DOPPLER RADAR SENSING OF FISH PHYSIOLOGICAL MOTION

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Abstract

The monitoring vital of signs for fish is critical for advancing the study of trophic and energetic strategies, distributions and behavior, environmental impact, and aquaculture approaches. Presented here is a new approach for monitoring fish metabolic state without the trauma and stress associated with capture, surgical ECG, or other implanted sensing systems. Original research contributions include analysis for radar operation under water, development of radar systems for aquatic operation, and application of these systems to non invasively sense the heart and gill motion of fish. Tilapia and Sturgeon were studied to test the efficacy across varied fish body shapes and sizes, ranging from 0.1 to 1.3 m in snout to tail length. Monitoring experiments were conducted with eleven tilapia and three sturgeons to assess activity level participated in these experiments, the results from which include activity level monitoring (tilapia: still or fidgeting 94 % of time observed), ventilation rate (tilapia: 42 bpm, sturgeon: 145 bpm), and heart rate (tilapia: 41 bpm, sturgeon: 35 bpm). Bland-Altman analysis of radar and ECG measured heart rate indicate agreement between the two measurement techniques and the suitability of radar as an alternative to ECG. The initial steps for developing a system for practical application is also presented including designs for radar system miniaturization and discussion on further characterization steps with less constrained environments.

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CHAPTER 1

Introduction

Fish provide important dietary nutrition for more than 2.6 billion people [1]. Aquaculture continues to grow more rapidly than all other animal food-producing sectors, with a worldwide average annual growth rate 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 [2], stress, and general health. Quantitative information about the health of fish (individually and across populations) can aid policymakers in regulations planning for fisheries activity.

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. Related to the difficulties of surgical procedures, while ECG provides good information about every subject so instrumented, it requires capture, handling, anesthesia, and then either a tether, a transponder, or recapture to acquire the data. 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.

Precise measurement of fish motion (body, gill, heart, and more) can provide vital sign data without necessarily requiring surgery. Remote sensing techniques such as radar and sonar can facilitate such measurements in a manner which is less labor intensive than visual inspection, while also avoiding other intrusive measures such as bright lights, and excessive handling.

In the course of my research, I have demonstrated an effective approach for radar monitoring of fish body motion, detection of heart rate, and respiratory movement. Effective reference measurements for such vital signs are difficult to realize. To validate my work, I have used video recordings to verify some radar measurements and ECG heart sensing for others, though the reference measurements have necessarily restricted the measurement conditions beyond what is fundamentally required for radar remote sensing alone.

This research builds on existing work involving physiological sensing of people with Doppler radar and also on prior work involving fish research. This work can lead to sensor systems for monitoring fish health in aquaculture, less invasive vital sign measurement of wild fish for research studies, as well as interesting and useful sensors for other applications, such as human diver heart rate monitoring. Techniques for signal analysis and data processing — for example extracting heart rage from clutter motion or canceling body motion — can be adopted from techniques developed for use with human subjects [3–5].

1.1 Fish Physiology and Importance

Fish are interesting from scientific and economic perspectives. In addition to the almost human habitable near-surface of water bodies, fish also live in much less accessible depths. Understanding fish and how human activity affects them can help us avoid inadvertent overfishing. Aquaculture is a growing industry and quantitative data can aid monitoring stress and health of the fish.

1.1.1 Physiological Data

Radar is unable to provide information about oxygen uptake or hormone levels in fish, but it can provide heart rate, ventilation rate, and body motion information [6]. These can be used to provide estimates of metabolic rate, energy budget, and relative stress levels. Patterns in activity or metabolism can illuminate when the fish is active (day, night, dusk/dawn), and relative health — which could be useful for aquaculture.

1.1.2 Fish Body Shape

Some fish, such as Tilapia or Pacu have bodies with a thin cross section while others, such as Sturgeon have a much rounder cross sectional body shape. All experimental subjects had a heart location near the gills. This affects useful locations for a body mounted radar sensor and likely the performance of a remote radar sensor (depending on angle of antenna from body).

1.2 Current Fish Physiological Sensing Techniques

Current techniques for sensing heart motion in fish require trans-dermal needle electrodes for electrocardiogram (ECG) or intravenous cannulae and a pressure transducer. Gill function (motion and oxygen uptake) are measured with cannulae (or catheters) implanted in or near the gills. Two studies of gill function examined gill function by measuring O_2 uptake. One compared measurements to less invasive estimates with a standard model [7]; the other investigates changes in gill function over temperature [8]. These techniques are similarly limiting to human ECG and spirometry measurements. Existing techniques for wireless transmission of heart rate data [9] allow less restricted swimming but require implantation of a radiotelemetry transmitter into the fish (similar to holter monitors).

1.3 Radar for Physiological Monitoring of Fish

Radar is a non-invasive alternative to ECG heart rate monitoring and can also provide information about gill and body motion. It is not the only non-invasive sensing technique as sonar is another candidate, with well known capabilities for long range underwater sensing.

1.3.1 Radar and Alternatives Sensing Techniques

Non-invasive sensing techniques include radar and sonar sensing of physiological motion. Sonar is widely used in aquatic environments for long range detection of fish and submarines, in air for short distance range finding, and also in medicine for imaging ultrasound diagnostics. Radar is widely used for detecting and tracking aircraft, in aid of meteorological study, and also for tracking surface vehicles.

Radar operation finds air a suitable medium; for short range sensing such as heart rate [10], detection of buried antipersonnel mines with ground penetrating radar [11, 12], or air search [13]. Physiological sensing with Doppler radar has been previously demonstrated with human subjects [14, 15]. Research involving vital sign monitoring with Doppler radar has demonstrated lung motion [14] and heart motion [10] and investigated radar performance at more sensitive aspects of heart motion detection [16, 17].

1.3.1.1 Comparison of Radar and Sonar

For short range underwater sensing of heart and gill motion, radar offers reasonable tradeoffs for range and rejection of environmental noise (section 2.3). For long range underwater sensing, sonar offers much greater range than radar — for active and passive modes of operation.

Underwater radio propagation has been studied [18] with a goal of improved wireless communications for remotely operated vehicles (ROV), autonomous underwater vehicles (AUV), and manned submersibles. Part of the impetus for this research stems from limitations of acoustic communication links (due to noise in the environment).

1.3.1.2 Radar Benefits for Physiological Sensing

For the task of detecting small motions of a fish heart, the drawbacks of underwater radio propagation can be an advantage in that a lower level of background noise or clutter can help increase system performance. A possible additional advantage is the lack of sensitivity marine animals exhibit for radio energy, as compared with sound.

1.3.1.3 Commercially available Off-The-Shelf Radar Systems

Commercially available Off-The-Shelf Radar modules exist for low cost applications such as advanced cruise control, backup sensors, and automatic door sensors. These have been used in physiological sensing with human and animal subjects [19, 20]. As useful as these radar modules are, they are designed for use in air and fare poorly for aquatic usage. The two main problems are water sensitive electronics proofing and antennas designed for use in air, not water.

1.3.2 Radar Operation

Many radar systems operate by transmitting pulses of energy and sensing the time before echos return. Pulse radar systems are commenly used for air search, tracing, meteorological observation, or navigation.

Air Search radar installations usually involve high power transmissions and large parabolic antennas to offer long range detection and tracking.

Continuous wave radar systems, as described by their name, continually transmit radio waves and rather than directly measuring the time for descrete echos to return. Some systems vary the frequency of the transmitted radio waves while others transmit a single frequency, known as Continuous Wave (cw) Doppler. CW radar provides information about velocity or relative range without directly finding the actual distance.

This work involves CW Doppler radar sensing at short ranges. Radar sensing of human vital signs typically operates at ranges of 1 to 2 m in air. Fish motion sensing underwater will operate at shorter ranges – less than 1 m.

1.3.2.1 Doppler Radar Basics

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.

1.3.2.2 Carrier Frequency Analysis

Some Doppler radar speedometers compare the shift in reflected RF carrier, traffic radar used by police is one such example. Using such a radar sensor, the speed of an object can be measured by comparing the frequency of the received signal to that of the transmitted signal. The frequency deviation is:

$$F_d = 2v\frac{F_0}{c} \tag{1.1}$$

with detected change in frequency F_d, object speed v relative to the sensor, frequency of operation F_0, and the speed of light c. Directly detecting this change in frequency can be difficult when the subject is moving slowly or with variable speed.

1.3.2.3 Quadrature Radar and Phase Interferometry

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:

$$B_I = A_I cos\left(\frac{4\pi x(t)}{\lambda} + \phi_I\right) + D_I \tag{1.2}$$

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, $D_I = D_Q = 0$.

The hardware arrangement of the radar is depicted in Fig. 1.1 with the baseband signals I and Q feeding from the mixers (inside the receiver section labeled B) to the baseband signal procesing.

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

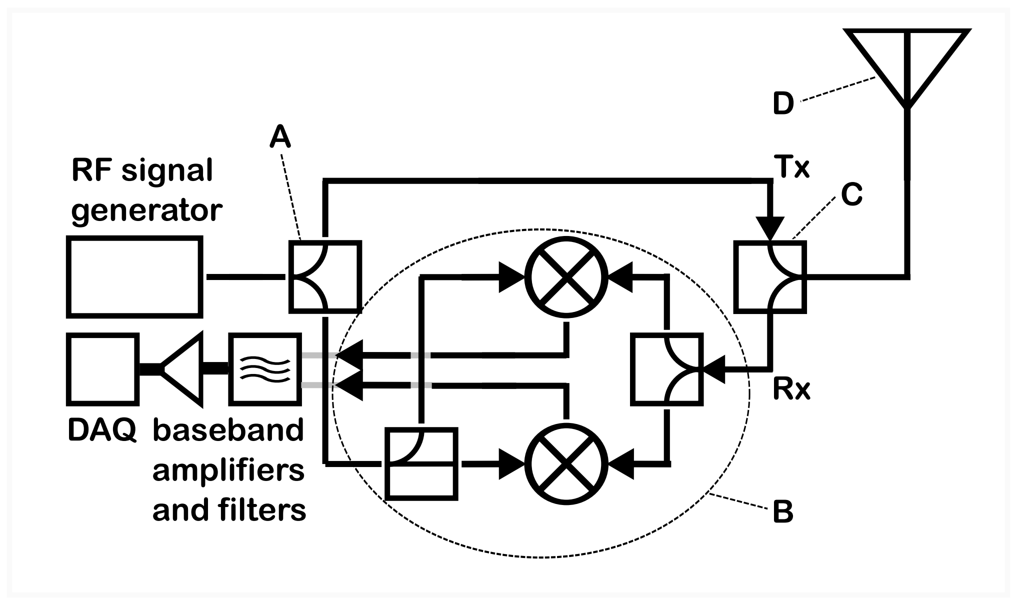


Figure 1.1: Doppler radar system used for experiments (not including computer). The generated RF carrier is split by a splitter (A) and sent to the receive section (B) and to be transmitted. The receive section uses the carrier to down convert the reflection from the subject. The splitter (C) near the antenna (D) sends the transmit signal to the antenna and the reflected signal to the receive section. The same antenna is used for both transmit and receive because the subject is directly in front of the antenna and one antenna requires less space than two antennas. Additionally, a quadrature receiver avoids the null point limitation from which single channel radars suffer.

motion, but without antenna-subject contact, the motion of interest will be added to large clutter sources, such as body motion while swimming.

1.3.3 Underwater Propagation

Underwater, radio propagation is limited due to dielectric and conductive properties of water. The relative permittivity of water, ε_r, at frequency ω is

$$\varepsilon_r = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + j\omega\tau}, \tag{1.3}$$

with the relative permittivities at zero and infinite frequencies (respectively) ε_s and ε_∞. The propagation constant (γ) depends on frequency (ω), relative permittivity (ε_r), and relative permeability (μ_r)

$$\gamma = \frac{j\omega}{c}\sqrt{\varepsilon_r \mu_r} = \alpha + j\beta. \tag{1.4}$$

This propagation constant can be used

$$E_x = E_0 e^{j\omega t - \gamma z} \tag{1.5}$$

to calculate the electric field strength of a plane wave traveling in the z direction.

While this limits the range of operation, it also isolates the system and subject from other motion further away in the environment [21–23]. For example, the radar may sense motion at a range of 0.5 m in the presence of significant clutter motion 2 m from the antenna.

1.4 Performance Envelope

Radar systems face different limitations from underwater use than those used above the waterline. Air search radar systems are typically limited in range by the curvature of the earth and line-of-sight propagation of radio waves. In aquatic environments, radar sensing will be used at relatively short ranges — likely under 2 m and possibly in contact with the subject.

Water as a transmission media limits the use of high frequencies (above 10 GHz) and for subject–contact situations, the body size provides limits on how large the antenna can be. Portability and hydrodynamic antenna drag will limit non-contact radar systems to antennas of modest sizes.

CHAPTER 2

System Considerations for Underwater Fish Monitoring

Physiological sensing with Doppler radar has been demonstrated with human subjects. Radar also has proven capable of object detection through ground [11]. As a medium of operation, water is uncommon for radar or other radio transmissions. Generally submarine sensing involves sonar, though radio transmissions at very low frequencies are a relatively common exception for short distances through water.

2.1 Vital Sign or Physiological Motion Monitoring Technology

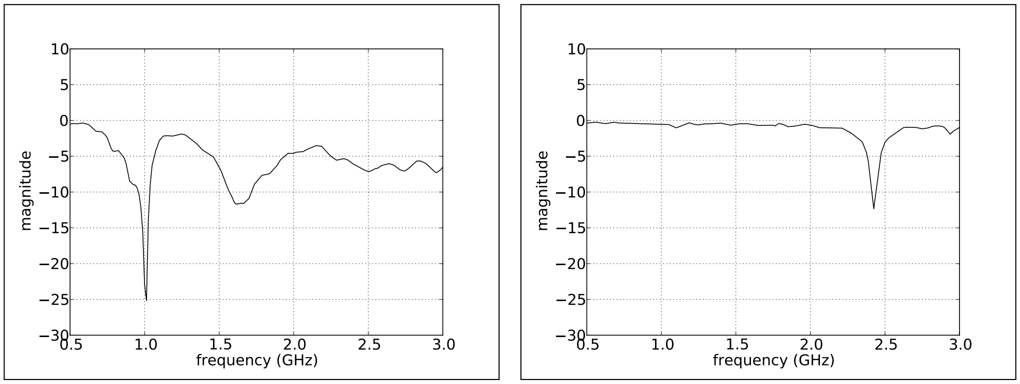
Fish heart rate monitoring currently entails the use of one of electrocardiogram (ECG) or intravenus cannula. Both of these require surgery to properly locate the sensor. In addition to the implanted sensor, a local transducer to digitize the signal before recording or transmitting [24] to a recorder is needed if the subject is not to be tethered by the sensor connections.

A list of less invasive sensing options might include Sonar, Radar, and Inertial sensors. Each of these technological bases has both benefits and drawbacks. Sonar is widely used in aquatic environments for long range detection of fish and submarines, in air for short distance rangefinding, and also in medicine for imaging ultrasound diagnostics. Radar is generally known for long range detection and tracking in aerospace environments, as well as radar guns for speed limit enforcement by police. Inertial sensors have been used for sensing activity patterns with whitetip reef sharks [25].

For short range underwater sensing of heart and gill motion, radar offers reasonable tradeoffs for range and rejection of environmental noise (section 2.3).

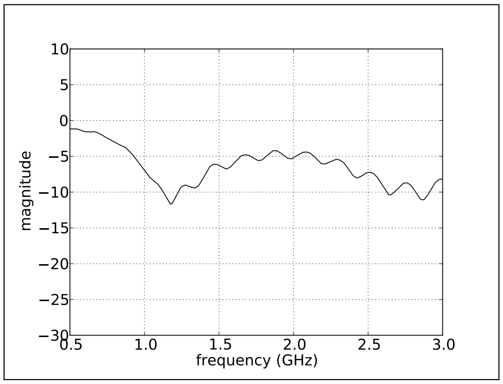
2.1.1 Coupling Radar Transmission into Fish or Water

Radar system operating in air or space need to efficiently couple energy from antennas into air. Likewise, underwater radar systems need to transmit radar signals into water (non-contact) or into the skin/fat/muscle of the subject (contact). This differs markedly from transmitting into air, as can be seen in



(a) return loss for spiral antenna in contact with skin

(b) return loss for patch antenna in air



(c) return loss for patch antenna in contact with skin

Figure 2.1: Return loss for the spiral antenna (a), patch antenna (b), and patch antenna on skin (c). The patch antenna in contact with skin shows moderate return loss over a wide frequency range compared to the sharp spike typical of patch antennas.

the plots of return loss (s11) over frequency in Fig. 2.1.

2.1.2 Effects of Media on Radio Transmission

Non-invasive sensing is a clear advance over invasive techniques requiring surgery and non-contact sensing offers benefits over contact sensing techniques.

Radar used for remote physiological motion sensing will have to overcome poor underwater propagation.

2.2 Performance Assessment Techniques for Doppler Radar Physiological Sensors

2.2.1 Background

2.2.1.1 Radar Performance

For physiological sensing systems, the ultimate measure of performance is how successful it performs the task of detecting physiological data (e.g. human heart motion). This is important and so most testing involves using the radar on humans. While testing with human motion is indispensable, it is not ideal for all cases: the pattern of motion constantly changes and people have limited parameters that they can safely experience. A target able to create repeatable patterns of motion with lessened constraints would enable testing of small adjustments in radar systems that may be obscured by the variation in motion when using human subjects to test these radar systems. This target could augment testing with human targets by providing complimentary coverage to enable better understanding of the radar performance.

