



Research article

Application of unmanned aerial vehicle with computer vision as a tool for welfare monitoring of cage-cultured, river-based hybrid red tilapia

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Abstract

Importance of the work: An unmanned aerial vehicle (UAV) was used to monitor cage-cultured red tilapia and provide cost-effective welfare insights by correlating fish swimming velocity (FSV) with environmental factors.

Objectives: To investigate the relationship between FSV and the rearing environment by combining computer vision techniques and a UAV.

Materials & Methods: Data were collected from five cages in two rearing crops. The UAV was flown in the morning and evening (1 hour before feeding), with a total of 22 flights. Tracker software was utilized for FSV, number of video frames (Frame), and displacement or distance in centimeters between the captured fish image and the last point or the average processing time (S) analysis. Fish weight (FW), dissolved oxygen (DO), water temperature (Temp), water pH level (pH), alkalinity (ALK), total ammonia nitrogen (TAN), nitrite-nitrogen (NO₂-N), and water transparency (Trans) were measured.

Results: The results showed that FSV had a positive correlation with FW ($p < 0.01$), Temp ($p < 0.05$) and NO₂-N ($p < 0.05$). The FSV (in centimeters per second) could be obtained from the regression equation $FSV = -7.681 + 0.007 FW + 0.416 Temp + 13.909 NO_2-N$ with a coefficient of determination of 0.701. There was no significant difference between FSV and the estimate obtained using the tracking software ($p > 0.05$).

Main finding: The study utilized UAV and computer vision technology to monitor the welfare of cage-cultured red tilapia. There were positive correlations between FSV and FW, Temp and NO₂-N, demonstrating a straightforward and effective approach to assessing aquaculture welfare. These results underscored the efficacy of UAV and computer vision in monitoring fish behavior, providing a cost-effective method. The findings should have important implications for enhancing farm management practices and advancing scientific knowledge in tilapia farming, ultimately leading to improvements in fish welfare and overall production efficiency.

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Introduction

Nile tilapia, *Oreochromis niloticus* (Linnaeus, 1758), is a worldwide farmed fish whose economic value is second only to carp (Li et al., 2023) with its advantages being good meat quality, wide adaptability and a fast growth rate (Abe El-Hack et al., 2022). Tilapia production increased from 2.6 million tonnes in 2010 to 4.5 million tonnes in 2018 (Food and Agriculture Organization of the United Nations, 2022). In Thailand, tilapia farming, especially red tilapia, has recently gained popularity, with its red color being similar to that of expensive marine fish species (Pongthana et al., 2010).

Aquatic animal welfare is a prerequisite for successful aquaculture (Huntingford et al., 2006; Green and Mellor, 2011; Barreto et al., 2021). It involves five factors: nutrition, physical environment, internal health, behavioral interaction and mental state (Mellor et al., 2020). These are relevant to fish behavior in response to surrounding environment changes (Kristiansen, 2004; McFarlane, 2004).

Measuring fish behavioral responses is important for evaluating stress, disease incidence, water quality problems and other factors that affect fish welfare. In particular, with aquaculture production, if behavioral changes due to stress can be detected quickly, the farmers can solve any problems that arise in a timely manner and reduce the loss of yield (Xu et al., 2006). Traditionally, stress measurement involves obtaining a blood sample; however, this can cause stress in aquatic animals during sampling and takes a long time. Therefore, computer vision techniques are applied, with most based on studying changes in fish swimming velocity (FSV) or fish swimming speed and behavioral or stress responses according to environmental changes or toxicity. Kane et al. (2004) used video-based movement analysis to quantify the FSV and stress responses of mummichog (*Fundulus heteroclitus*) as they related to a reference toxicant, tricine methanesulfonate (*m*-aminobenzoic acid ethyl ester methanesulfonate, MS222). Zhang et al. (2015) used a video-based 3D-biosensor to investigate the swimming behavior of zebra fish (*Danio rerio*), Japanese medaka (*Oryzias latipes*) and red carp (*Cyprinus carpio*) for a concentration-dependent toxicity effect of sodium dodecyl benzene sulfonate. Georgopoulou et al. (2021) used tracking and analysis of the movement behavior of European seabass (*Dicentrarchus labrax*) in aquaculture systems. Wu et al. (2022) used locomotor posture and swimming-intensity quantification to detect starvation-stress behavior of darkbarbel catfish (*Pelteobagrus vachelli*). Huang et al. (2023) applied trajectory

analysis and studied the movement behavior of carp to devise an ecological health evaluation system. However, the carp were tagged with acoustic devices featuring an edited code.

