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Non-contact Doppler Radar Monitoring of Cardiorespiratory Motion for Siberian Sturgeon

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Abstract— **This paper presents the first reported use of Doppler radar to remotely sense heart and ventilation rates of fish. The Radar reported 35 to 40 BPM heart rate and 115 to 145 BPM ventilation rates for Siberian Sturgeon, with agreement from a video reference. Conventional fish vital signs measurements require invasive surgery and human handling — these are problematic for large scale monitoring, for measuring deep sea fish, and other situations which preclude human interaction with each individual subject. These results show a useful application of radar to augment existing cardiovascular and ventilatory activity sensing techniques and enable monitoring in a wider range of situations.**

Index Terms— **Biology, Doppler Radar, Physiology, Zoology**

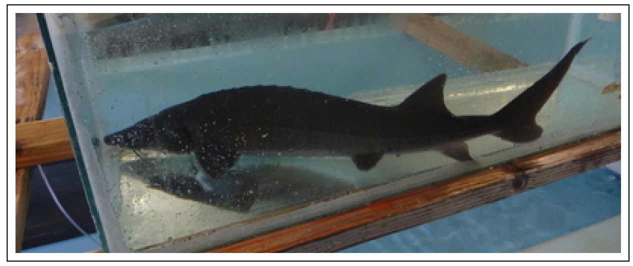

Fig. 1. Photo of Siberian Sturgeon in tank before experiment. The subject massed 8.2 kg and measured 0.87 m from snout to tail at the time of test.

I. INTRODUCTION

Fish provide important dietary nutrition for people. Aquaculture continues to grow more rapidly than all other animal food-producing sectors, with an average annual growth rate for the world of 8.8 percent per year since 1970. Changes in fish, fish populations, and fisheries affect human food supply as well as the rest of the ecosystem.

Vital signs like heart and ventilation rates can provide indicators of metabolic activity [1], stress, and general health. Quantitative information about the health of fish (individually and across populations) can aid policymakers in regulations planning for fisheries activity.

Underwater environments present considerable difficulty for vital sign monitoring with traditional techniques. Subjects are rarely cooperative, and fish, in particular, have scales and mucous covering their skin which both renders pad attachment difficult and low impedance electrical contact less likely. The current technique of preference is needle or wire electrodes for ECG, with the sensor electronics attached externally, or surgically inserted into the body cavity. This suffers from multiple limitations, including: surgery, high invasivity and poor test coverage. While ECG provides good information about every subject so instrumented, it requires capture, handling, anesthesia, and surgical procedures to measure the heart rate. This precludes observational monitoring of fish — either in aquaculture situations, or in studies of wild populations.

Sonar is typically used for underwater sensing with sufficient resolution for locating fish (individually or in schools) or submarine objects at multiple km ranges. Radar systems have been used for non-contact physiological monitoring [2] and radar has exhibited reduced susceptibility to noise as compared to ultrasound [3]. Fish heart rate monitoring via radar has been demonstrated with antenna–subject contact, sidestepping the issue of underwater propagation [4] and experiments conducted without fish show how short range radar sensing can be used and radio attenuation through water can isolate the radar and measurement subject, providing isolation from more distant clutter motion and acoustic noise that is difficult to attain with sonar [3].

Sensing the vital signs of fish is difficult — involving surgically implanting electrodes or monitors. Gill motion is visually detectable and can be extracted from video recordings, but only in favorable conditions (lighting, visibility, overall body motion) and requires painstaking analysis of the recorded motion. For these sensing techniques the subjects can be affected by handling or environmental changes, affecting measured results. Additionally, performing these measurements is costly, further reducing the opportunities for data collection.

Previous research has shown Doppler radar useful for physiological monitoring [2] and motion sensing. While it has also proved capable of sensing heart motion in fish [4], such demonstrations have entailed heavy sedation of the subject, handling, and contact between part of the radar system and the subject body.

The results described herein show heart and ventilation rate monitoring without requiring subject contact with the radar antenna — the first reported demonstration. While these experiments did include handling (and consequently some sedation) and only Siberian Sturgeon were tested, the technique has no fundemental limitations restricting its use to restrained fish or barring its use with other species.