2.2.1.2 Issues Affecting Performance

A Doppler radar system detects motion by transmitting a specific at frequency and then determining the doppler shift in the reflected signal. The direct conversion radar system used here accomplishes this by using a single local oscillator (LO) for the transmitting and receiving portions of the radar. The received signal is mixed with the LO directly converting the signal to baseband. For small, slow targets with constantly varying speed, various effects can reduce accuracy: phase noise, electrical noise, RF interference and clutter from other motion. System variations to mitigate these effects may, individually provide some benefit, but not enough to provide noticeable changes in overall performance with human targets.

2.2.1.3 Performance Assessment with Humans and Animals

Radars for human measurement are often tested using people. This has the benefit of directly testing actual performance and no special effort is required to generate the motion. Some of the problems with using human generated motion for assessing performance or characterizing these systems include: uncontrolled motion, reference measurements, variation between (and during) tests, variation between individuals, excess motion clutter, and limits on the possible motion. A simple example of this is separately generating motion with heart or lungs — stopping a person's heart is dangerous, and certainly not something to do when there exist alternatives. A more interesting example is the extraneous motion that people create. In addition to cardiopulmonary motions, people have minute motion in various parts of their bodies — these movements are small compared to visible motions (walking, breathing), but are large enough to interfere with experiments to characterize small differences in measurement technique.

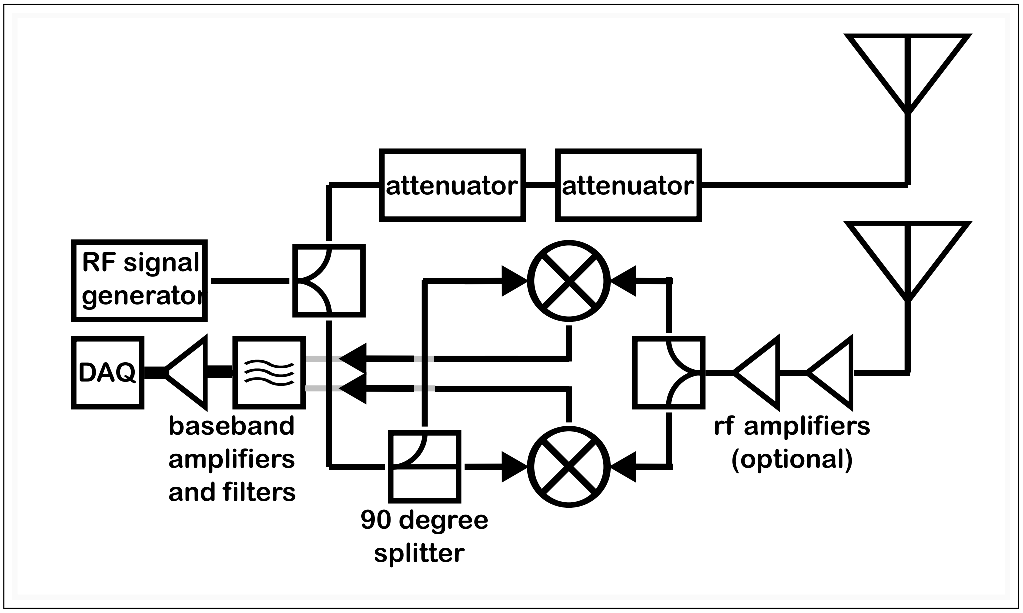


Figure 2.2: Diagram of Doppler radar with mechanical radar target used for assessing the capabilities of the radar system. The target provides a pattern of motion similar to that of a human heart to be measured by the radar.

These issues with using human test subjects in experiments for assessing the performance of various radar systems become worse with non-human subjects, such as fish. Testing radar systems in experiments with live fish subjects is appropriate for determining performance with those tested fish. It is not an appropriate method for investigating parametric changes in performance, for example system sensitivity to motion at multiple frequencies. Controllably repeatable phantom movers can serve as mechanical targets for radar tests not requiring a real fish or other live subject. This allows for a reduction in quantity of experiments undergone by fish.

2.2.1.4 Performance Assessment with Mechanical Targets

Using a simple mechanical target for testing radar systems can provide improved control for motion — eliminating some variations between experiments. The largest drawback for using non-human targets for assessing performance on humans is assuring correspondence between the two. The more obvious differences include: rhythm of motion, waveform shape of the motion, size of target, reflective characteristics of target. Since humans show variation between individuals, a mechanical target cannot both provide the same characteristics and match multiple people equally well. Using mechanical targets can be seen instead as offering complimentary capabilities that allow testing of performance in ways that human targets do not.

2.2.2 Experimental Setup

2.2.2.1 Radar

The radar was assembled using coaxial components: Agilent E4433B RF signal generator, Mini-Circuits ZFSC-2-2500 splitters, Mini-Circuits ZFM-4212+ mixers, Narda 4033C hybrid splitter, Laird Technologies PA24-16 16 dBi panel antennas, ZX60-6013E-S, SRS SR560 amplifiers, and a NI USB-6009 data acquisition card. The attenuators were used to reduce the transmitted power by up to 60 dB. Since the RF signal generator was set to 13 dBm, the resultant transmit powers (after one 3 dB splitter and the two attenuators) ranged between 10 dBm and −50 dBm (10 mW to 10 nW). For longer range tests (20 m and greater), RF amplifiers were optionally used. These amplifiers have a max-

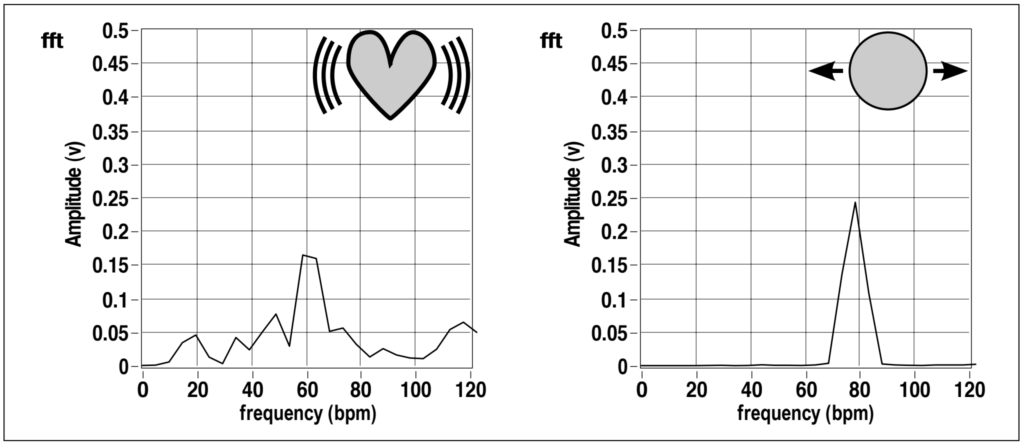


Figure 2.3: Frequency domain plots for human and mechanical motion at 1m. Even with lung motion filtered out, the heart shows variation in rate during the 12s fft window in addition to extraneous motion at other frequencies in the band of interest. The mechanical target demonstrates a high degree of repeatability (constant single frequency in motion pattern) and can be easily reprogrammed with a more complex pattern to create a higher fidelity copy of the motion a human heart produces.

imum output power of little more than 13 dBm and were therefore connected on the receive side where they could each provide almost 15 dB of gain.

2.2.2.2 Mechanical Targets

The mechanical target used was created with a 5 cm diameter spherical reflector on a pivoting arm. The arm was mounted directly to the output shaft of a small servo, controlled and powered by a simple microcontroller. During experiments, the target was placed on a second cart so its height would match that of the radar antennas and additionally to enable easy adjustment of radar-target distance. The only portions of the mechanical target that move with the same pattern of motion as the reflector are the arm, the screws mounting the arm to the servo and the servo horn that connected to the shaft. The arm was made from 3 mm thick plastic, to reduce radar reflections from it. The screws

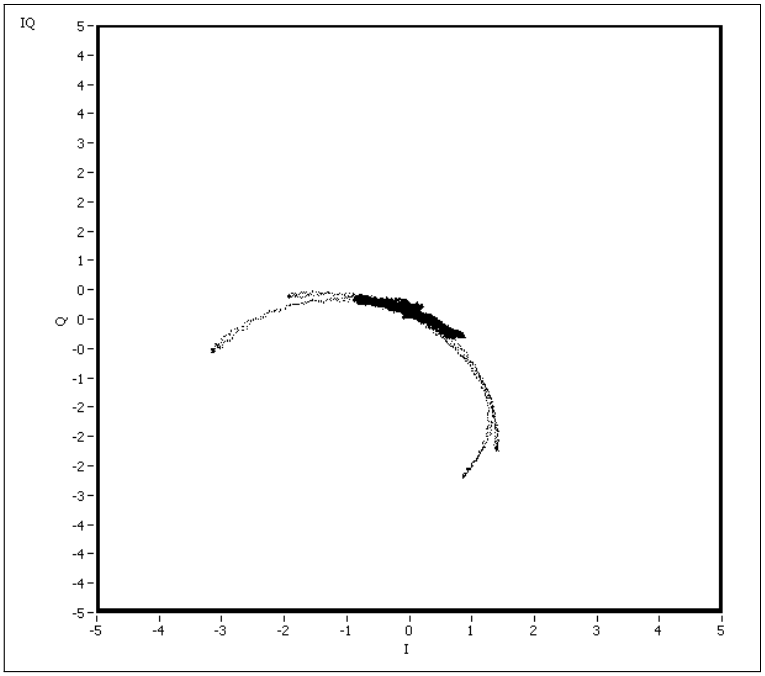


Figure 2.4: Plot showing circular arc in IQ output of radar.

were small compared to the wavelength (125 mm $\gg$ 1.5 mm) and moved much less than the reflector. As Fig. 2.4 shows, for small angular displacements, the motion can be considered essentially linear (along the tangent to a circle centered on the axis of rotation). For larger motions, this no longer holds. The motion desired from the targets is limited to 10 mm peak to peak, so the reflector was positioned 70 mm from the axis so that the target would be at most 0.2 mm from the ideal straight line position.

2.2.2.3 Environment

The testing was conducted in a building hallway to allow for greater radar-target ranges. The only special consideration for using the hallway was arranging to test the radar early in the morning when the building was empty to reduce

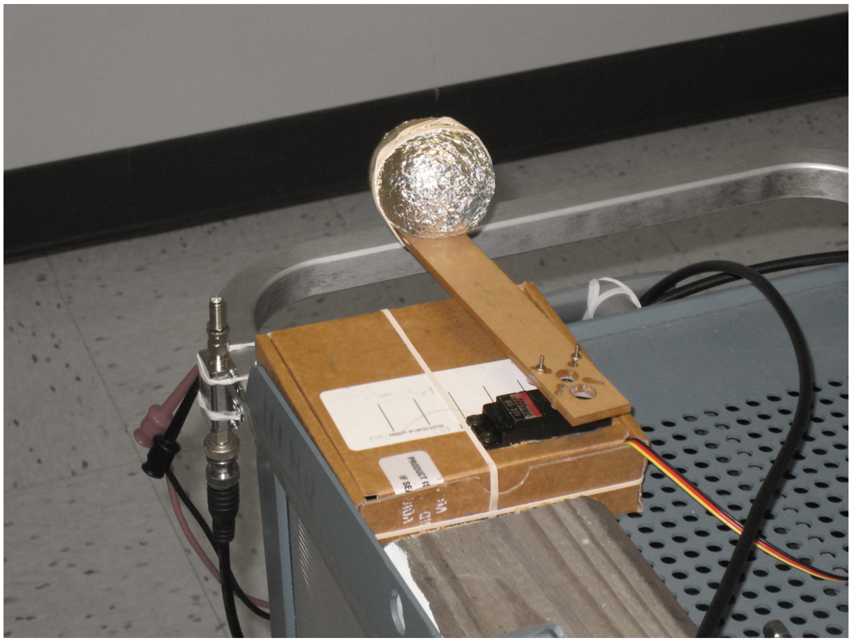


Figure 2.5: Moving radio reflector for characterization of Doppler radar system for physiological motion sensing across varying ranges. This controllable motion source is mounted on an equipment cart to elevate it and to ease repositioning of the mechanical phantom along with the support. The metallic sphere has an aspect independent radar cross section and the support arm does not reflect radio frequency energy.

clutter from people walking in the hall. The 2.4 GHz radios (802.11) present were left on and operating during the testing. The target was positioned 1, 5, 10, 15, 20 and 30 m from the radar and moved in a sinusoidal motion at 1.3 Hz with first a 10 mm and then a 1 mm range of motion.

2.2.2.4 Performance Assessment

For these tests the radar (including motion detection software) was considered to have successfully detected the motion of the target if the reported frequency of motion matched that programmed into the target. Correctly detecting the

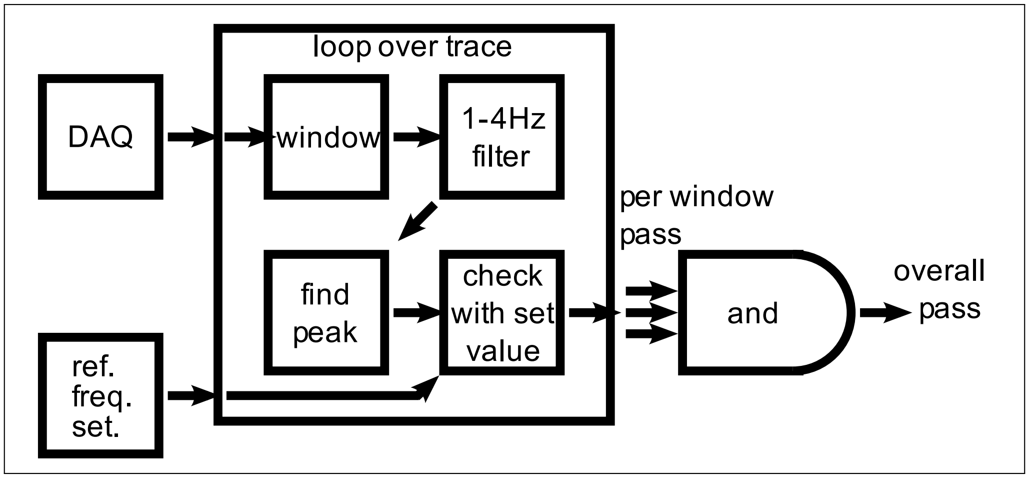


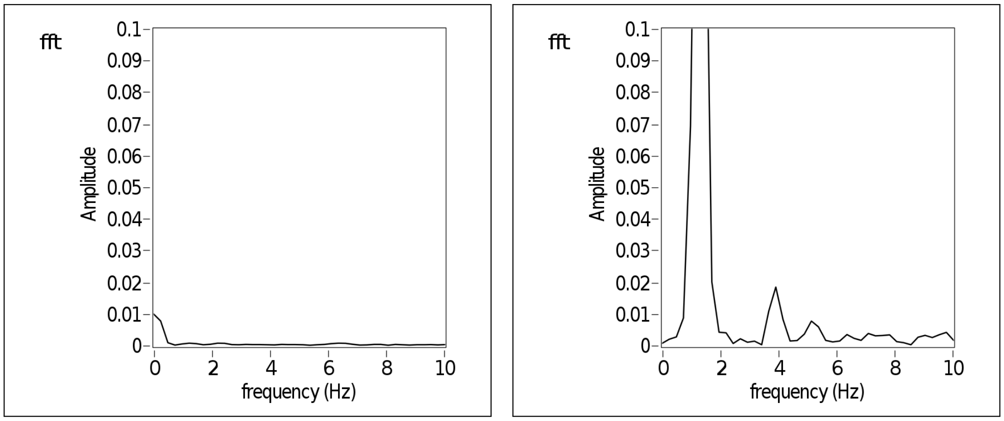
Figure 2.6: Motion detection and grading algorithm. The logic that creates the pass/fail indicator requires a signal to correctly match the frequency programmed into the target for all positions of the window as moves over the trace.

motion using the in phase or the quadrature phase channel was considered sufficient. The motion detection portion of the software (Fig. 2.6) performed frequency domain analysis of the signals in four second blocks by searching in the 1–4 Hz (60–240 bpm) range and selecting the frequency bin with the highest energy. The assessment portion of the software checked for a match between the selected frequency with the specified frequency of motion — anything other than the two matching (same frequency bin) was counted as a failure.