The use of computer vision in most fish behavioral studies is still complex. Researchers often develop algorithms and processing techniques independently. Some of those techniques may inadvertently impact fish welfare, leading to stress, physical impact and behavioral changes. As a result, some techniques cannot be used further. Therefore, tracker software was used in this study because it can create physical simulations based on the study of kinematics and dynamics (Claessens, 2017) and has been used in studying the movement of animal such as lemurs (Ballesta et al., 2014), mice (de Chaumont et al., 2012) and cats (Ramadhanti et al., 2021). Studies in fish, such as by Ilma et al. (2022), used tracker software to investigate the jumping speed of gourami, while Taparhudee and Jongjaraunsuk (2023) used tracker software-based computer vision techniques to assess FSV and the behavioral response of Nile tilapia caused by different formalin concentrations.

Nonetheless, regardless of the image processing technique used in any form, major limitations arise are in terms of the operational area, as it is not possible to evaluate the image based on a wide-angle view or cover the entire rearing system. Most studies used a single camera image that had a set distance and a small area to receive images, especially on farms or in river cages. In response, aerial photography technology using UAV has been applied for many purposes in the fisheries and aquaculture sectors. For example, Rieucan et al. (2018) used UAV surveys and image analysis to study the shoaling behavior of reef shark (*Carcharhinus melanopterus*). Fong et al. (2022) used UAVs to assess the swimming behavior of manta rays. Taparhudee et al. (2023) used a UAV and area image analysis for red tilapia weight estimation. However, there has been no reported study on tilapia behavior using a UAV in combination with image analysis.

Therefore, this study aimed to investigate the relationship between FSV and the rearing environment (water quality) using computer vision techniques combined with a UAV. The results could be used in guidelines for fish welfare on fish farms. In addition, the findings from this study should provide a major contribution to the existing body of knowledge and practical applications in tilapia farming in several ways such as helping aquaculture operators to understand fish behavior and welfare, providing early detection of stress and health issues, improving farm management practices, enhancing monitoring techniques and contributing to the scientific literature.

Materials and Methods

Fish samples and experimental site

The study occurred on Fishbear Farm, on the Mae Klong River in Kanchanaburi province, Thailand (13°58'15"N, 99°34'46"E) using five fish cages (5 m × 5 m × 2.5 m, length, width, depth, respectively). Each cage was used to raise 1,500 fish (24 fish/m³). The fish were hand fed with 30% protein (SPM 042R; S.P.M. Feed Mill Co., Ltd.; Thailand) until the fish were satiated. Data were collected for two rearing (crop) cycles (approximately 4 mth each) and 1 d before water quality sampling, wind sampling measurements and image acquisition using the UAV. A sample of 20 fish/cage was randomly selected and weighed using a digital scale (CST-CDR-3; CST Instruments (Thailand) Co., Ltd.; Thailand).

Water quality and wind sampling measurement

The water quality samples were collected at a depth of 30 cm below the water surface 22 times (prior to each UAV data collection flight). Dissolved oxygen (DO) and water temperature (Temp) were measured using a YSI Pro20i instrument (YSI; USA). The pH was measured using a YSI pH100A instrument (YSI; USA). Water transparency (Trans) values were collected using a 2-color disc (Secchi disc). Alkalinity (ALK), total ammonia nitrogen (TAN) and nitrite-nitrogen (NO₂-N) were monitored under laboratory conditions, following the guidelines of the American Public Health Association (2005). The wind speed was checked using an anemometer (model AM-4836; Comcube Co., Ltd.; Thailand), measured above the cage at a height not exceeding 3.00 m due to the limitation of the measuring device length. In general, environmental conditions, seasonal variation or farm management practices may influence the results. Therefore, in this study, data were collected for two crops to help understand the effects of these factors.

Unmanned aerial vehicle and image acquisition

The UAV used was a DJI Air 2S (Mavic; DJI 13 store authorized dealer Thailand Co., Ltd.; Thailand), weighing 595 g, with a maximum flight time of 34 min in winds up to 10.7 m/s. The UAV was fitted with front bumper and rear bumper detectors. The UAV-mounted camera had a maximum resolution of 20 megapixels and was fitted with a wide-angle lens with a focal length of 22 mm. The UAV was controlled remotely using a handheld unit with a screen (Figs. 1A–1B). The video recording mode was used as the

default mode with the 4K Ultra HD mode (size 3,840 pixels × 2,160 pixels). The video compression format used was MPRG-4 or MP4.