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Fig. 2. Interior view of converted shipping container used as testing area for the experiments. This area was located near the tanks used for raising the fish and provided a controlled environment for initial experiments.

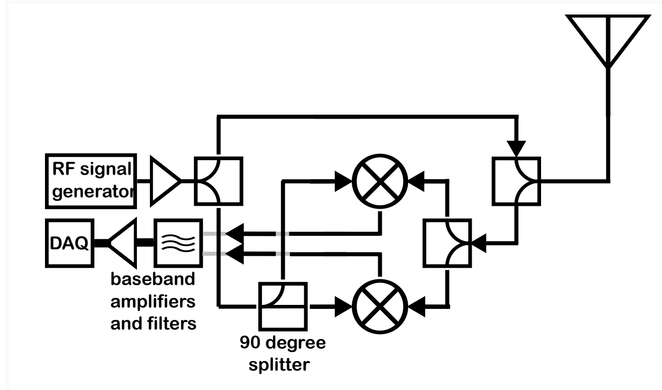

Fig. 3. Block diagram of radar system used for these experiments. The rf blocks (splitters, mixers, antenna) are each indicated in this schematic while the two SR560 amplifiers (one for per channel) used for baseband signal conditioning are noted as a single unit before the computer based data acquisition.

II. Background

A. Sturgeon

Sturgeon are of interest for ecological and aquaculture purposes. They are fished or farmed for their roe (to make caviar) and additionally for their meat. Because they mature slowly, they are especially vulnerable to overfishing and pollution. [5]

B. Visual Monitoring

Visual analysis (video or cinematic) has been used for motion analysis of fish [6], but with swimming rate or body motion as the measured parameters.

C. Doppler Radar Theory

The Doppler effect is a change of frequency when a radio wave reflects off a moving object. Doppler radar operation involves transmitting a radio signal towards an object, receiving the reflected signal, and comparing the two. Directly detecting a continually changing shift in frequency can be difficult and the information about the object motion can be extracted from baseband signals created by mixing the transmitted and received signals. For a continuous wave system with a target position of $x(t)$ over time, the baseband radar output signal B_I can be expressed as:

$$B_I = A_I cos\left(\frac{4\pi x(t)}{\lambda} + \phi_I\right) + D_I \quad (1)$$

with received signal amplitude A, wavelength λ, phase offset ϕ, and DC offset D — B_Q differs only by an offset of $\frac{\pi}{4}$. For an AC coupled system, $D_I = D_Q = 0$.

Periodic motion can be detected as repetitive changes in the relative phase of the transmitted and received signals. As the baseband signals contain information about the relative phase, they will vary corresponding to object motion.

Non-contact sensing is more challenging than contact sensing due to the additional path loss (through the water between the fish and antenna) as well as clutter motion from fish motion. Contact radar does sense some clutter motion, but without antenna-subject contact, the motion of interest will be added to large clutter sources, such as body motion while swimming.

III. Experimental Setup

Each of these experiment required a test subject (Siberian sturgeon), a test sensor (Doppler radar), and a reference sensor (video recording). The testing was conducted inside an enclosure (Fig. 2) to avoid extra stress on the test subjects.

A. Animal Care and Ethics

These experiments were authorized by the Institutional Animal Use and Care Committee at the University of Hawaii and conducted in accordance with an approved protocol.

B. Subjects

Siberian sturgeon (A. baerii) were used as test subjects for these experiments. The first test subject can be seen in Fig. 1 The subjects used for this work are part of an experimental program investigating breeding and raising them in warmer climates. Vital signs may provide early indications of stress and negative reactions to their holding environment.

C. Radar

The low power 2.4 GHz radar system used for these tests was assembled from connectorised components with SR560 low noise amplifiers for conditioning the baseband radar outputs. The local oscillator signal (LO) generated by an Analog Devices ADF-4350 evaluation board required modest amplification to run the mixers at an appropriate drive level. This provided 10 dBm to a printed circuit patch antenna on a Rogers 4003 substrate. A simple diagram of the radar can be seen in Fig. 3.