2.2.3 Results and Discussion

2.2.3.1 Short Range (1 m)

The short range test results show the correspondence between the signal produced as a result of human heart motion and that produced from the mechanical target. Fig. 2.3 shows the radar output for a human (heart and lung motion)



(a) stationary

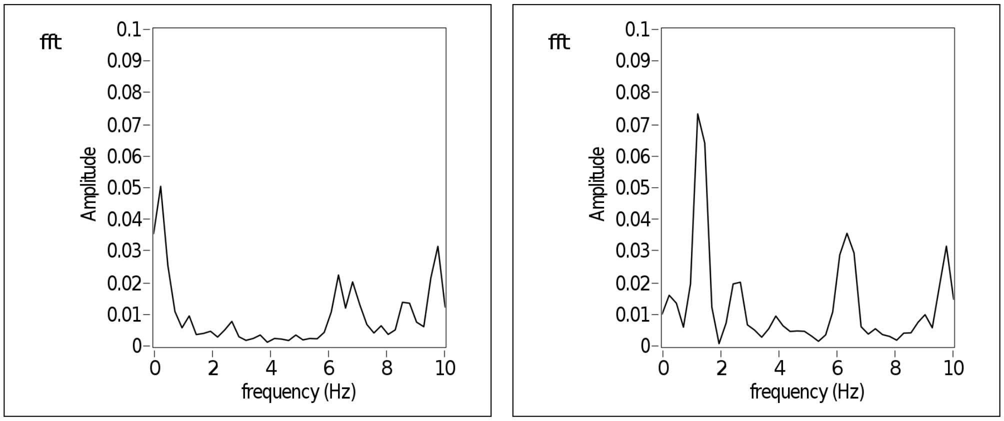
(b) moving

Figure 2.7: Frequency domain plots of the radar I channel first (a) with the phantom subject standing still and (b) then with it moving at a frequency reasonably close to that of a human heart rate. The radar output for the stationary phantom (a) shows the low noise floor of the radar output in a motionless environment and the plot with the moving mechanical phantom plot (b) shows large peaks at its frequency of motion. The harmonic frequencies in that plot are a predictable result of the non-sinusoidal pattern in the motion.

and additionally the radar output for a mechanical target. Fig. 2.7 shows the fft from the I channel from the radar with the mechanical target at 1 m.

2.2.3.2 Long Range (30 m)

At longer ranges, the radar signals showed artifacts from the interference caused by the 802.11 network in addition to the lower signal levels expected at these ranges. Though these artifacts can be clearly seen in Fig. 2.8, the radar is still able to correctly detect the motion of the target. The spikes in the frequency plot at 3.5, 6.1, 8.5 and 9.8 Hz are not harmonics of the target motion (1.3 Hz) but rather other RF energy (nearby 802.11 equipment).



(a) stationary (b) moving

Figure 2.8: Frequency domain plots of the radar I channel with mechanical phantom at long range first stationary (a) and then following an oscillating pattern of motion (b). The radar data from the moving phantom subject (b) shows clearly the motion and also environmental noise from nearby radio transmitters and clutter motion. This noise floor can be seen in the stationary plot (a) without signal contributions from the subject motion.

2.2.3.3 Detection Algorithm

The detection algorithm was checked for false positive results by sequentially setting the frequency of interest to an other value as well as setting the target at a different rate. While the detection algorithm provided stable (and correct) results when tested with a moving target, control tests (with no target motion) resulted in various incorrectly detected frequencies that changed within each test as well as between successive tests. Generally, the "detected motion" had little relation to that programmed into the target (since the target was switched off). Most tests used a single frequency of motion — 78 bpm (1.3 Hz), but the detection algorithm also correctly detected the frequency of motion when the target was programmed for 0.3 Hz as well as other values in the 1–4 Hz range.

2.2.4 Discussion

The three tests presented include one comparing the radar response to a human target and the response to a mechanical target, one showing the the radar response for a close target and one showing the response of the radar for a far target. Even with directional antennas, the radar was sensitive to nearby movement. This was not a problem for tests with the target located close to the radar but long range tests resulted in low return power from the target and showed much more sensitivity to extraneous motion. To prevent non-target motion from interfering with the radar, a short timer was used to delay the start of test until after people moved away from the radar. The long range test, which used RF amplifiers in the receive section, showed significant noise before the target started moving. The signal generated by the motion of the target is easily greater than that of the noise in the frequency range of interset, but for some of the lower transmit power tests, the noise at 6.5 Hz and 10 Hz was greater than the signal from the target. In these cases the brick wall filter at 4 Hz allowed the motion detection algorithm to correctly identify the target motion, despite this noise. The noise seen in tests with lower return power (low transmit power, long range or both) had a similar appearance to what an idle 802.11 network might produce (10 Hz beacon). This is significant for a direct conversion doppler radar system since the range correlation effect lessens as range increases [26].

This experiments show environment configurations in which the additional attenuation in water could be useful: with significant noise or clutter sources located at least a moderate distance from the radar system and the experimental

Table 2.1: Output from motion detection grading module. −50 dBm transmit power was only tested at 30m with two amplifiers.

	transmit power (dBm)		
Range (m)	10	-30	-50
1	✓	✓	-
10	✓	✓	-
20	✓	✓	-
20 w/amp	✓	✗	✓
30 w/amp	✓	✗	✓

subject located close to the radar system, the subject will be isolated from the rest of the environment by the high attenuation of water propagation. This would point to a range of frequencies low enough to offer sufficient high antenna–subject range for a usable system, but high enough to allow signal attenuation through water to cut out clutter and noise that would otherwise complicate measurements.

2.3 Noise and Range Considerations for Close-Range Radar Sensing of Life Signs Underwater

Measuring the heart rate of aquatic animals is particularly difficult, with current techniques involving invasive procedures. The safest and least invasive is surgical Electrocardiogram measurement, which still requires needle electrodes to be inserted subcutaneously. Contact radar sensing of heart motion improves on this be obviating the transdermal electrodes, but still requires handling with the subject.

Non-contact sensing offers many advantages, in addition to non-invasive monitoring with reduced stress on the subject, it can be used outside the laboratory setting for remote or automated sensing — possibly also for animal detection. Sonar is typically used for underwater sensing, but standard sonar systems lack sufficient resolution for detecting heart motion. Radar systems have been used for non-contact heart rate monitoring [14], but radio waves suffer from poor underwater propagation. Fish heart rate monitoring via radar has been demonstrated with the antenna touching the fish [27], sidestepping the issue of propagation — this is interesting, but remote sensing has much wider use.

For the initial investigation, simplified test cases will provide easier to analyze data and reduce the amount of testing for live subjects to techniques that have already been refined.

2.3.1 Background

Doppler radar operation involves transmitting a radio signal towards a target, receiving the reflected signal, and comparing the two. For continuously moving targets (e.g. an automobile), the speed of the target can be measured by comparing the frequency of the received signal to that of the transmitted signal. For oscillating targets (e.g. a mover in an aquarium, or later, a heart), the variation of phase difference from the transmitted to the reflected signal will be more useful for detecting the target motion. For a continuous wave system with a target position of $x(t)$ over time, the demodulated signal can be expressed as:

$$B_I(t) = A_I cos\left(\theta + \frac{\pi}{4} + \frac{4\pi x(t)}{\lambda} + \Delta\phi(t)\right) \tag{2.1}$$

for one of the channels (with the other offset by $\lambda/4$). This is the same as eq. 1.2 but with components of the phase shift for the return signal (θ, $\frac{\pi}{4}$, $\Delta\phi(t)$) included separately.

Underwater, radio propagation is limited due to dielectric and conductive properties of water. The relative permittivity of water, ε_r, at frequency ω is

$$\varepsilon_r = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + j\omega\tau}, \tag{2.2}$$

with the relative permittivities at zero and infinite frequencies (respectively) ε_s and ε_∞. The conductivity (γ) depends on frequency (ω), relative permittivity (ε_r), and relative permeability (μ_r)

$$\gamma = \frac{j\omega}{c}\sqrt{\varepsilon_r \mu_r} = \alpha + j\beta. \tag{2.3}$$

While this limits the range of operation, it also isolates the subject and radar system from distant noise sources and clutter motion in the environment [21–23]. Examples of noise include noise pumps in an aquaculture tank or waves on a beach near a monitoring area.

2.3.1.1 Radar Performance

As with radar systems used for cardiopulmonary sensing with human subjects, for underwater radar operation, the important characteristics are physiological motion sensing. Fish offer less repeatability than human subjects and their random motion can obscure some details of radar performance. A controllable

Figure 2.9: Moving reflector for underwater characterization of Doppler radar system for fish sensing.

underwater source of motion can provide a repeatable system input and additionally reduce the amount of experimentation involving animal subjects. Testing with these phantom motion sources can augment radar tests with fish by providing complimentary coverage to enable better understanding of the radar performance.

2.3.2 Experimental Setup

The testing involved a measured amount of water in an aquarium with a mover controlling the position of a plastic sphere in the water. The clear plastic sides of the aquarium allowed visual monitoring of the antenna and mover. Tap water was added for the first set of tests (freshwater), then “Instant Ocean” salt was added to simulate sea water with a salinity of 30 %■ for the second set of tests (salt water). A powered mixer was used to evenly distribute the salt through the water volume.

The mover used in place of a live test subject provided simple, controlled, repeatable motion along a straight line to the antenna. A small plastic sphere with a thin metal covering was used as the radar visible target – without the metal cover, the ball and supporting rod were effectively invisible to the radar system. Rather than using a submersible motor, a standard servo actuated the ball through a linkage of control rods and bel cranks. Control for the servo was provided by a small microcontroller – both amplitude and frequency of motion were run without computer interaction. The settings used for all tests were a frequency of 78 bpm (1.3 Hz) and an amplitude of 5 mm.

A radar system for these experiments was assembled from coaxial components with the LO power supplied by an HP 83640B, a diagram of which is presented in Fig. 2.10. The amplitde of the transmitted signal was only 10 dBm and the frequency of operation ranged from 600 to 3600 MHz.

The baseband signals were filtered and amplified by SR-560s and then digitized with a NI USB-6009 multifunction DAQ device. The signals were recorded on a computer using software written in LabVIEW. Software written in Python aided in post-test analysis and visualization.

For comparative testing between radar and sonar sensing of small motion at close range, an ultrasonic heart rate monitor was modified to access the mixer output directly to provide a similar output to that of the radar system. The

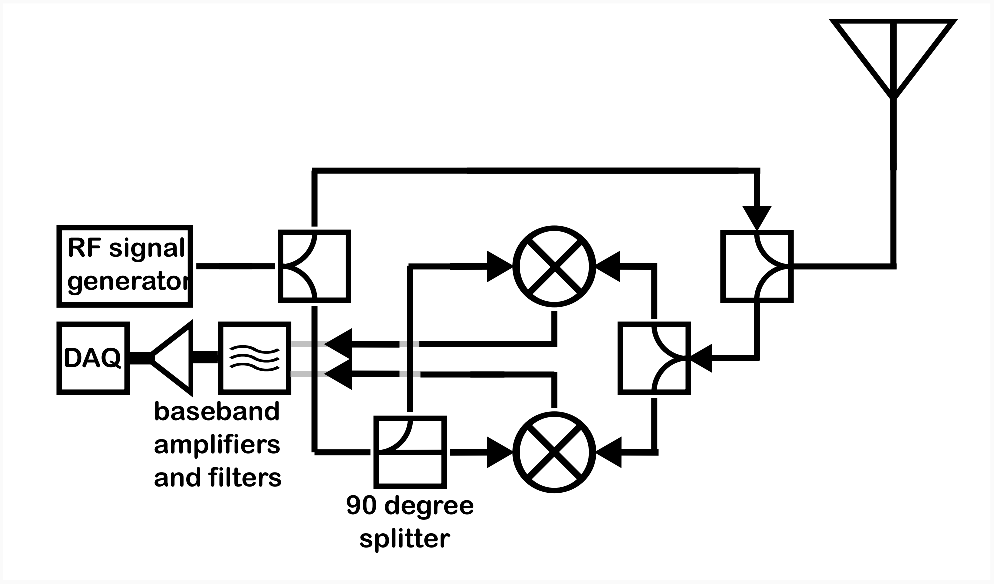


Figure 2.10: Doppler radar system used for experiments (not including computer). A quadrature receiver avoids the null point limitation from which single channel radars suffer.

mixer output was sent to an SR-560 for amplification and then digitized with the radar outputs.

2.3.3 Results

The consistent motion of the mover can be observed as consistent oscillations in the time (Fig. 2.11) and sharp spikes in the frequency (Fig. 2.12) plots. While the mover follows a pattern of $\sin(t)$ along its axis of motion, the radar output has an appearance closer to $\text{abs}(\sin(t) + 0.3)$ as can be seen in Fig. 2.11. This is due to the range of motion exhibited by the mover and the large angel traced out by its movement can be easily found in Fig. 2.13. These three plots, from a signal recorded in freshwater, show very clean signals with negligible clutter.

The three plots in Fig. 2.14 show the radar output for the two higher

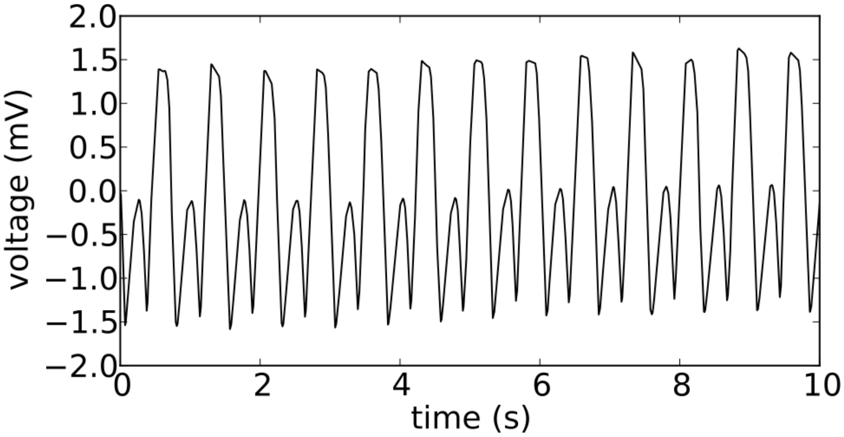


Figure 2.11: Short plot of radar output over time showing repetitive motion of sphere.

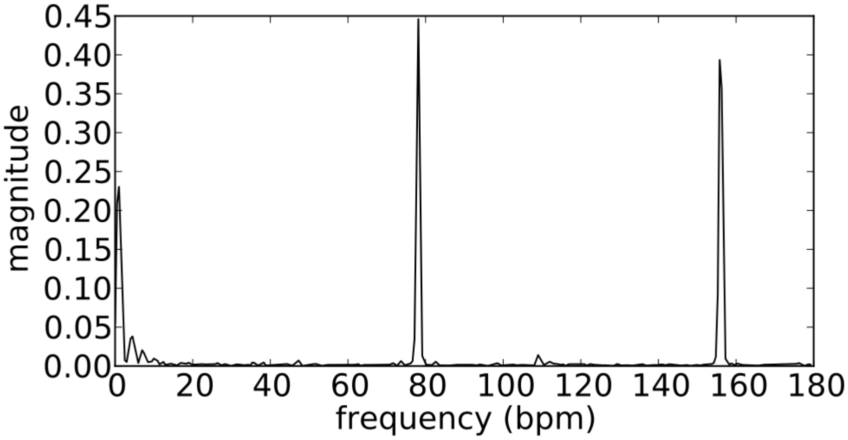


Figure 2.12: Frequency plot of radar output showing clear spikes at the programmed frequency of oscillation for the phantom mover (78 bpm) and twice the frequency (156 bpm) from the oscillation of the sphere moving with a constant period.

frequencies of operation — 2400 to 3600 MHz. They have been scaled so that the value of the frequency with the maximum magnitude is unity. This is to allow a visual inspection of the comparative noise from 15 to 180 bpm (0.25 to 3 Hz). The noise spectrum in Fig. 2.14a (2400 MHz in salt water) is

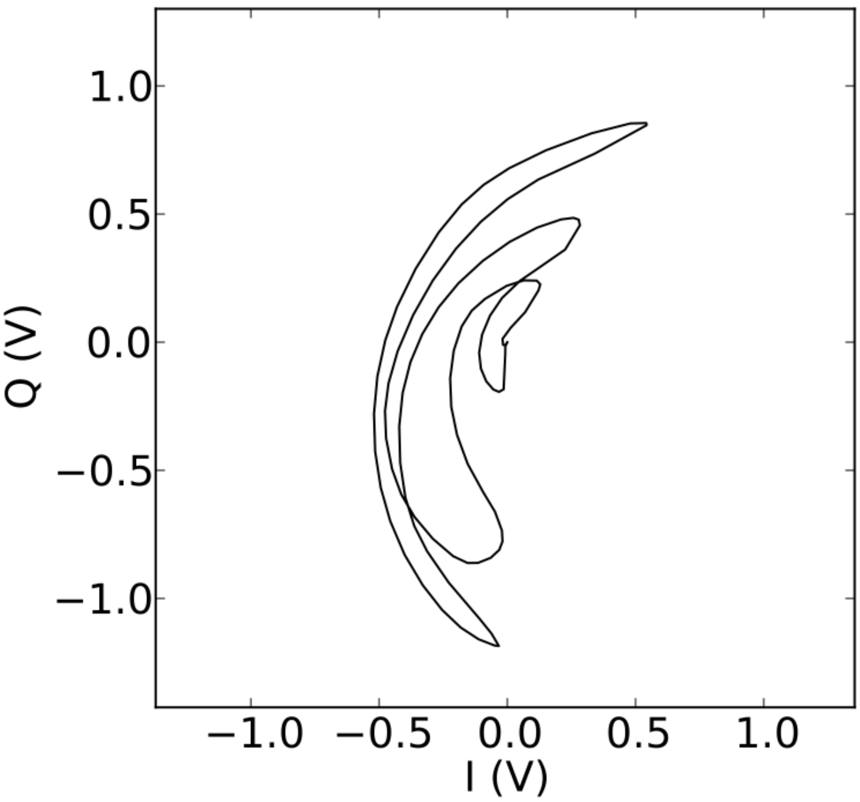


Figure 2.13: IQ plot showing the large angle of motion. The I channel shows twice the oscillating frequency of the Q channel due to the range and phase offset. A single channel cannot unambiguously resolve the oscillation rate of the subject, because the the output singal produced by a motion at frequency f might also be produced a motion at frequency 2f. Two oscillation rates do not always result in the same signal, but without the phase information provided by the second output, this possibility cannot be eliminated. The radar outputs can be combined to find the angle from the center of the circle containing the arc they form, or the frequency of oscillation can be extracted from each signal separately and then combined to provide an accurate rate measurement.

similar in amplitude to that in Fig. 2.14c (3600 MHz in tap water) relative to the signal from the mover while the signal to noise ration for operation at

2400 MHz in tap water (Fig. 2.14b) is much higher. This relation can be seen compactly in Fig. 2.17.

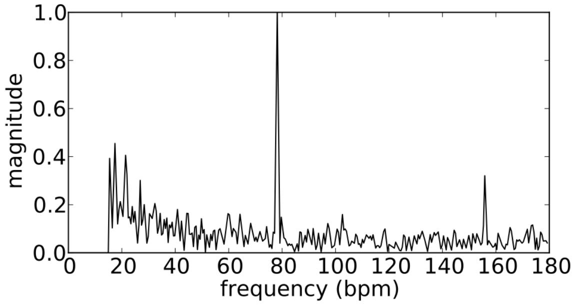
The plots in Fig. 2.14 show the data used to generate Fig. 2.17. They are normalized to facilitate judging the relative signal to noise ratios by comparing the noise levels given constant signal levels. These examples include experiments in salt and fresh water at 2400 MHz and also 3600 MHz in fresh water. The un-normalized radar output indication of the mover activity varies with the conditions, but considering the signal to noise ration, rather than simply signal strength allows for comparison of radar performance in these environmental conditions.