The UAV elevation above water level was 3.5 m (the lowest practical elevation that did not cause changes in fish swimming behavior) when the UAV was used to capture animation in the morning and evening before feeding (Taparhudee et al., 2023). In the recording process, continuous images were recorded in each cage for 1 min, with three videos (three repetitions) to find the best quality video for processing. The 22 data collection times in the two crops consisted of 15 flights during the first crop and 7 flights during the second crop, with 12 flights in period 1 (0700–0800 hours) and 10 flights in period 2 (1500–1600 hours.), as illustrated in Table 1.

Video processing

After obtaining the video of each cage from the UAV, each video file was processed using the tracking software (Tracker; Physlets.org/tracker/; Copyright (c) 2024 Douglas Brown, Wolfgang Christian, Robert M Hanson) to collect FSV data. The FSV data were analyzed based on comparison with a value of known length in the video, which in this work, used the 90 cm long buoyancy tanks in each cage. The coordinate axes were placed in the center of the video and selected objects (Tilapia) to capture their velocity. Then, the search button was used to capture the velocity of the fish in the video (Figs. 1C–1F). The FSV calculation utilized a frame rate of 3 frames per second (3 fps) following Taparhudee and Jongjaraunsuk (2023). The FSV was calculated based on Equations 1 and 2:

$$FSV_{\text{average}} = V_1 + V_2 + V_3 + \dots + V_n / N \quad (1)$$

$$\text{where } V = S / T \quad (2)$$

and V represents the velocity of the fish in centimeters per second, N denotes the number of images used for analysis, S is the displacement or distance in centimeters between the captured fish image and the last point and T in seconds is the duration from the beginning of image capture until the end of the recording, where each V must have S not less than 10, as mentioned by Xu et al. (2006) and Taparhudee and Jongjaraunsuk (2023). Thus, for example, Equation 3:

$$V_n = S_{f1} + S_{f2} + S_{f3} + S_{f4} + \dots + S_{f11} + \dots + S_{fn} \quad (3)$$

where, f_1 – f_n represent frames, with FSV processing utilizing 10 fish (Fig. 1D).

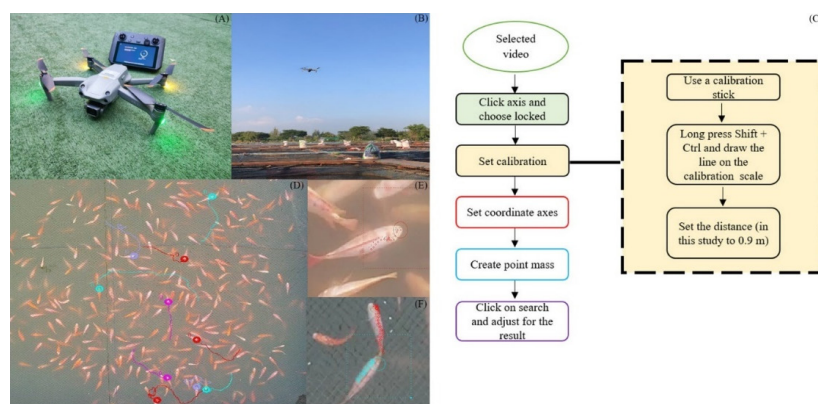


Fig. 1 Images of: (A) unmanned aerial vehicle (UAV; DJI Air 2S-Mavic); (B) UAV during fish swimming velocity (FSV) surveying; (C) setting calibration and tracking algorithms; (D) overview and behavioral insights resulting from post-processing analysis of motion trackers in FSV tracking, based on 10 fish; (E) fish being tracked; and (F) example of termination of a program trace due to object collision or overlap

