) velocity sampling station in test area; (e) upstream fish blocking net; (f) downstream fish blocking net.

test fish was retained in the inlet area by a blocking net (2). After a 10 min acclimation period of the test fish in the test channel, we removed the blocking net to allow the fish to move volitionally throughout the channel, and started collecting video data on fish movements. Each test lasted 30 min or was terminated earlier when a fish moved to the downstream blocking net area for ≥ 10 s. During tests, water depth in the test channel was 10 cm. After testing, we removed the test fish with a dip net and temporarily held it in another circular tank (same size as the holding tank) until we returned it to the hatchery.

2.3 *Simulation and measurement of the flow field*

We selected nine sample stations in the cross-section of the water inlet (5 cm between sampling stations) to define the flow-field regime in the test channel. The arithmetic mean of the measured flow velocity was the input boundary condition for the ANSYS Fluent software. Also, we selected 10 velocity sampling stations in the water channel to verify the flow field as determined by the ANSYS Fluent simulation. The distribution of sampling stations, along and on either side of the central longitudinal axis of the test channel is shown in 2. We measured water velocities with a Nortek ADV, with the data collection frequency set at 200 Hz and used 30 s as the sampling time at each station. Thus, each sampling station obtained 6000 velocity values. We used WinADV software to process the data (Plew, Klebert, Rosten, Aspaas, & Birkevold, 2015).

For simulation and verification of the flow field in the test channel, we used AutoCAD 2010 software (Autodesk Inc., Singapore) to make a 3-D digital model of the test channel, and applied ANSYS ICEM CFD software (ANSYS Inc., USA) to construct different computational meshes. For increased simulation accuracy, all the computational meshes applied in the study were structured hexahedral meshes and body fitted anisotropic meshes were encrypted on the two sides and the bottom of the test channel. These efforts resulted in the use of 2.0252 million mesh units and 6.1497 million nodes, which were imported into ANSYS Fluent to be set and solved. With the power of the pump constant, and the water levels at the inlet end and outlet end the same, the steady state in ANSYS Fluent was chosen to conduct the calculation. The standard k-ε model was selected as the viscous model and the standard wall was chosen as the wall function. We set the boundary condition at the inlet side of the test channel as the velocity-inlet and the boundary condition at the outflow side as the velocity-outlet.

2.4 *Fish trajectory and flow field coupling method*

The conventional coupling method manually locates a swimming fish in the video frames. We used a 5-minute experimental video of *H. molitris* in the test channel to determine the time needed for the manual method to determine velocity preference.

The automatic analytical method used three phases to track the fish swimming position and count how long the fish stays in a specific velocity area by utilizing a computer vision algorithm without user interference. The preferred velocity area was determined by recording the percentages of time the fish stayed in each velocity area. In the first phase, the method divided the video into frames, converted colour frames into grey frames, spatially filtered the video frames, removed partial interference, and then, based on computer vision algorithms, automatically located *H. molitris* positions during fish swimming. In the second phase, the method employed the fuzzy c-means clustering algorithm to extract the velocity diagram and separate different velocity areas. In the third and final phase, the preferred velocity area of *H. molitris* was determined by the time fish spent in various velocity areas, which was calculated automatically by mapping the swimming trajectories of fish on the velocity diagram to derive the coordinates of each test fish centroid in the separated velocity images.

3 Results

Analysis of flow-field velocities in the test channel found velocity in the test channel gradually increased from the inlet to the outlet (3a). The simulated velocity was verified by velocity measurements using the Acoustic Doppler Velocimetry (Nortek China Ltd., China) and the results agreed with the simulated velocity (5% standard deviation). Each velocity partition had a characteristic shape and the size of each velocity partition gradually decreased as velocity increased. The range of velocities at the inlet was the greatest, while the range of velocities at the outlet was the smallest (3a).

According to the flow-field diagram simulated by the Fluent model and computer vision based on the fish tracking algorithm, the total time spent by *H. molitrix* in various velocity areas while swimming was calculated to determine the flow velocity preferred by test fish. The movement tracks of fish and the numerical values of the flow field can be superimposed, based on the flow-field simulation images and video processing, to intuitively reflect the distribution of areas where fish stayed in the test channel (3b). The velocities preferred by *H. molitris* were 0.24–0.26 m s^{-1}, because fish spent the greatest amount of time in these velocity areas (Table 1).