The radar outputs for 3600 MHz and 600 MHz at a range of 20 cm to the mover are plotted in Fig. 2.16. Both signals show a fair amount of noise, but reflection of the higher frequency signal is attenuated below the noise floor before it returns to the radar system.

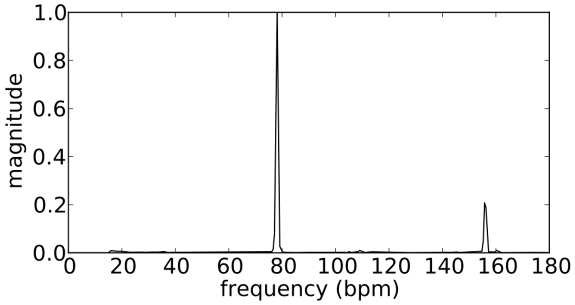
The radar was also compared to sonar by testing the capability of an ultrasound heart monitor to sense the mover. Fig. 2.15 shows the output of the sonar with no added clutter or noise as well as both the sonar and radar outputs in the presence of added noise (in the form of water pouring into the tank away from the mover).

2.3.4 Discussion

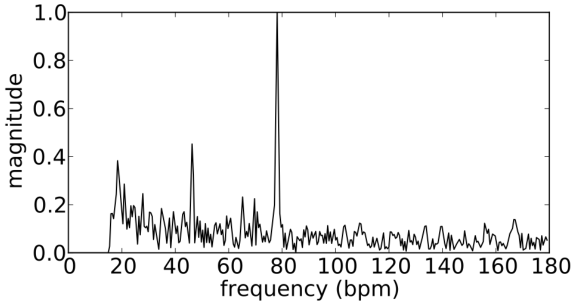
Discussion The ratios of signal to noise for 600 to 3600 MHz in water with and without salt are plotted in Fig. 2.17. The pattern formed is higher signal returns for tap water (less attenuation) and lower returns for the highest frequency



(a) Salt Water, Lower Frequency

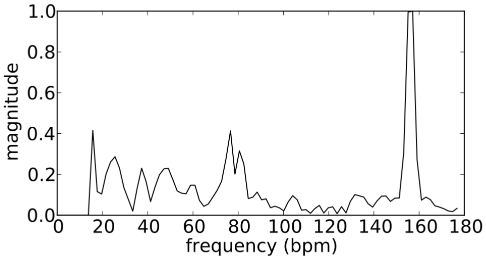


(b) Fresh Water, Lower Frequency

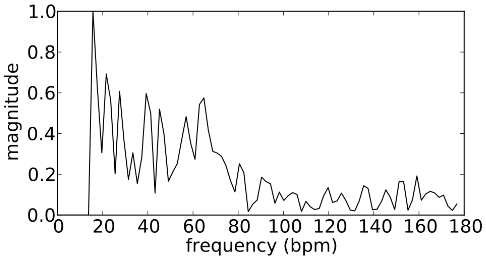


(c) Fresh Water, Higher Frequency

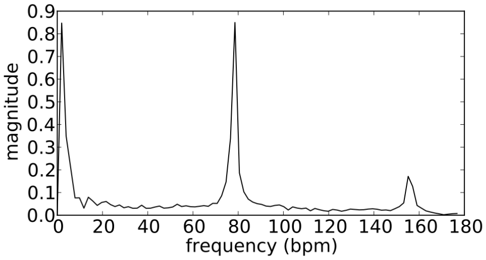
Figure 2.14: Frequency plots of the radar output for multiple frequencies of operation. The plots have been scaled to normalize the signal level to ease comparison of signal to noise ratios by observing the noise levels. Visual inspection shows that operation in salt water at 2400 MHz and tap water at 3600 MHz, (a) and (c) respectively, have similar levels of signal compared to noise while 2400 MHz operation in tap water (b) exhibits significantly lower noise relative to the signal.



(a) Sonar, Low Noise

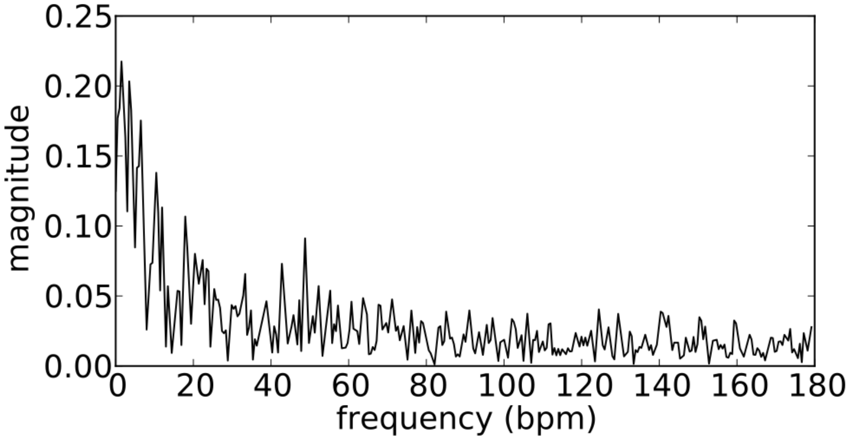


(b) Sonar, High Noise

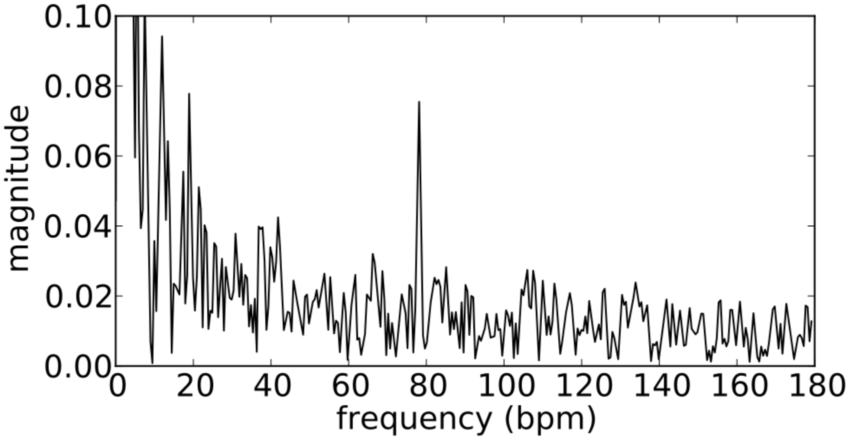


(c) Radar, high noise

Figure 2.15: Frequency plots of sonar and radar output in tap water. Because these plots have been normalized with the same maximum, the signal from the mechanical source in the low noise sonar data (a), appears much lower in the high noise sonar data (b), because the environmental noise is obscuring the signal from the motion of interest. The radar data the same high noise conditions (c), show a much larger signal because it is not sensing the noise, just the motion of the phantom subject. For all of these experiments, mechanical phantom was programmed to oscillate at about 80 bpm. The first harmonic is visible at twice that frequency, though the high noise sonar data shows little indication of any motion.



(a) 3600 MHz



(b) 600 MHz

Figure 2.16: Frequency plots for the radar detection of motion at long range for (a) 3600 MHz and (b) 600 MHz. The signal in (b) has at least as much noise as the signal in (a), but the mover's oscillating motion can clearly be seen above the noise in (b) – and not in (a).

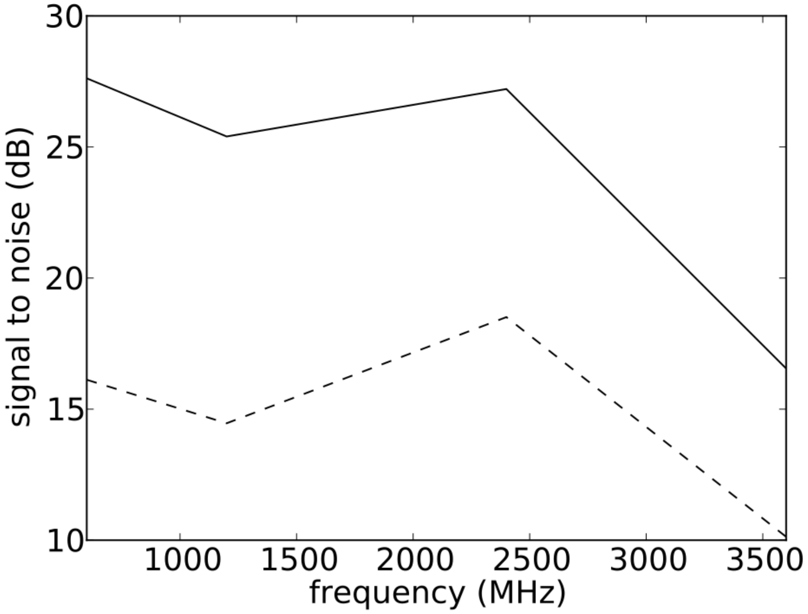


Figure 2.17: Plot of signal to noise ratio of radar output over frequency in tap water (solid line) and salt water (dashed line). The signal is reduced at high frequencies in both tap and salt water, but for lower frequencies, there is less of a pattern - though the radar return is much stronger in tap water than salt water.

(3600 MHz), but for the lower frequencies, it is not as clear. Both show lower relative signal power at 1200 MHz, but lower frequencies appear to offer more benefit in tap water than salt water.

For short range operation, UHF frequencies (<3 GHz) offer better transmission in both salt water and fresh water than microwave frequencies (>3 GHz). Much lower frequencies (<1 MHz) may offer improved transmission loss, but require significantly larger antennas which could be difficult to transport, situate, or steady underwater. For a hand portable monitoring system, the antenna should probably be about the size of a notebook computer, to minimize mounting or transport problems.

Comparative tests between the radar and sonar systems showed the sonar to provide greater range, without adverse effect from saltwater. In the course of testing the sonar did, however, show a propensity for sensing noise. Tests with possible noise sources showed this to be a significant problem, as can be seen in Fig. 2.15. While the sonar detects the target motion in a quiet environment, the noise of water pouring into the tank adversely affects the sonar motion detection while the radar shows little to no change with the acoustic noise and vibration.

Increased range can be accomplished simply by transmitting at higher power levels, but operation in water will still be limited to very short ranges – for long ranges, sonar is a better choice. Some uses for short range sensing include: monitoring fish in conjunction with video recording, especially when bait is used to attract fish to the cameras; and monitoring fish in constricted spaces such as fish ladders or elevators, or even inside a baited fish trap (which can release the fish after measuring it).

CHAPTER 3

Contact Heart Motion Sensing

3.1 Introduction

Radar sensing usually involves transmitting a radio signal from an antenna and detecting reflections from distant objects. While most radar systems operate in air, Ground-penetrating radar (GPR) systems transmit their signals through soil or similar materials — contact radar is like GPR, sensing heart motion.

3.1.1 Motivation

Non-invasive methods of monitoring heart rate, respiration rate, and other physiological signals would obviate the need for survival surgery, a clear refinement in animal care during testing. This improvement would also provide for lower stress levels affecting results, less risk of death for test subjects. Radar can be used as a non-invasive alternative for heart rate monitoring with fish. While the radar system presented here still maintains physical contact with the fish, it is significantly simpler to adhere a patch to the body than surgically implanting electrodes.

3.1.2 Background

A useful application of radar motion sensing is non-invasive detection of heart motion for fish. Problems for such measurements include limitations of underwater radio transmission, isolating the subject, and separating heart motion from clutter motion. A straightforward to alleviate most of these issues is to attach the antenna to the test subject. While no longer non-contact, it is still non-invasive and the attenuation of radio energy in water becomes a beneficial quality that reduces environmental noise and clutter. The target, directly in front of the antenna, is much easier to sense than other, more distant, sources of motion. This helps isolate the subject from clutter motion in the environment for the sensor. Attaching a small sensor to the subject fish also eases longer term monitoring of an individual and provides a platform for other sensors, for temperature, water properties or other variables. Data transmission could be provided by various forms of acoustic telemetry systems, as demonstrated for ECG sensing [28], for untethered monitoring, or umbilical cables for more constrained situations.

Figure 3.1: Photo of fish testing table. A white foam plate, visible near the Bucket for Sedation, found use as a sunshade for the fish during testing. The umbrella was required for maintaining a bit of readablity in the computer display as well as the SR560 amplifier indicators.

3.1.3 Experimental Setup

3.1.3.1 Animal Care and Ethics

These experiments were authorized by an Institutional Animal Use and Care Committee and conducted in accordance with an approved protocol (UHM IACUC #10-912).

3.1.3.2 Subjects and Facility

Tilapia at the Windward Community College Aquaculture Complex were selected as test subjects for these experiments. At the time the experiments were conducted, the fish were roughly 35 cm in length. Each tested fish was netted from an enclosure and placed in a bucket filled with fresh water and anesthetic [29] for sedation. After sedation, the fish was moved to a shallow bath for testing. This bath was shallow to ease work with the fish but still deep enough to keep the mouth and most of the body submerged as can be seen in Fig. 3.2.

This water level was sufficient to support respiration and hydrate the skin, while still allowing easy placement of the antenna and minimal handling of the fish. After a brief period of testing, the fish would then be returned back into the enclosure. For these tests the fish were heavily sedated. The sedation reduced pain, stress and motion. The fish required heavy sedation to sufficiently reduce body motion. At this level of sedation, natural respiration was undependable, necessitating artificial respiration in the form of forced ventilation (pumping water over the gills). While this effectively provided oxygen to the fish, the pump used to move the water also generated significant electromagnetic noise, which could be separated from the signal (see results below).