Table 1 Video recording during each unmanned aerial vehicle flight

Crop	Flight	Time of day	Number of cages	Number of videos recorded/cage	Total number of videos recorded
1	1	1500–1600 hours	5	3	15
1	2	0700–0800 hours	5	3	15
1	3	1500–1600 hours	5	3	15
1	4	0700–0800 hours	5	3	15
1	5	0700–0800 hours	5	3	15
1	6	1500–1600 hours	5	3	15
1	7	0700–0800 hours	5	3	15
1	8	1500–1600 hours	5	3	15
1	9	0700–0800 hours	5	3	15
1	10	1500–1600 hours	5	3	15
1	11	0700–0800 hours	5	3	15
1	12	1500–1600 hours	5	3	15
1	13	0700–0800 hours	5	3	15
1	14	1500–1600 hours	5	3	15
1	15	0700–0800 hours	5	3	15
2	16	0700–0800 hours	5	3	15
2	17	1500–1600 hours	5	3	15
2	18	0700–0800 hours	5	3	15
2	19	1500–1600 hours	5	3	15
2	20	0700–0800 hours	5	3	15
2	21	1500–1600 hours	5	3	15
2	22	0700–0800 hours	5	3	15
					330

Data analysis

The correlation between average FSV data obtained from both the rearing crops for each cage and the mean weight of the fish and the water quality were studied using the Pearson product moment correlation coefficient method. If a relationship were found, multiple regression analysis was performed. Then, the results from using the FSV equation were compared with the tracking speed, based on the self-test method. Statistical analysis was performed to compare the mean differences using an independent samples *t* test at the 95% confidence level.

All statistical analyzes were performed using the IBM SPSS Statistics version 26 software (IBM; USA).

Unmanned aerial vehicle flight permission

The UAV used in this study was a DJI Air 2S (Mavic) that had been certified for registration of radiocommunication equipment for unmanned aircraft in research, trial and testing purposes, according to the announcement of the Office of the National Broadcasting and Telecommunications Commission, Thailand (certificate no. T040465013010).

Ethical approval

This study was approved by the Ethics Committee of Kasetsart University, Bangkok, Thailand (Approval no. ACKU 66-FIS-006) under the project “Application of unmanned aerial vehicle (UAV) with computer vision as a tool for health/welfare monitoring of river-based hybrid red tilapia cage culture”.

Results

Water quality, image analysis and fish swimming velocity

The average DO content was 4.00 ± 0.54 mg/L (range 3.09–5.04 mg/L), average Temp was $27.96 \pm 1.20^\circ\text{C}$ (range 25.20–30.46°C) and average pH was 7.43 ± 0.12 (range 7.11–7.59). The average ALK was 103.04 ± 10.62 mg/L (range 92.00–126.00 mg/L), the average TAN was 0.14 ± 0.04 mg/L (range 0.09–0.21 mg/L), the average $\text{NO}_2\text{-N}$ was 0.05 ± 0.05 mg/L (range 0.00–0.14 mg/L) and the average Trans was 67 ± 23 cm (range 19.6–100.0 cm).

The image analysis showed that the average number of frames used in the analysis was 376.03 ± 197.88 frames/s (range 61–890 frames/s) and the average processing time was 16.36 s (range 11–28 s). The average minimum FSV was 4.53 cm/s and the average FW was 204.05 g/fish, while the average maximum FSV was 11.97 cm/s with an average weight of 767.76 g/fish, as shown in Fig. 2.

Relationship between FSV and environmental conditions

The results showed that FSV had positive correlations with FW ($p < 0.01$), Temp ($p < 0.05$) and $\text{NO}_2\text{-N}$ ($p < 0.05$), as shown in Table 2. The regression equation for the performance indicator was $\text{FSV} = -7.681 + 0.007 \text{ FW} + 0.416 \text{ Temp} + 13.909 \text{ NO}_2\text{-N}$ (Equation 4) with an R^2 value of 0.701, as shown in Table 3.

Table 2 Pearson’s correlation coefficients, residual correlation between water quality and results from image analysis

Variable	FW	DO	Temp	pH	ALK	TAN	$\text{NO}_2\text{-N}$	Trans	Frame	S
FSV	0.766**	-0.207	0.462*	0.111	-0.338	0.162	0.530*	0.412	0.164	0.066
	0.000	0.354	0.030	0.624	0.124	0.470	0.011	0.057	0.465	0.771

FW = fish weight; DO = dissolved oxygen; Temp = water temperature; pH = water pH level; ALK = alkalinity; TAN = total ammonia nitrogen; $\text{NO}_2\text{-N}$ = nitrite-nitrogen; Trans = water transparency; Frame = number of video frames; and S = displacement or distance in centimeters between the captured fish image and the last point or the average processing time

* = correlation significant at 0.05 level (2-tailed); ** = correlation significant at 0.01 level (2-tailed)