The automatic analytical method for fish trajectory and flow-field coupling can quickly and accurately calculate the time *H. molitris* spent in different velocity areas, compared with the

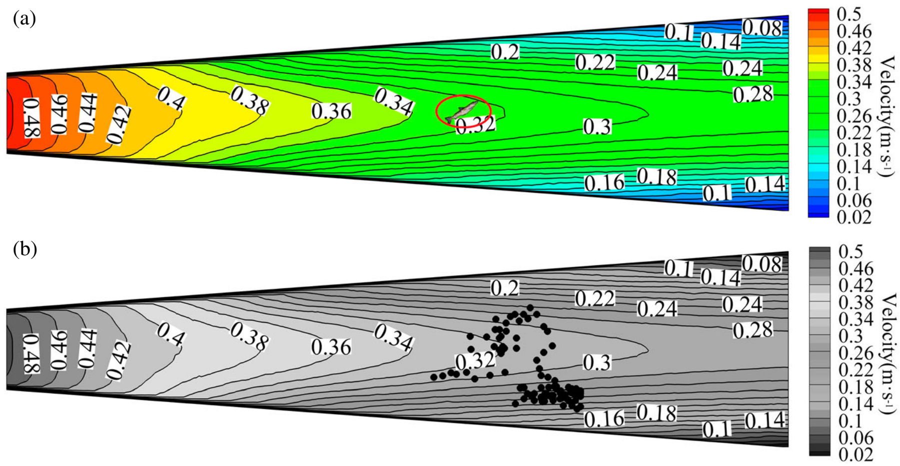

Figure 3 Fish trajectory coupled with flow field: (a) cloud chart of flow velocity in the experimental channel, with one fish marked in red oval; (b) trajectory of *H. molitrix*; areas with different grey levels denote fish swimming at different flow velocities

Table 1 Time spent by *H. molitris* in each velocity area and time used to process results using manual and computer statistical methods for video at 25 fps

	Time spent by *H. molitris*	
Velocity areas (m s^{-1})	Manual	Computer
0.16–0.18	3	3
0.24–0.26	128.0	128.4
0.26–0.28	96.8	96.4
0.28–0.3	37.8	38
0.3–0.32	12.2	12
0.32–0.34	5.8	5.8
0.34–0.36	12.8	12.8
0.36–0.38	3.6	3.6
Video time (s)	300	300
Total time cost (s)	2000	30
Processing efficiency (fps)	1.5	100

manual coupling method. The manual process for determining fish preference for velocity area took more than 200 minutes to interactively acquire the fish's swimming track (Table 1). The track of *H. molitris* in each velocity area was recorded by manually locating the fish in each frame with video analysis software (Logger Pro 3.0, Vernier Software and Technology, Georgetown, ON, Canada). The preferred velocity area was determined by recording the percentage of time the fish stayed in each velocity area. The manual statistical method took much longer time to process results, making it inefficient (Table 1). The manual processing efficiency was 1.5 fps, while the computer processing efficiency was 100 fps. The efficiency of the computer counting method is much greater than the manual method.

4 Discussion

Using experimental channels (or fish ladders; Rodríguez et al., 2015), extracting fish movement tracks from video analysis and analysing kinematics is an effective tool for quantifying fish behaviour. For instance, Delcourt et al. (2013) conducted 3-D automatic tracking of fish based on single-camera videos. Paglianti and Domenici (2006) used WINanalyze to study the escape behaviour of staghorn sculpin (*Leptocottus armatus*). Wu and Zeng (2007) developed a mobile video platform to study the kinematics related to fish swimming. However, using an automatic video processing method to facilitate fish behaviour studies has not been applied extensively, particularly in ecohydraulics research (Goettel et al., 2015).

The present study demonstrates that, compared to traditional manual statistics, a method based on computer vision to determine flow velocities preferred by *H. molitris* has significant advantages. This method not only saves personnel and material resources but can also obtain accurate estimates of multiple physical factors, such as defined velocity areas, time fish use specific areas, fish position coordinates, and swimming speeds.

With the help of advanced video analyses, the present study applied the self-programming method to obtain a 2-D fish path, and further, coupled fish movement tracks with a 2-D flow field. However, in its present state of development, this method has several deficiencies. It is limited to 2-D (x and y axes), and therefore is unable to achieve a coupling with 3-D flow fields. Video processing should be further developed to obtain 3-D paths for fish movements and allow analyses of fish velocity preference in 3-D flow fields.

Apart from obtaining fish tracking data, video processing can also obtain kinematic data related to fish swimming (Paglianti & Domenici, 2006). By positioning the central line of the fish body in separated sections, the coordinates of different parts of the fish can be obtained, the speed of each part can be determined, and data on tailbeat amplitude and frequency can be calculated (Tytell, 2004). The combination of hydraulic simulation, based on CFD modelling, and fish swimming behaviour and kinematics, based on videography analyses, can contribute greatly to the field of ecohydraulics.

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