3.1.3.3 Safety

Low power RF transmissions are safe at the frequency of operation for the radar system used in these experiments. Short range radio communication devices have a limit of maximum Equivalent Isotropically Radiated Power (EIRP) of up

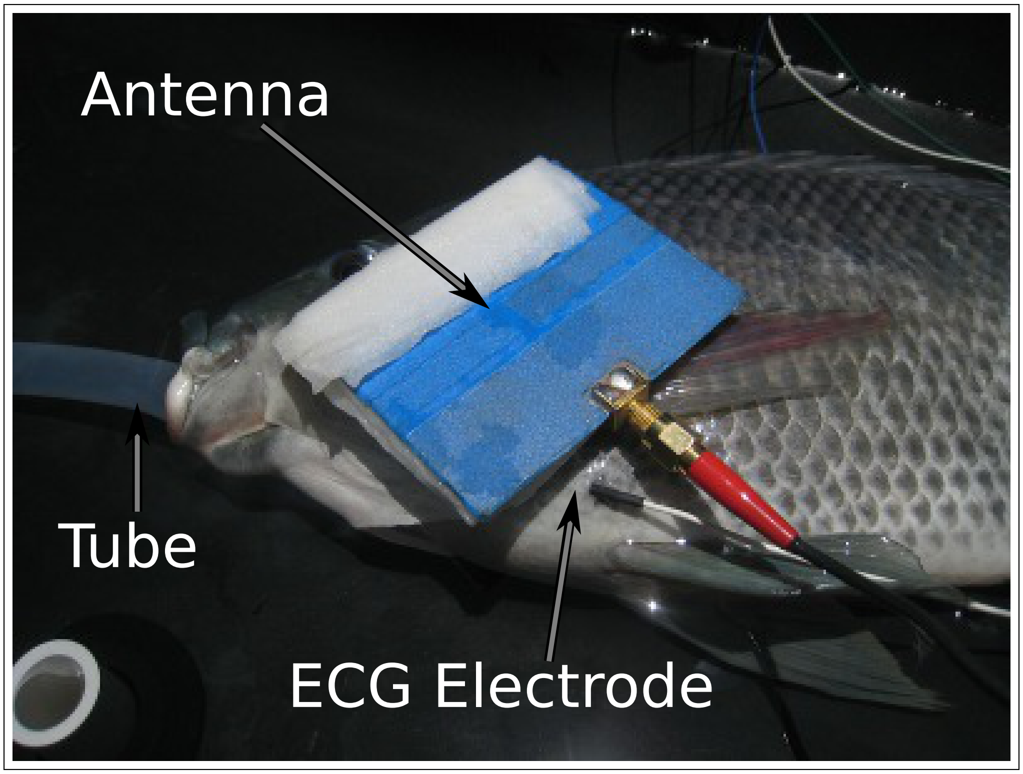
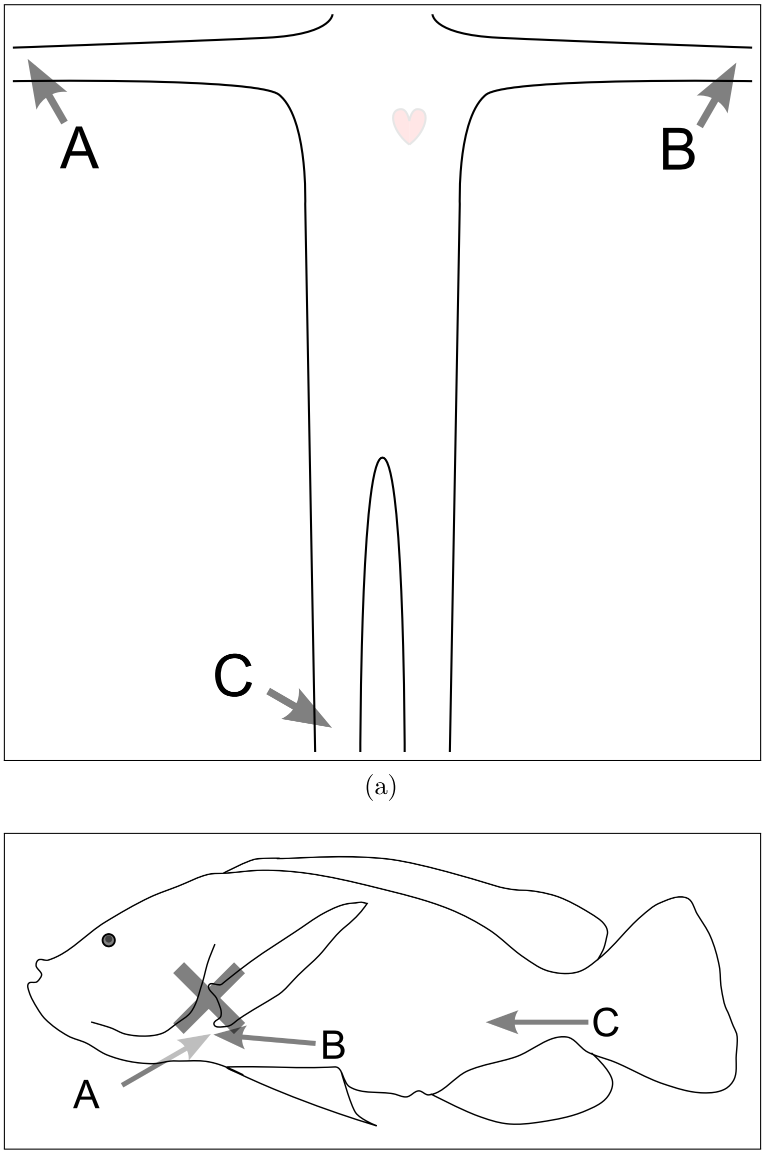


Figure 3.2: Photo of fish ready for testing. The antenna is resting on the fish, immediately behind the head and directly over the heart. One of the ECG electrodes can be seen under the antenna - the electrode was located to sense the ECG signals without risk of touching the heart. The tube going to the mouth of the fish provides water for respiration during the test to remove risk of suffocation.

to 25 mW including at 2.4 GHz [30]. The, admittedly improbable, dangers from RF exposure presented by the low power radar 5 mW was minimized by limiting the exposure time to short test times. Larger dangers from electrocution and sunburn were minimized by using battery power for the ECG amplifier and using a sunshade for the testing area.



(a)

(b)

Figure 3.3: Diagrams of ECG electrode placement on human (a) and fish (b). The ECG electrodes A, B, and C are located on the fish and used analogously to those used for 1-lead ECG measurements (for human subjects (a). The large cross close behind the head of the fish indicates the location of the antenna – located above the heart. Whereas the electrodes used with human subjects are pad electrodes that lightly stick to the skin surface, those electrodes do not work with fish and so needle electrodes are required.

3.1.3.4 Reference Measurement

Standard pad electrodes used with humans would be unsuitable for use on these fish. Issues include wet scale covered skin, mucus displacement, curved shape, available area (near heart – between fins and gill covers). Needle electrodes (used for human Electroencephalogram (EEG) and Electromyogram (EMG) measurements) were the most straightforward replacement (standard practice). Three electrodes were used – two sense electrodes (differential) with one ground reference electrode with one reference electrode close to the tail and two sense electrodes each ventral of a pectoral fin.

The sense electrodes were connected to the inputs SRS SR560 amplifier while the reference electrode was connected to the amplifier ground. The SR560 had the same settings as those used with the radar, but with differential input. The ECG signal was digitized using the same NI USB-6009 as the radar outputs.

This electrode arrangement is depicted in Fig. 3.3 for human and fish usage. For a one lead human ECG measurement, three electrodes are commonly used with two on the upper extremities (A and B) use for sensing and one on a lower extremity (C) used as a ground reference or displacement current cancellation. The ECG signal is measured differentially across the two sense electrodes. For fish, the setup is similar to the pictured human single lead ECG and as can be seen in Fig. 3.3b, with the two sense electrodes located near the heart (A and B) and the reference electrode is situated near an extremity (C).

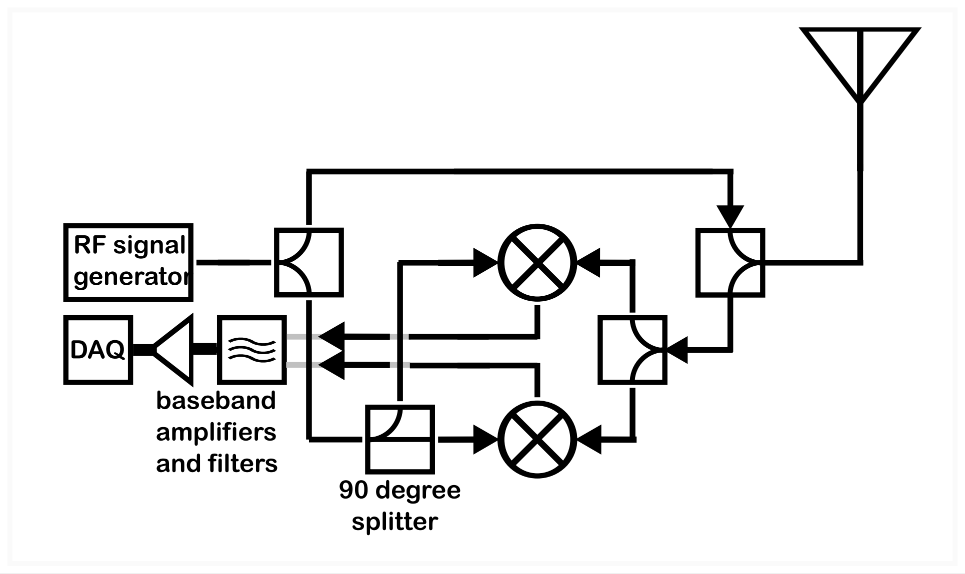


Figure 3.4: Radar used for contact heart rate measurement.

3.1.3.5 Radar Measurement

A radar system also used for human physiological motion sensing, similar to that described in [31] and [32], was used for these experiments. This system, depicted in Fig. 3.4, was assembled from bench equipment and coaxial components including: E4433B RF signal generator, Mini-Circuits ZFSC-2-2500 splitter, Mini-Circuits ZFM-4212+ mixers, Narda 4033C hybrid splitter, SRS SR560 amplifiers, NI USB-6009, and a computer running custom LabVIEW data acquisition software. The RF signal generator was set to output an unmodulated 13 dBm carrier at 2.4 GHz and the amplifiers settings were: ac coupling, 0.3 to 30 Hz filtering passband, and gain of 5000 V/V.

Operation with a 2.4 GHz carrier frequency offers a reasonable tradeoff of size and motion resolution and additionally leverages commonly available electronics. The baseband signals were lowpass filtered for both antialiasing and

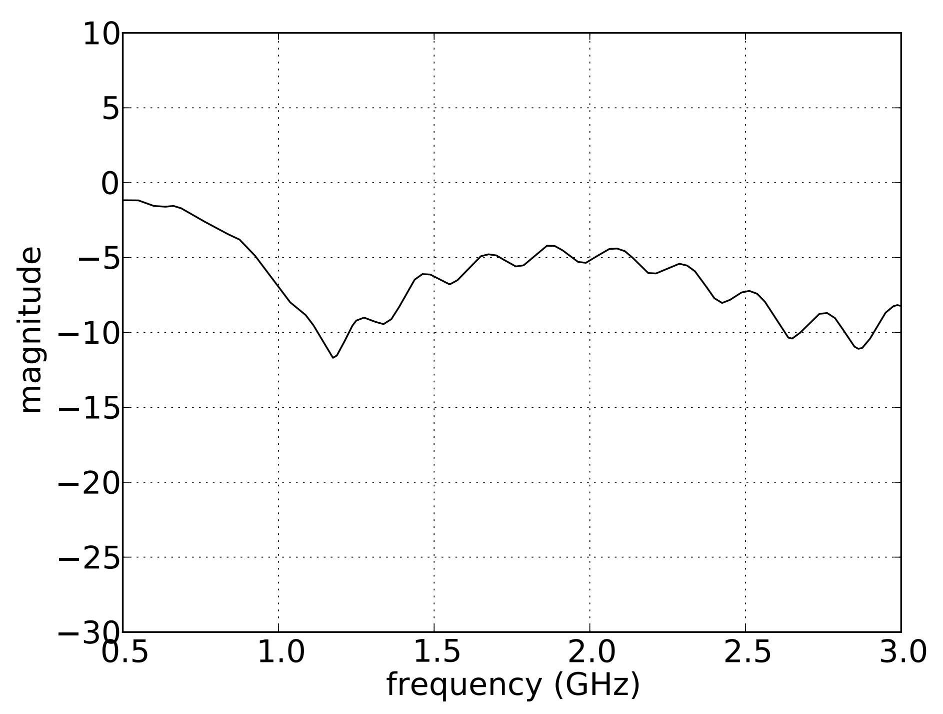


Figure 3.5: Return loss for the patch antenna on skin.

to reduce extraneous higher frequency noise. These signals were also highpass filtered (ac coupled) to allow for higher signal amplification in the face of both constant offset and slow variations in the signal offset; e.g. from the radar system and also a continually changing offset from body motion. Digital filters were also used to clear 60 Hz noise and prepare the signals for analysis (e.g. peak finding).

A printed circuit patch antenna designed for operation in the 2.4 GHz ISM band was fabricated on Rogers 6002 substrate. The return loss of this antenna against skin can be seen in Fig. 3.5. The antenna location on the fish (indicated by the × in Fig. 3.3b), though larger than the heart, is centered over the heart to sense its motion.

Pad electrodes (for ECG) would be unsuitable, and the radar antenna shares superficial appearances with pad electrodes; but because mode of operation for the radar differs from ECG, some of the problems with using pad electrodes are obviated for the radar due to differences in the two sensing modalities. ECG requires electrical contact — scales or mucus could interfere with this. Radar does not require direct electrical contact, though transmission through various materials can affect the signal. Interference from a thin layer of mucus would be improbable.

3.1.3.6 Testing Process

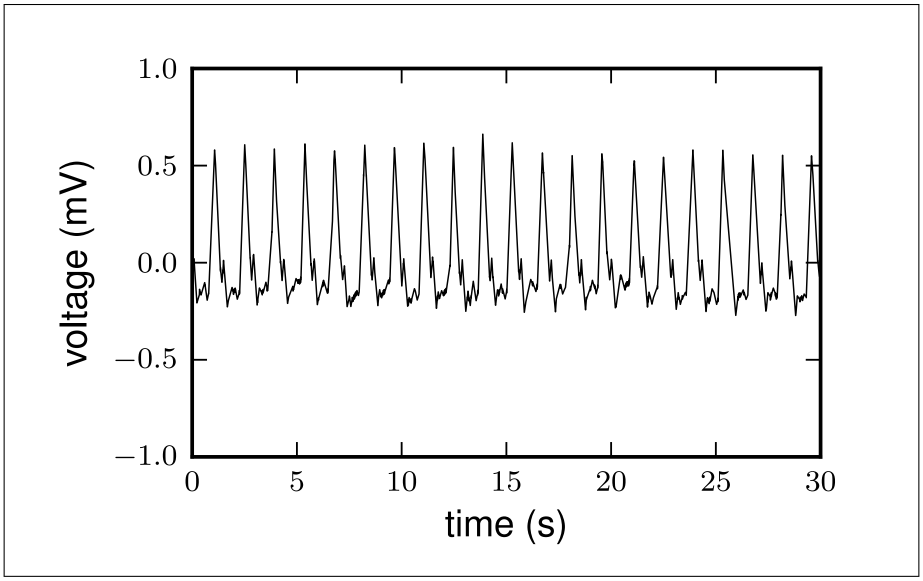
For each test the radar antenna was carefully placed on the fish over its heart. With the heart located slightly anterior to the pectoral fins, the antenna rests not only on the skin, but also on the operculum and pectoral fin. For tilapia, the patch antenna provided adequate performance and covered less of the body – though still more than optimal.

In tilapia the heart is located longitudinally between the gills and pectoral fins, vertically at the base of the pectoral fins (near the ventral end of the gills). To better sense heart motion, the antenna was located above the heart – also over the gill cover and pectoral fin, centered as shown in Fig. 3.3b. This location was useful for heart monitoring and did not require surgery, but interfered with the gills and pectoral fin on the side of the antenna. It is possible other fish with different body geometries would have more room for locating an antenna, but many, including all members of the extremely diverse order Perciformes, would have similar arrangements to tilapia.

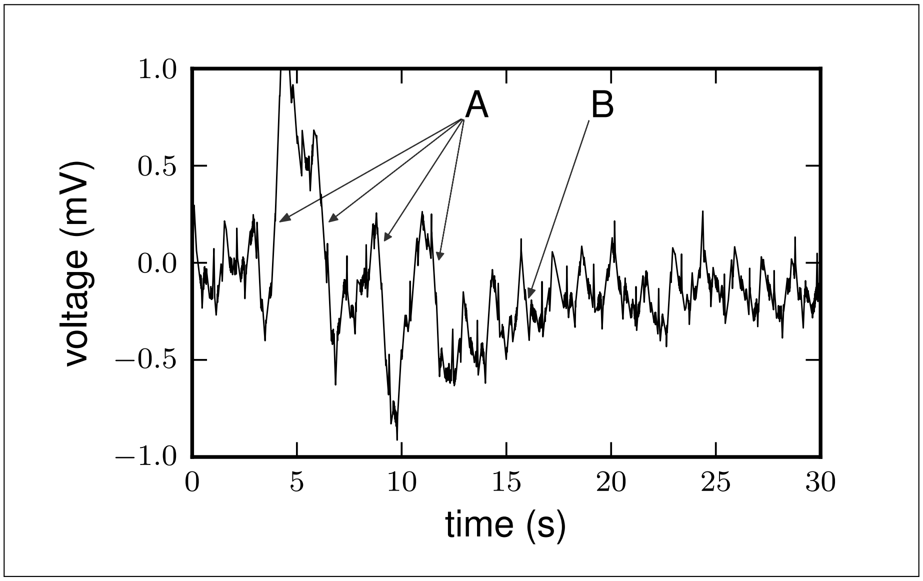
3.1.4 Results and Discussion

The same filters were applied to the simultaneously recorded ECG and radar signals to allow more straightforward comparison between the two and to avoid introducing artifacts that cause untoward changes in the results. The 1 kHz sampled signals were used for time domain peak detection of individual heart beats and Fourier transformed for frequency domain analysis. The plot in Fig. 3.8 is a 20 s section of the trace using a hamming window and with no zero padding. This provides a frequency resolution of about 0.05 Hz or 3 BPM. The rates used for Fig. 3.9 were determined with a Fourier transform on a 24 s window. Though the radar was run with battery power, the pump providing fresh water to the fish ran off ac power (60 Hz or 3600 BPM) and introduced significant out of band interference. The pump interference did not affect heart rate detection, but did clutter the time plots – the filtered data is easier to inspect visually. For time domain analysis and also the frequency plot of the radar and reference data, one of the output channels from the was used — $B_I(t)$. This is the projection of a vector with angle proportional to $x(t)$ the real axis. This projection involves some distortion, removable by appropriately combining the two baseband channels $B_I(t)$ and $B_Q(t)$. For these experiments, the distortion did not adversely affect the performance and this signal processing was not required.