The antenna was located under the tank (facing upwards) to provide a clear view the fish skin covering the heart. This also allowed sensing of gill motion.

The baseband outputs from the radar were connected to Low noise amplifiers and then digitized using an National Instruments USB-6009 data acquisition device at 1000 Samples/s. Data was collected using software written

Fig. 4. Still frame from video reference showing a side view of the test subject (Siberian sturgeon). Visible in the right side of this frame is a hand holding the subject in the camera field of view and also over the radar antenna. This is more handling than the developed radar systems would require, and the subjects were gently restrained for these tests to simplify both the radar and reference measurements. The alternate (to video) reference would be ECG for heart motion and EMG for gill motion. These video recordings provided a less surgically traumatic option.

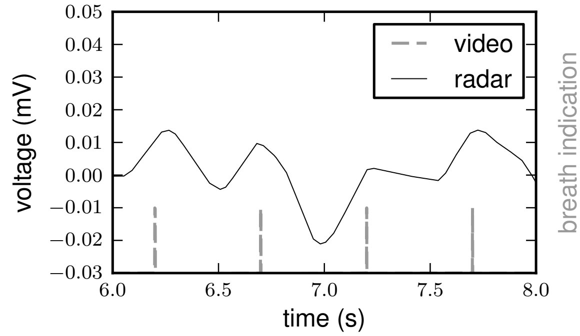

Fig. 5. Plot of simultaneously recorded radar and video data showing the radar output varying in sync with the breathing cycles extracted from the video. Voltage scale is for radar only, with unitless vertical spikes indicating timing for each breath in the video trace.

in LabVIEW, with a live display for instant feedback and traces stored as for off-line analysis.

D. Video

To reduce the impact and risk to the test subjects, video recordings were used as a reference measurement of ventilation rate. As with the radar antenna, the camera was located outside the tank and aimed through one of the tank faces. Later visual analysis of the recordings provided timing information for ventilation.

E. Testing Process

The tests involved moving the fish from the nearby holding tank to the testing tank and lightly sedating them. The sedative helped reduce the stress of handling and reduced the risk of injury to human and fish. After starting the video recording, the radar start could be captured in the video recording for later synchronization. During each test, the subject was held in the field of view of the camera and above the radar antenna. After a limited number of tests, the subject was moved back to the holding tank.

IV. Results

Data from two separate experiments are shown in Fig.5-7. In one test, both video and radar indicate 115 BPM (Breaths Per Minute), and radar indicates almost 40 BPM (Beats Per Minute). The video, recorded simultaneously with the radar, did not provide information on heart rate. In a different test, radar and video (recorded in close sequence) show agreement for heart and ventilation with a heart rate of about 35 BPM and a ventilation rate of about 145 BPM.

A. Video

We extracted respiratory timing information from the video recordings by scanning through them frame by frame and noting the frame number when the motion changed direction — when the gill cover stopped opening and started closing, or vice versa. The still frame in Fig. 4 provides a example of the video appearance, but the image was often blurred by condensation on the tank. Heart motion was not discernible with the camera (live, or in post-test analysis). Since the motion was visible to the eye, we made auditory indications for heart beats and used the audio track for extracting heart rate.

An example of the extracted reference signal is the breath indication in Fig. 5. This same data (from a 24 s excerpt) is plotted over frequency in Fig. 6 overlaid with data from the radar sensor, showing good agreement between the two methods for ventilation rate (in this case 115 BPM.As the video did not provide information on heart rate for this test, only the ventilation rate is comparable.

Since the video was unable to discern the faintly visible skin motion indicative of heart motion, we also used sequential radar and video measurements to allow some checking of the radar detection of heart motion. The heart and ventilation rate from the video recording are indicated in Fig. 7 with the radar data. Evident is the higher ventilation rate of close to 145 BPM as compared to the heart rate which was 35 BPM.