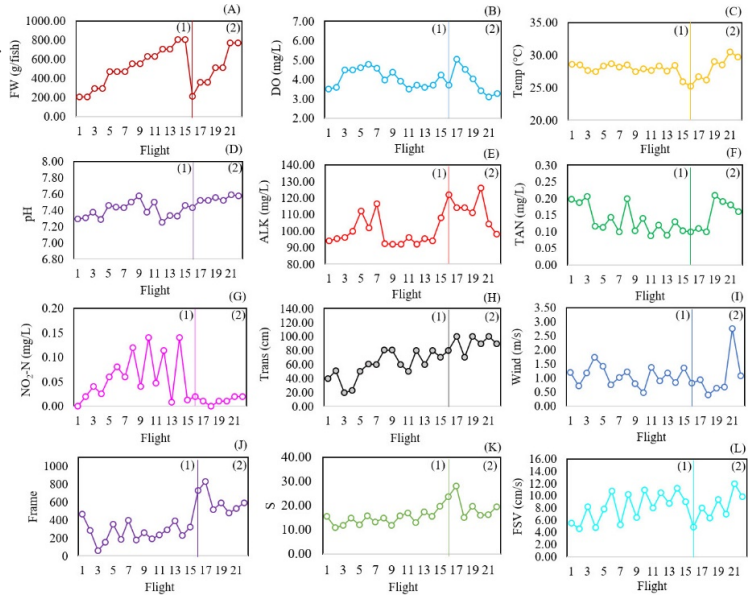


Fig. 2 Distribution of measured variables during each flight for fish weight (FW) (A); dissolved oxygen (DO) (B); water temperature (Temp) (C); water pH level (pH) (D); alkalinity (ALK) (E); total ammonia nitrogen (TAN) (F); nitrite-nitrogen ($\text{NO}_2\text{-N}$) (G); water transparency (Trans) (H); wind speed (Wind) (I); number of video frames (Frame) (J); displacement or distance in centimeters between the captured fish image and the last point or the average processing time (S) (K); and fish swimming velocity (FSV) (L); where (1) refers to information from first crop and (2) refers to information from second crop; horizontal line in each subfigure indicates the number of rounds of flight in each crop, with flight 1-15 belonging to first crop and flights 16-22 belonging to second crop

Table 3 Factor analysis and regression model of variable for prediction

Factor	Variable	Equation	R^2
FSV (cm/s)	3	$-7.681 + 0.007\text{FW} + 0.416\text{Temp} + 13.909 \text{ NO}_2\text{-N}$ (4)	0.701

FSV = fish swimming velocity; FW = fish weight; Temp = water temperature; $\text{NO}_2\text{-N}$ = nitrite-nitrogen; R^2 = coefficient of determination

Fish swimming velocity test

The test results showed that there was no significant difference between using the equation to calculate the FSV and using the Tracker program for every flight, as shown in Fig. 3.

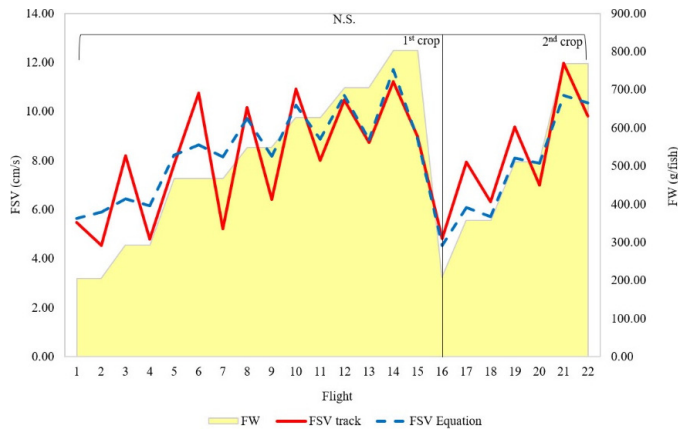


Fig. 3 Comparison between fish swimming velocity (FSV) using Tracker software and FSV equations, where FW = fish weight and N.S. indicates no significant difference ($p > 0.05$) between the curves