For the multiple trial comparison, both radar output channels were used. The average heart rate was individually calculated for each radar channel and

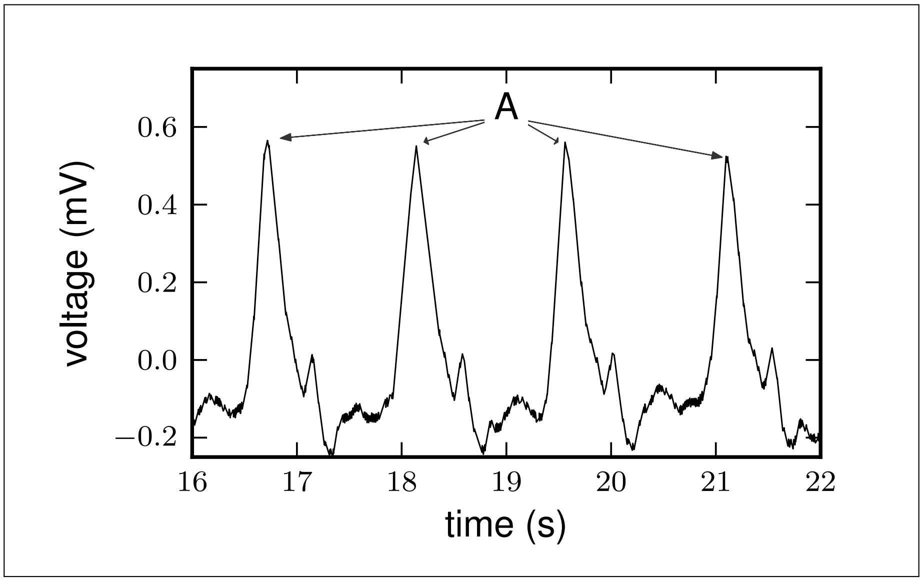


(a) radar

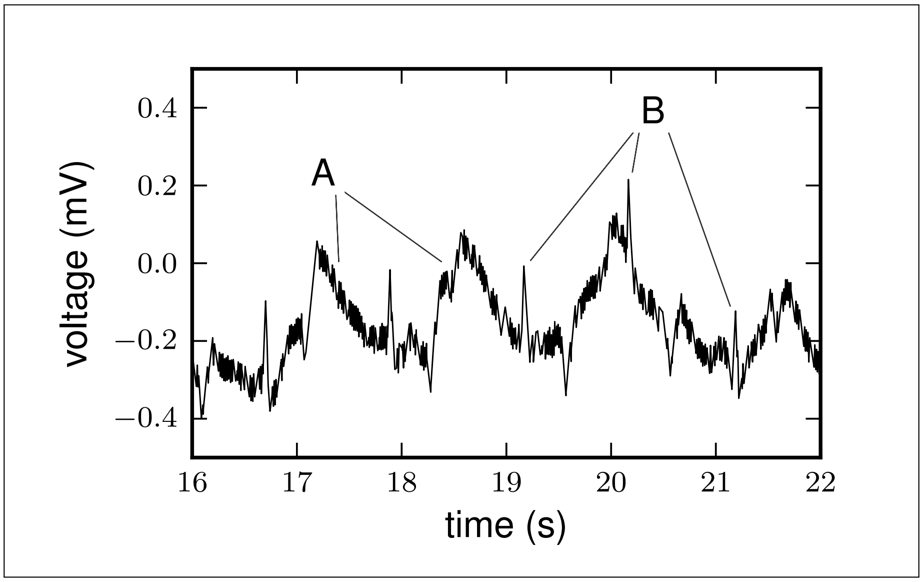


(b) ECG

Figure 3.6: Signals from the radar (a) and the ECG (b) showing the physiological signals of the fish. Though the fish was sedated, the ECG signal shows significant muscle activity in addition to that of the heart. Visible in the plot are both large transients A and the highpass filter response following them B.



(a) radar



(b) ECG

Figure 3.7: Signals from the radar (a) and the ECG (b) over a shorter time span. Both the radar and ECG show 41 BPM waveforms from the heartbeat indicated by A with the ECG shows an extraneous signal, B, at a higher frequency.

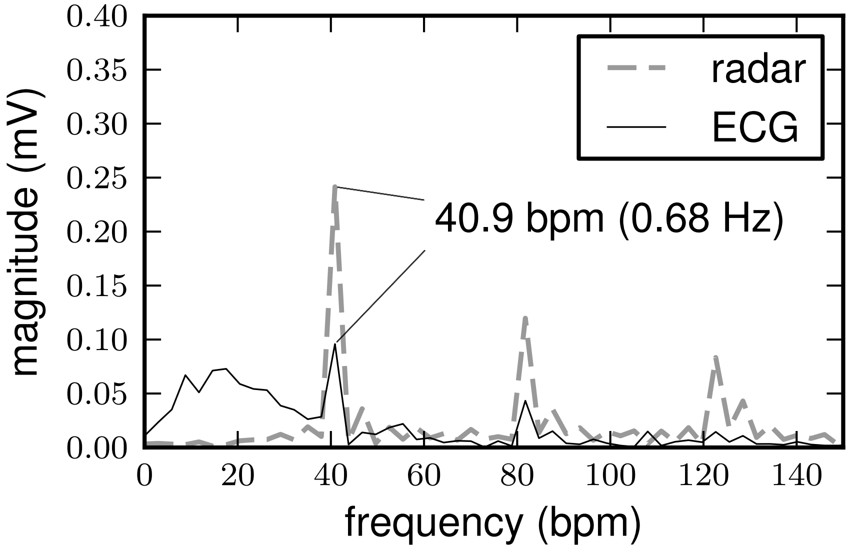


Figure 3.8: Plot of radar (In-phase output) and reference (ECG) signals over frequency. The heart rate of 41 BPM is clearly visible as are the harmonics.

the reference. Others' work relating to single channel and quadrature output Doppler radar systems for physiological motion sensing [16,33–38] indicate that for some antenna–subject ranges, one of the outputs may indicate an oscillation rate twice that of the true subject oscillation rate. This was factored into the data analysis for combining the two signal from the radar system. If the ratio of the rate for one radar channel was close to double the rate of the other radar channel, the lower rate was used; otherwise the average of the two rates was used as the radar reported heart rate. As is visible in Fig. 3.6, the radar provided a clear signal with out extraneous motion and these results show how the periodic motion detected by the radar system matches the heart beats detected by the ECG. The large variations in the ECG data visible in Fig. 3.6 are a result of large, non-repetitive motion in other muscles while the smaller amplitude,

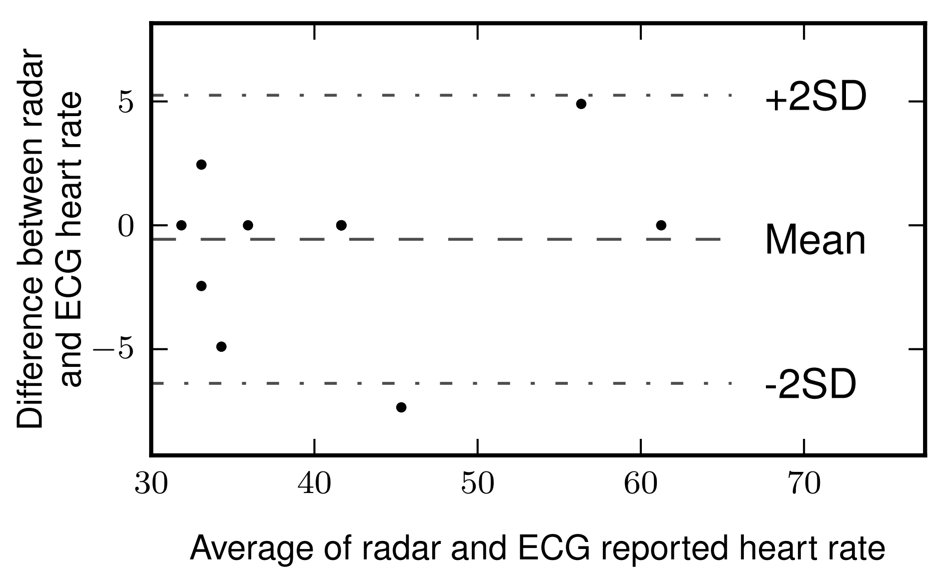


Figure 3.9: Bland-Altman plot showing agreement between radar and ECG heart rate measurements for five individuals (with multiple independent tests for some of them). Each point in this plot is from a different test, with the two measurements combined for both of the axes. The distribution showing a mean near zero and closely spaced limits (two standard deviations above and below) indicate the radar provides a useful alternative to ECG for general heart rate monitoring, though these results indicate this radar system does not yet provide sufficient accuracy for situations requiring high precision measurement.

higher frequency signal visible in Fig. 3.7 likely stems from other body motion such as small twitches in the caudal fin. Moving the ECG electrodes may have improved the appearance of the signal, but the existing placement provided an adequate signal. A comparison of the heart beat timing shows the radar and reference data to match closely (see Fig. 3.8). Plotting the differences against the means for the radar and reference measurements is a graphical alternative to correlation coefficients for assessing the level of agreement between the two. As described by Bland and Altman [39], the correlation coefficient can vary depending on the range of the quantity measured, plotting the data in this manner provides information on the agreement between two methods even when the value measured varies over a wide range. This graphical depiction can be seen in Fig. 3.9 with the radar and ECG reported heart rates matching within two standard deviations. The heart rate measurements used for this plot were generated for each trace through a Fourier transform (using 24 s long window) and then selecting the highest bin. While other plots are from a single test subject, data collected from five individuals were used in this comparison. The fifteen points were discrete sample points — one per test. Multiple tests were performed per test session to reduce the impact of these tests. The ECG electrodes were left in place but the radar antenna was removed then replaced, sometimes with subject orientation changes.

Realistically, for monitoring heart rate (and not the intervals from one beat to the next), the base line for performance is detecting all the heart beats and the radar is clearly performing above this level. The correspondence in detected heart rate for the radar and reference also can be easily seen in the frequency domain plot, Fig. 3.8. The peaks for the heart rate is at 41 BPM with harmonics at 82 BPM and 123 BPM – a reasonable rate for fish and comparable to that reported for tilapia at warm temperatures [40]. Also visible in this plot is spectral content in the ECG signal at low frequencies. A large contribution of this is the transient visible in the trace when viewed for a longer time span in Fig. 3.6.

Heart rate monitoring can be useful as an indicator of metabolic output, which is useful for energy strategies and investigating environmental impact. Apart from heart rate, the radar can provide information about respiration as well as body motion, both of which could prove useful insights for health (e.g. in aquaculture).

In addition to applying the radar as a heart rate monitor, the data can be used as an indication of metabolic rate. Information about these rates are used for studying fish energy management, environmental impact and also for fish farming. For the data collected in these experiments the heart rate is of comparable quality to that provided by the ECG, but the testing still involves handling the fish, sedating it, and restricting its motion. All these affect heart rate and cause stress. One path of refinement to eliminate these problems may entail small physical features in holding tanks to guide fish past radar antennas without requiring subject handling. Some possible alterations to the radar to improve upon this location include reducing the antenna size to one that would fit between the gill cover and pectoral fin, using the radar to sense motion related to that of the heart in the swim bladder, and mounting the antenna ventrally. Each of these involves different challenges and should be explored.

CHAPTER 4

Non-Contact Sensing

4.1 Fish Activity Monitoring

4.1.1 Opening

Quantitative assessment of activity levels for various aquatic organisms is essential for understanding the impact of ecological and environmental changes. For such research to be effective, it is important that measurement techniques have little or no influence on subject behavior and that the subjects not be harmed. The goal of this study is to develop a non-contact system capable of monitoring biological signals of deep sea fish in their native habitats. These signals include motion of heart, gills, fins, and whole body movement. Monitoring whole body motion and speed over time can provide useful data on sustained locomotory capability and metabolic rate variation. Heart and gill motion (ventilation and heart rates) are useful indicators as to the health, metabolic rate and energy usage of the fish, similar to respiratory and heart rate measurements for humans.

Conventional underwater or fish sensing techniques include contact transducers, sonar, and video [41–43]. Each has a different performance envelope: videographic techniques can determine body and gill motion, usually in a controlled environment; sonar can sense the presence and location of fish over significant distances; radar can accurately sense smaller motion at shorter ranges than sonar; and contact transducers/in vitro techniques can provide detailed information about internal functions, most often in a laboratory environment.

Studies of live deep-sea organisms are typically performed by two different methods: 1) video recording on location, or 2) capturing and transporting to the surface in pressure maintaining tanks. Video recording allows the study to be conducted in the organisms' natural habitats; however, visibility limitations at the bottom of the ocean may interfere with the accuracy of the observations.

Doppler radar has shown promise as a powerful means of unobtrusive and ubiquitous detection and monitoring for human vital signs [14, 15]. Our previous studies have demonstrated the separation technique of heart signals from two subjects using blind source separation (BSS) with a real constant modulus (CM) approach [44]. Described here are early experiments showing the feasibility of sensing fish motion with Doppler radar, which could provide a useful tool to assess activity quantitatively and potentially extract information on cardio-respiratory levels.

4.1.2 Background

A Doppler radar motion sensing transceiver transmits a radio wave signal and receives the motion-modulated signal reflected from a target. The RF wave reflected at a moving surface undergoes a frequency shift proportional to the surface velocity. The experiment was done using a single-channel Doppler radar operating at 500 MHz. This frequency was selected as it provides sufficient transmission through water and reasonable antenna sizes [22].

4.1.2.1 Goal

The goal of these experiments was to determine the feasibility of remote Doppler radar sensing of fish activity and motion. Activity information can be used to analyze energy use and to flag periods of activity for off-line analysis of data from other sensors.

4.1.3 Experimental Setup

The experimental setup consisted of three major portions: the radar, the reference, and the subject.

4.1.3.1 Radar System

The Doppler radar system used for these tests was assembled using commercial off the shelf hardware, specifically:

1) HP E4433B Signal Generator,
2) Mini-Circuits ZFSC-2-2500 Splitter,
3) Mini-Circuits ZAD-1-1 Mixer, and

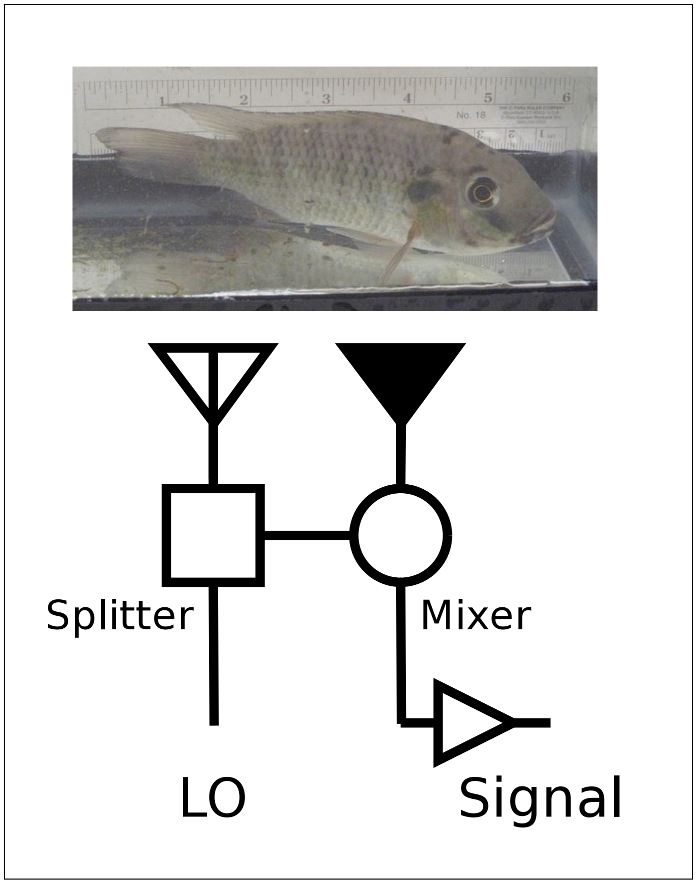
4) Stanford Research Systems SR560 Low Noise Preamplifier

with the output from the radar simultaneously displayed on a Tektronix TDS 3014 Oscilloscope and captured with a National Instruments USB-6009 DAQ module (connected to a computer). The system setup is depicted in Fig. 4.1. The E4433B generated a 500 MHz LO which the splitter then fed to the transmit antenna and the mixer. The analog output was generated by mixing the received signal and LO and then passing the down-converted signal through the SR560 for amplification and filtering.

Two half wave dipole antennas were used in this system. The antennas were located outside the tank, and thus required appropriate dimensions for in-air use. They were attached to one of the short faces of the aquarium, as can be seen in Fig. 4.2a.

4.1.3.2 Video Reference

A tripod stabilized camera (Canon Power Shot SD800) captured video at 15 fps. A small LED visible in the field of view enabled straightforward synchronization between the Doppler data and the video reference. The video footage was used as a reference for comparison with the Doppler data for whole body motion and some fin motion. The video was time synchronized with the radar measurements during analysis by matching the visible LED state to the measured voltage across the LED at multiple points in time.