B. Radar

We analyzed the recorded radar data using small programs in Python [7] with additional libraries for data processing [8] and visualization [9]. We used digital filters to clean noise and baseline drift not handled by the baseband filtering. Matching ventilation rates can be seen in Fig. 6, with ventilation and probable heart motion indicated with B and A, respectively. The heart motion was not detectable in the video reference for this set of data and is thus shown only in the radar output. The plot of motion in the frequency domain in Fig. 7 shows two large peaks (heart A, ventilation B) at approximately 35 BPM and at 145 BPM which correspond to the heart and gill motion observed with the video reference. Both frequency plots were generated using 24 s long windows of data.

V. Discussion

The radar reported heart and ventilation rates matched those from the reference. Both the radar and video showed

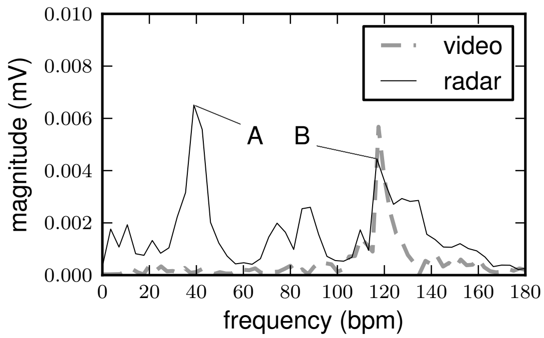

Fig. 6. Plot of ventilation over frequency for both radar and video showing good agreement between the two for ventilation. Two peaks in the radar trace are indicated with A and B (heart and gill, respectively) indicating detected physiological motion with the ventilation matching that from the video reference and the heart rate shown only in the radar trace due to trouble with monitoring heart motion in the video recording.

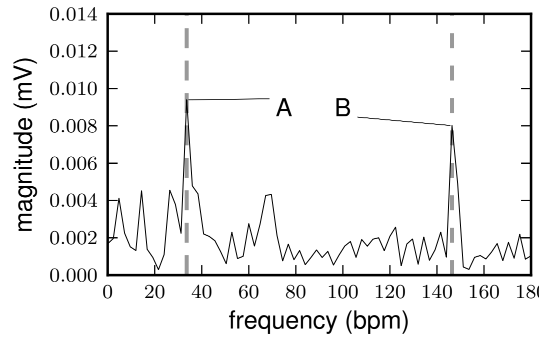

Fig. 7. Plot of radar sensed motion over frequency with heart and ventilation (A, B) motion marked. Radar and reference agreement can be seen in the overlap between the indicated peaks and the dashed vertical lines.

the variation in ventilation rate over time in the course of testing. The video reference was labor intensive and difficult to interpret in low visibility conditions. The radar worked at short ranges ($<$10 cm) with no clutter motion (inside or outside the tank), but was sensitive to human motion near the testing area. A few radar systems working in cooperation should be able to detect one of these fish in a larger tank and identify heart or gill motion using signal processing techniques such as a generalized likelihood ratio test (GLRT) [10] or blind source separation (BSS) [11]. While such a system would detect all motion sources, the physiological motion signals may be identified by characteristics, such as: amplitude, frequency, repetitiveness, and radar cross section (RCS) of the motion source [12]. If such a combined system is not able to continually provide heart and ventilation rate information, it should be able to provide data or an indication that that data is unavailable.

For aquaculture, these fish are not raised in separate tanks, one for each individual, but rather with many sharing each tank. In such a situation, rather than using signal processing to isolate useful signals from the body motion, it may be prudent to add a feature to the enclosure that can serve to isolate just a few fish at a time for a quick check of vital signs. By cycling the fish through the monitor, the overall condition can be assessed.

VI. Conclusion

These experiments are the first reported demonstration of Doppler radar detection of cardiovascular and ventilatory activity motion without antenna–subject contact. While these experiments did include handling (and consequently some sedation), they are not required as an integral component of radar as a measurement technique. This measurement technique may have useful applications in aquaculture in addition to offering the capability to add some vital sign information to fish with no more disturbance than observation.

Acknowledgment

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