Discussion

Water quality parameters (DO, Temp, pH, ALK, TAN and $\text{NO}_2\text{-N}$) were considered within ranges suitable for tilapia culture. Specifically, DO exceeded 3 (Kolding et al., 2008; Tran-Duy et al., 2012), with suitable ranges for Temp of 25–32°C (Azaza, 2008), pH of 7–8 (Lawson, 1995; El-Sherif and El-Feky, 2009), ALK of 75–400 mg/L (Lawson, 1995; Boyd and Tucker, 2012), TAN of <0.5 (Hargreaves and Tucker, 2004) and $\text{NO}_2\text{-N}$ of <1 mg/L (Lawson, 1995; Stone and Thomford, 2004). Trans has a reported optimum value for tilapia culture in ponds of 15–40 cm (Boyd, 1982). However, raising tilapia in cages, especially in river cages, has not been studied; nonetheless, trans value throughout the study period did not affect the eating habitats and growth of the tilapia. Therefore, from the above results, it could be concluded that none of the water quality parameters in the current study had any effect on the fish throughout the culture period.

After FSV evaluation, the average FW was positively correlated with FSV. This was consistent with the theory of swimming in general, namely that small fish usually have lower swimming efficiency than large fish and may also have problems with current resistance (Nikora et al., 2003; Baker, 2014).

The results of the current study were also consistent with the research on swimming performance of Murray cod (*Maccullochella peelii*), eel-tail catfish (*Tandanus tandanus*) and silver perch (*Bidyanus bidyanus*) by Shiao et al. (2020) and on guppies (*Poecilia reticulata*) by Kent and Ojanguren (2015). For tilapia, Mengistu et al. (2021) reported the mean ($\pm$ SD) critical swimming speed (U_{crit}), which can be used to determine fish well-being, for a fish of average weight (10.8 g) was 69.1 ± 5.5 cm/s. For the current study, the maximum detectable swim velocity was 11.78 ± 2.12 cm/s in average-sized fish (767.76 ± 87.84 g). Although the fish in the current study were much larger, their detectable swim velocity was considered to be much lower than the aforementioned U_{crit} . Therefore, it could be concluded that all the velocity findings in the current study showed that tilapia were not suffering from any condition that affected their well-being.

The positive correlations between Temp and $\text{NO}_2\text{-N}$ with FSV were consistent with several studies, including Kent and Ojanguren (2015), who reported that an increase in Temp from 17°C to 32°C resulted in increased swimming velocity of guppies. In addition, Nofrizal et al. (2020) showed that in jack mackerel (*Trachurus japonicus*), a Temp increase of 10–22°C increased the swimming velocity. In tilapia, Sangwan et al. (2019) reported that at a higher average Temp, tilapia had a greater swimming velocity. However, when the average Temp exceeded the optimum level for fish welfare (>32°C), the average swimming speed decreased. With $\text{NO}_2\text{-N}$, although there was a positive correlation with a higher FSV, since the highest $\text{NO}_2\text{-N}$ levels observed in the current study averaged 0.14 mg/L, this was much less than the level affecting fish welfare (<1 mg/L). Therefore, the positive correlation with FSV was due to the increase in FW and the accumulation of waste as the culture period increased. However, when $\text{NO}_2\text{-N}$ concentrations are higher than the appropriate level for the welfare of a fish species, oxygen consumption will be affected (Lefevre et al., 2011).

The method applied in the current study was simple and uncomplicated and could be used to monitor fish movements or behavior as effectively as other complex image analysis techniques that are more difficult to apply, such as the network framework that was used to detect the swimming behavior of spotted knifejaw (*Oplegnathus punctatus*) by Wang et al. (2021) or the use of an angular-feature web framework and limb-mask generation together with remapping to detect starvation-induced stress behavior of darkbarbel catfish by Wu et al. (2022). In addition, the use of the Tracker software combined with a UAV provided wide-angle image evaluation that could cover the entire farming system within a short period of time.

Conclusion

The current study demonstrated the potential of a Tracker-based object tracking method applied in conjunction with the use of UAV to detect FSV. The results showed that this technique could be applied rapidly to detect swimming and as the work process is not complicated, it could be applicable to other studies, such as applications with marine animals, such as mammals or large aquatic animals swimming freely in water that can be seen clearly. Further study of tilapia behavior to indicate fish welfare should investigate using different Ucrit sizes in real farming situations. The information gained could be used to standardize the swimming velocity of tilapia as a further indication of their welfare.

The limitations of this technique were that it can only be used for fish with body colors different from the water surface color. Furthermore, it cannot be applied if the water turbidity is too high so that the fish body cannot be distinguished. Additionally, if the wind speed exceeds 10 m/s, the DJI Air 2S UAV model cannot fly. Finally, further research should aim to develop real-time FSV results using UAVs.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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