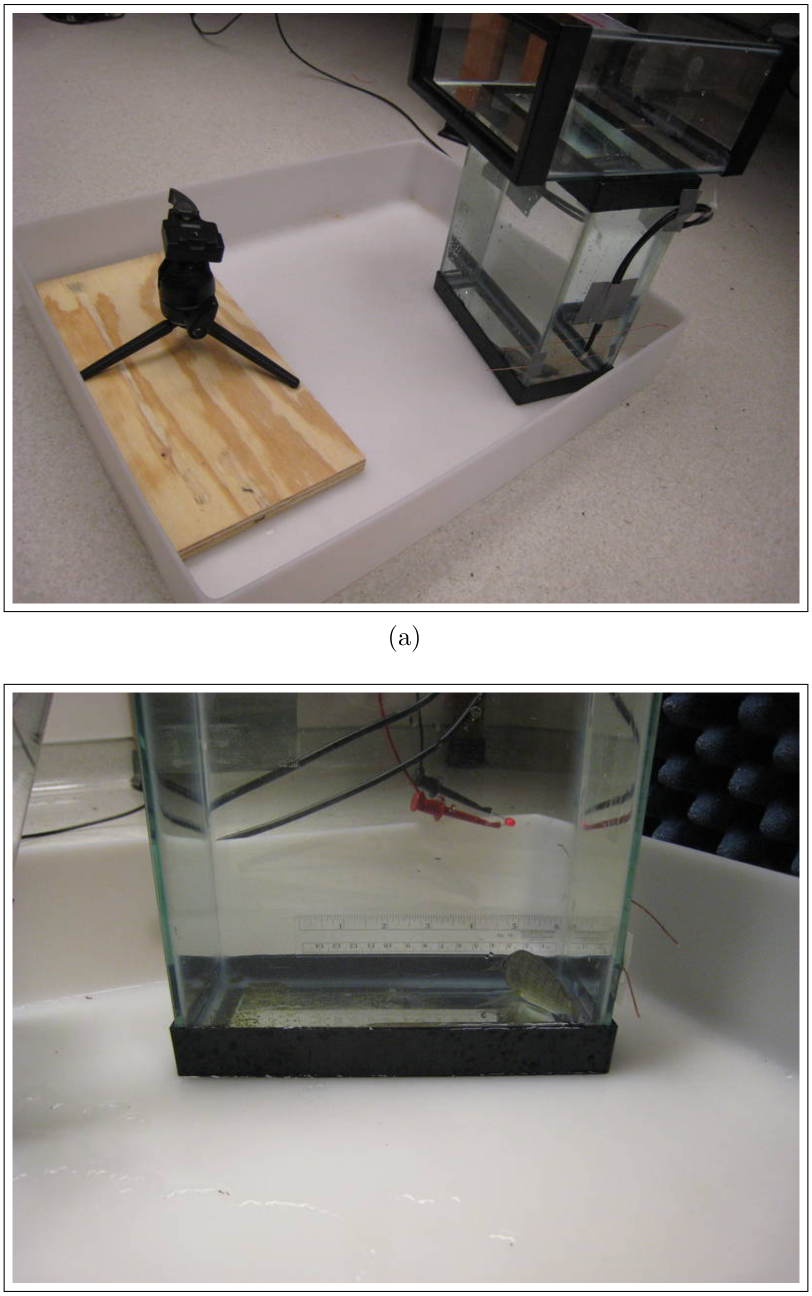


(a)

Figure 4.1: Radar Block Diagram showing single channel radar with separate transmit and receive antennas.

4.1.3.3 Test Subject

Tilapia in small aquariums were used as subjects for these in these experiments in place of deep sea fish in hyperbaric fish traps. Though the tests were conducted using freshwater (low salinity), these same fish could (with appropriate acclimatization) be used for testing in saltwater. Neither the fish, nor the enclosures would be suitable for hyperbaric experiments, which could be conducted after this experiments validated the concept in more accessible



(a)

(b)

Figure 4.2: Arrangement of fish, aquarium, and camera: (a) test setup, and (b) camera view of tank. Visible behind tank in (b) is the LED used for time synchronization.

conditions. The fish was located in a small, flat sided aquarium. The top was covered to eliminate surface ripples. For these tests, the antennas were located on the outside of a short face of the aquarium - this resulted in some inefficiencies (reflections, multiple media transitions), but it allowed for the elimination of all air inside the tank.

The tank was sealed to eliminate the air-water interface (with its surface ripple generated noise contributions) and a small Light Emitting Diode (LED) was placed behind the tank to facilitate synchronization of radar and video recordings. The duration of each test was limited due to the lack of a fresh oxygen supply for the fish during the tests. While the LED sync signal caused interference for the Doppler radar, it was problematic only close in time to the sync pulses. Optically transmitting the sync from a more distant LED would provide similar function and should eliminate the interference.

Another potential source of interference was nearby human motion. To prevent this problem radio absorbing material (RAM) for coating anechoic chambers was located between the radar antennas and the rest of the room and additionally the room was kept empty during tests.

4.1.4 Results

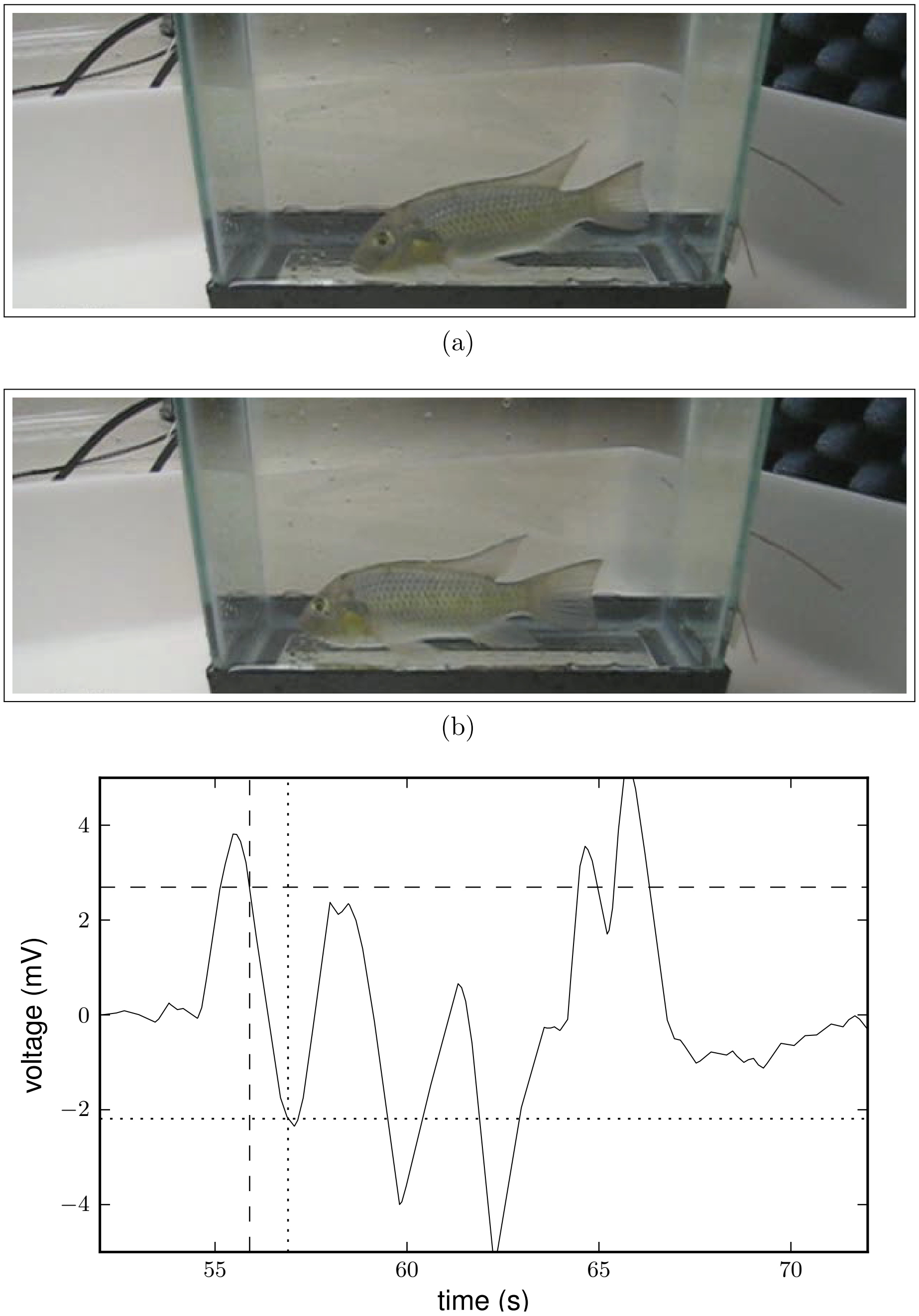
4.1.4.1 Data and Analysis

The data captured with the radar and the video reference were time synchronized and merged for easier analysis. As the combined video and Doppler radar recordings show in Fig. 4.3, whole body motion of the fish can be clearly sensed by the radar. The two still frames from the video are one second apart and show the motion of the fish in that time. The radar trace indicates motion before and after the two video frames – from about t=55 to t=67. The video has a resolution of 40 px/in, thus it can be determined that the fish swam at a rate of 1 inch /second and the corresponding output from the radar system had a slope of about 5.5 volts /second.

In a different test, the SR560 was set to a much higher gain for testing the measurement of gill motion. In this setup, the amplifier became saturated whenever the fish swam or even moved its body significantly. When the fish was visibly motionless, the radar detected small amounts of motion, displayed in Fig. 4.4. In this setup, signals are assumed to have been caused by heart, gill, or fin movement with an amplitude below that visible by the camera, but additional tests would be required to determine the exact source.

4.1.4.2 Video Motion Analysis

In addition to using the reference video recording for comparison with the radar reported motion, a few longer video recordings were used to analyze motion patterns to determine the usability of radar for physiological monitoring of unsedated fish. An unsedated fish spent 82 % of the observed time floating in place. Of the remaining 18 % of monitored time during this experiment, the fish spent 6 % of it actively swimming for and the remaining 12 % of the time fidgeting and drifting. A small portion of the sedentary time was interleaved with short periods of motion, but a much larger portion of the sedentary time was contiguous. The short sedentary periods might allow spot measurements of heart rate — the longer periods could allow tracking of heart rate over time and



(a)

(b)

(c)

Figure 4.3: Video at time t (a), and t+1s (b) above a radar plot with the corresponding instances marked with dashed and dotted lines, respectively (c).

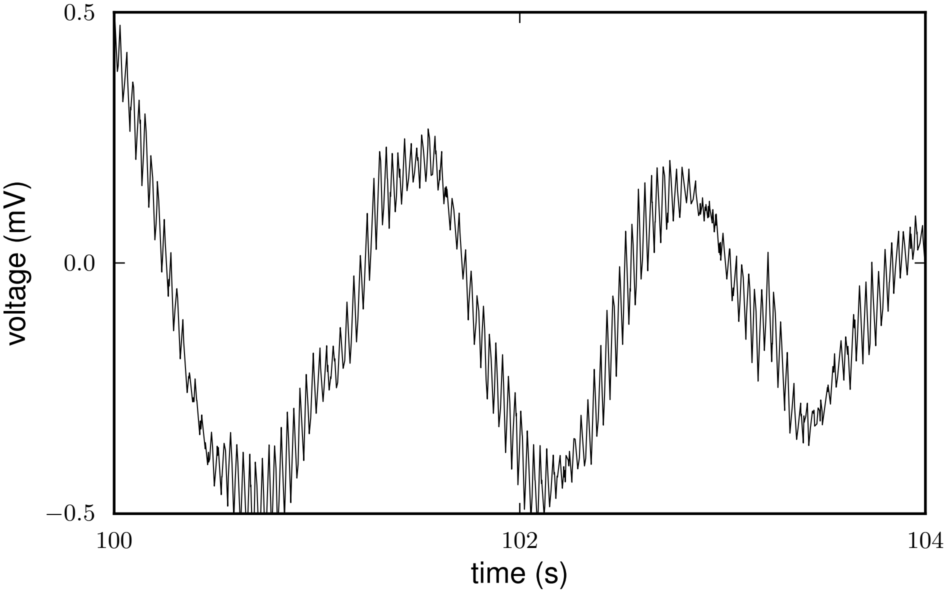


Figure 4.4: High gain measurement showing periodic 1 Hz motion while fish was visibly stationary. The radar system could be detecting motion internal to the fish, such as heart beats, or it could be detecting fine external motion, such as fine adjustments of its fins. The source of this motion is too small to be monitored visually with the reference measurement. Further experiments with more suitable references have show tilapia with heart rates close to 60 bpm (1 Hz).

the pattern offers positive indication that fish like these should be reasonable subjects for non-invasive physiological monitoring.

Fig. 4.5 shows both radar output and algorithmic classification output. This motion identification can be used in place of visual monitoring or in conjunction with simultaneously recorded video to identify the times on which to focus. Mechanical analysis of radar data can be controlled with manual parameter tuning or with automatic adaptation to detect the times with significantly more activity then the baseline in the recorded trace.

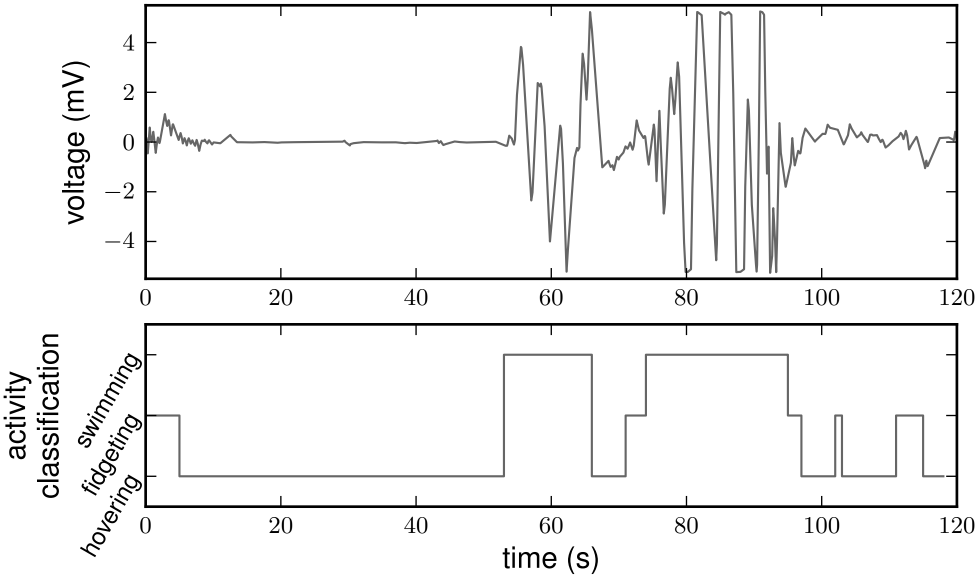


Figure 4.5: Plot of radar detected fish motion over time with automatic classification into categories. The classification algorithm used for these results used hard coded thresholds; an adaptive algorithm could also have been used, with attention to altered adaptation for shorted data set excerpts.

4.1.5 Discussion

These experiments demonstrated the capability of the Doppler radar system to detect both gross body motion as well as minute motion. Though this system is not currently able to analyze and separate these two types of motion, other Doppler systems [44] have demonstrated the separation of multiple physiological motion sources of varying amplitudes through digital signal processing and similar algorithms could be applied here to isolate particular types of physiological motion of interest.

Algorithms developed for monitoring the activity levels of lizards [20] may be translatable to aquatic applications. The data presented here have sufficient resolution to serve as inputs to those algorithms

4.1.5.1 Field Application Potential

While the through-air radar used here demonstrates the sensing of fish motion in a laboratory environment with minimal tank-sealing issues, sensing fish in their natural environments would typically require underwater operation of the radar antennas, which is technically feasible.

Water, as a transmission medium is obviously different from air. While characteristics such as ε_r generally vary over temperature and frequency, at "room temperature" and between 100 and 500 MHz, the characteristics were basically constant with $\varepsilon_r = 78 + j \cdot 0.5$. The main difference for water vs. air is slower propagation, and consequently shorter wavelengths [21].

The conductivity of saltwater adds additional power loss for radio signals results in reduced propagation range, though the interaction of saltwater and radio waves propagating through it has conflicting reports of the interaction complexity [18, 23, 45]. The Doppler radar sensing described here is intended for short range use and can operate with very small received power levels, and thus saltwater operation should be feasible, with appropriate adaptation.

For further development toward application in zoological research, refinements of the radar system and the reference are needed to enable verification of gill motion sensing, heart sensing, and range finding. Other potential improvements to the radar system involve different antennas with much more directed radiation patterns to enable better targeting when multiple fish are within range and to reduce interference from surface waves when the system is used in shallow water.

4.1.5.2 Closing

The results of these experiments show that Doppler radar can be used for effective underwater measurement of movement - but more development will be required for cardioventilatory rate sensing. The current system uses bench equipment for LO generation and signal amplification. Improvements for zoological research applications of this system include design for use in larger tanks, multiple frequencies and quadrature output.

4.2 Radar Monitoring of Gill Motion in Unrestrained Subjects

4.2.1 Intro / Background

A step beyond non-contact heart and gill motion sensing, and for some situations more interesting than body motion sensing is unrestrained sensing of ventilation for free swimming fish. Previous work, in section 4.1, involved sensing body motion of free swimming fish, but not ventilation. The results in this section demonstrate radar monitoring of respiration rate for tilapia (*Oreochromis niloticus*) without restriction on body motion.

4.2.1.1 Contact radar

Received signal power decreases with fourth power of the antenna–subject distance (r^4) as can be seen from the radar equation [46]

$$P_r = \frac{P_t G_t}{4\pi R^2} \times \frac{\sigma}{4\pi R^2} \times A_e \tag{4.1}$$

when simplified

$$P_r = \frac{P_t G_t \sigma A_e}{\left(4\pi R^2\right)^2} \tag{4.2}$$

with constant terms grouped:

$$P_r \propto \frac{\text{const}}{R^4} \tag{4.3}$$

and a fish moving in water presents extra difficulties in signal attenuation, clutter motion and antenna motion (moved by water). Holding the antenna on the fish reduces many of these, and this contact is no additional hardship to the reference (ECG). Some use cases can be handled with this approach: small tag adhered to selected fish (with radar and data recorder/transmitter); enticing a fish into a constricted volume to bring the fish in contact with a wall mounted antenna. Contact between the antenna and subject requires less power — both at the transmitting antenna and at the subject (which reflects the signal back to the receiving antenna).

While contact radar sensing is significantly less invasive than needle electrodes or cannulae which are the other options for heart rate sensing in fish, it still requires physical contact — this limits the situations this radar can be used for monitoring. A part of this limitation is the need for on-board recording or a wireless datalink for data transmission, as well as an on-board power supply.

4.2.1.2 Non-Contact Radar

Non-contact sensing entails a different set of challenges than contact sensing: (a) longer, uncontrolled antenna – subject range requires variable transmit power with a higher maximum; (b) fish motion will add clutter, either as the fish approaches (or recedes from) the antenna or as less interesting aspects of body motion are sensed by the radar; (c) antenna motion will add clutter as the world will appear to be approaching (or receding) as the antenna moves; (d) other motion sources (out of the water) may also present clutter (as well as other fish nearby).

Non-contact radar monitoring 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 most of the large sources can be avoided with a directional antenna.

4.2.2 Fish and Facility

The tilapia used in these tests are kept at the Windward Community College Aquaculture Complex (Fig. 4.10). The testing tank for these experiments was located in a shaded area to prevent sunburn for the tested fish. Subjects were returned to their holding tank after they finished a round of tests.

4.2.3 Experimental Procedure

For these tests, the procedure included lightly sedating each subject, moving it to the testing tank, and then running multiple short tests before moving it to

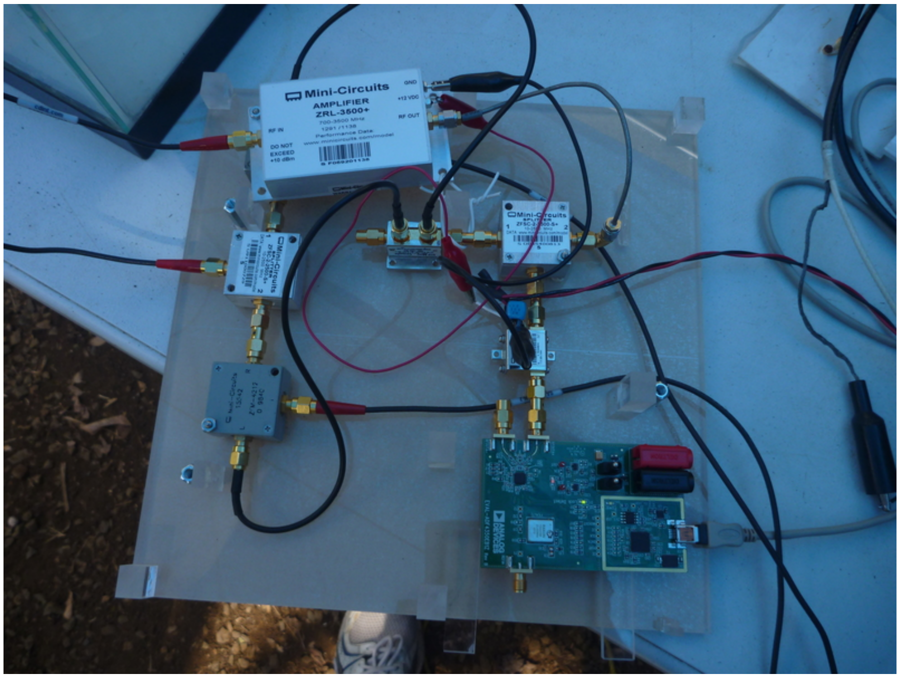


Figure 4.6: This photo shows a compact radar system (radio section only). This system, with minor changes, was used for other experiments as well. The large component is a high power amplifier, used to transmit a stronger signal through the fish tank wall, water, to the fish, and back.

a recovery tank. The antennas were located either next to the tank, or below it. Similarly, the video camera for reference measurement was located above the tank for some subjects and next to the tank for others.

4.2.4 Results

Test conditions were messy, which was not unexpected for fish experiments. One problem that was not caught in time was antenna malfunction due to water ingress. For these experiments, drying and external mounting provided a workaround, but for use in larger volumes of water, sealed or submersible antennas will be required.

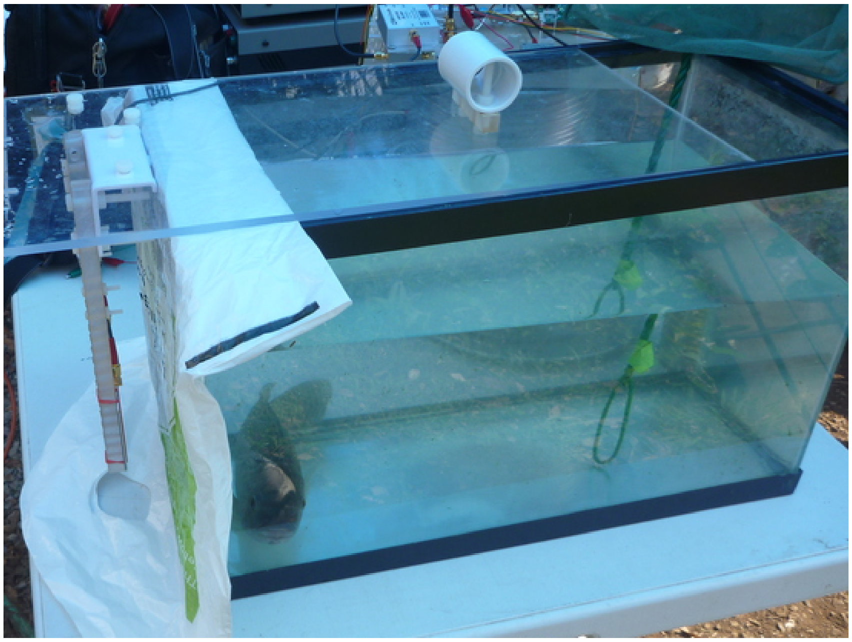


Figure 4.7: Photo of testing tank with test subject and radar antennas (to the left of the tank). Obscured behind the tank is the radar (radio and baseband signal processing).

Figure 4.8: Photo of testign tank with test subject and radar antennas (mostly obscured below fish).

Fig. 4.11 shows the correlation between the radar and the reference. The spikes indicating each breath in Fig. 4.11b are simply the marks from the

Figure 4.9: Example video frame showing murky conditions with reflections complicating visual analysis. The fish fills enough of the camera field of view so that gill motion is visible, if blurry.

Figure 4.10: Windward Community College Aquaculture Complex — Visible in the foreground is a fish tank used for combined cycle aquaculture in combination with the plants visible in the background.

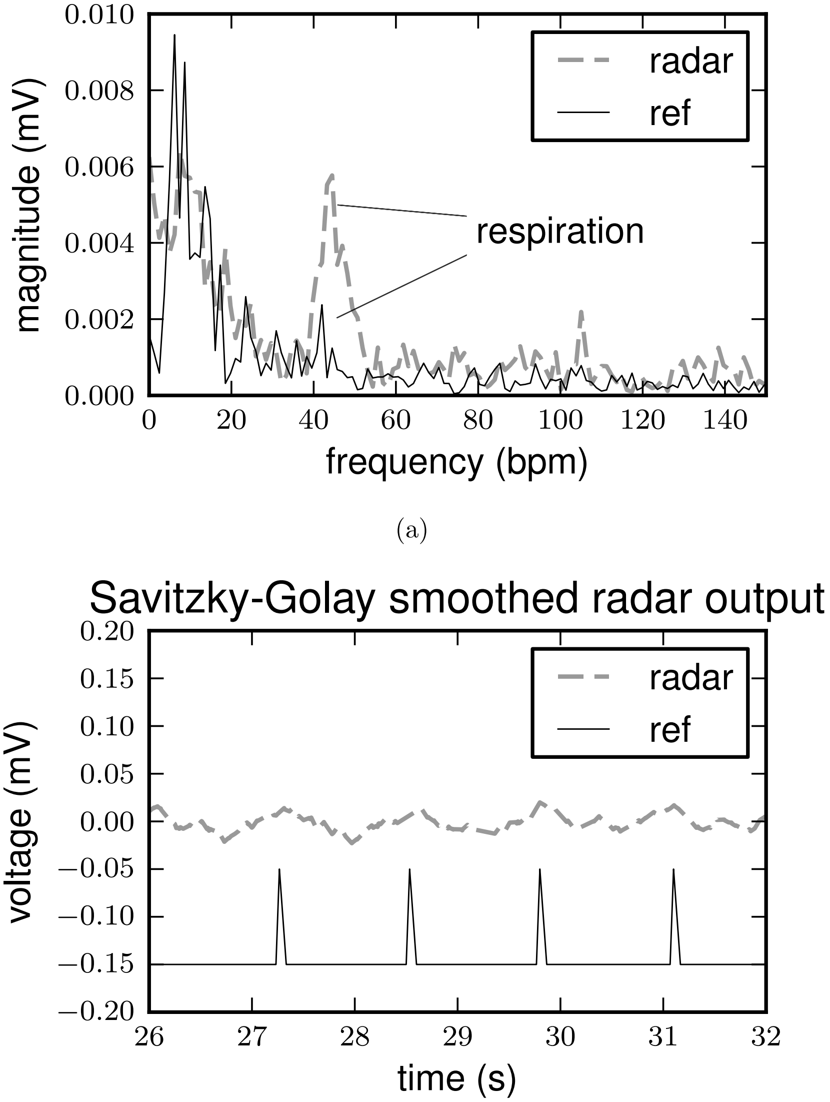
video timed to match the change of motion of the gill covers (in to out, or the reverse). Disagreement between the video and radar can stem from inaccuracies in either measurement. Given the difficulty of identifying the motion from video recordings, the radar may provide more reliable timing information. There is some jitter in the timing of the gills from the 30 Hz sample rate of the video and some from determining the exact point in time when the direction of motion changed.

The radar data in Fig. 4.12a drift/clutter as well as noise — all of which required filtering and smoothing for further analysis. In Fig. 4.12, the data is only plotted for the overlapping window of time (the radar recording started prior to the video recording for the fish, and the video recording stopped after the radar). The video timing was adjusted to match that of the radar data, which is used for both plots.

Table. 4.1 radar and reference reported respiration rate for multiple experiments. These results show that radar can repeatably monitor physiological motion in multiple subjects.

Table 4.1: Data for tilapia respiration rates over multiple experiments.

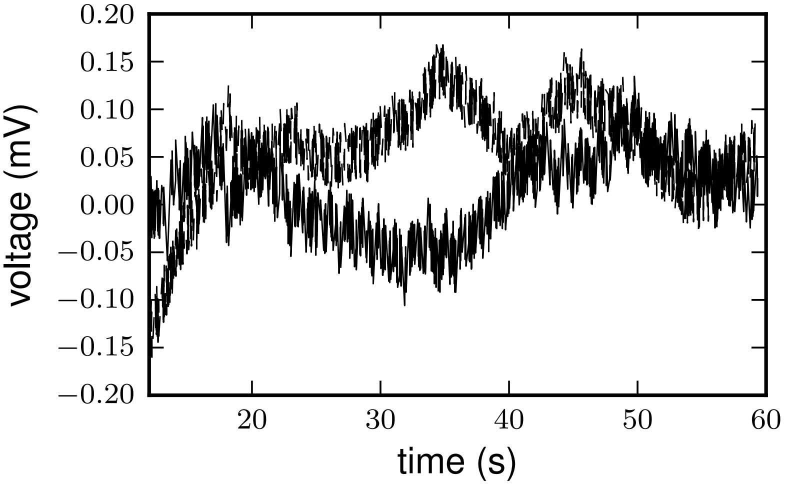
experiment identification	respiration rate (bpm)		
	radar	reference	difference
t2c	63.9	58.1	5.8
t3b	17.7	20.0	-2.3
t3c	78.6	81.3	-2.7
t3d	19.4	23.8	-4.4
t4b	53.2	58.1	-4.9
t4c	44.5	46.5	-2.0
t4d	44.5	45.7	-1.2



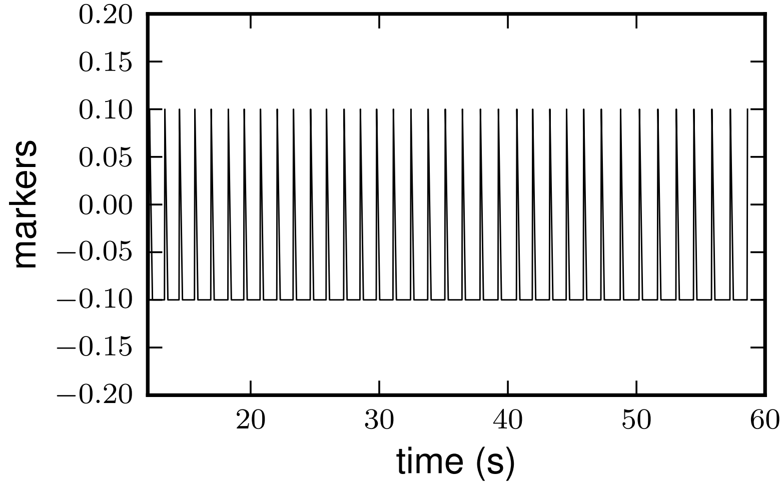
(a)

(b)

Figure 4.11: Data for larger tilapia. The radar had high frequency content and for now I am using Savitzky-Golay smoothing to ease visual analysis. Not as visible is the high-pass filtering to provide a level signal. The respiration reference frequency content is not as clean as I would have expected, and I am still working on how I want to handle the translation from 30 fps video to a 1 kHz timebase signal.



(a)



(b)

Figure 4.12: Data for larger tilapia – longer section. This is the overlapping portion of the test run - there is extra video and radar before this, but they do not both have useful information.

4.2.5 Discussion

The results of this set of experiments are positive — respiration is detectable with radar antennas located to the side or below the test subject. The video used as a reference to verify the radar detection of gill motion showed some trouble with water clarity, reflections form tank walls and labor intensive data analysis.

These are favorable results, but do not yet demonstrate heart rate sensing — that will be shown next along with respiration monitoring with other subjects.

4.3 Sturgeon Heart and Gill Motion Sensing with Doppler Radar

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 test coverage. Related to the difficulties of surgical procedures, while ECG provides good information about every subject so instrumented, it requires capture, handling, anesthesia, and then either a tether, a transponder, or recapture to acquire the data. 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 [14] and radar has exhibited reduced susceptibility to noise as compared to ultrasound [47]. Fish heart rate monitoring via radar has been demonstrated with antenna–subject contact , sidestepping the issue of underwater propagation [27] 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 [47].

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 [14] and motion sensing. While it has also proved capable of sensing heart motion in fish [27], 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

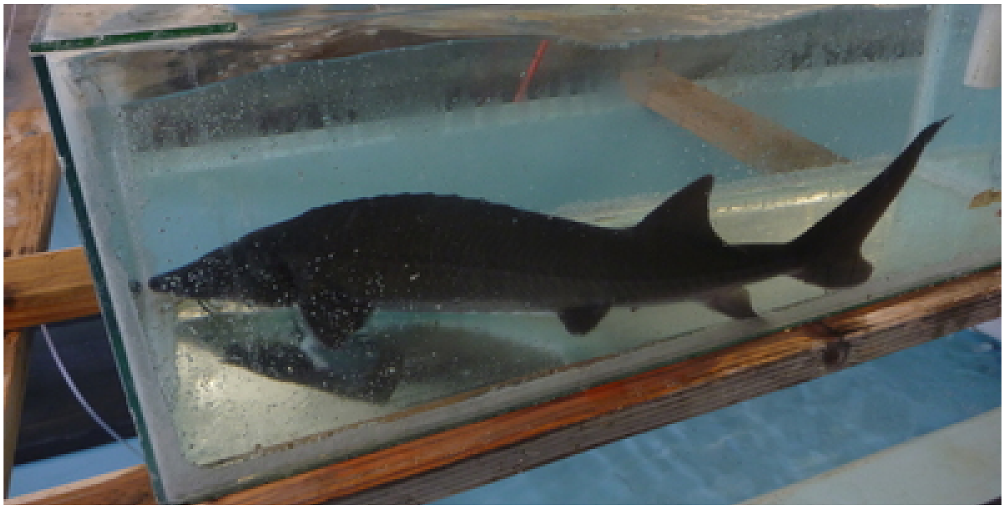


Figure 4.13: Photo of Siberian Sturgeon in tank before experiment. The subject massed 8.2 kg and measured 0.87 m from snout to tail at the time of test.

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.

4.3.1 Background

4.3.1.1 Heart motion

Heart motion, periodic with successive beats, can be detected as repetitive shifts in Doppler shift or alternately as repetitive changes in the relative phase of the received signal. This motion may be detected as motion of the wall of the heart or it may be detected as motion of the chest wall (moving in time with the heart). The specifics of the motion detected depends on steps in material properties (e.g. dielectric constant).

Figure 4.14: 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.

4.3.1.2 Visual Monitoring

Visual analysis (video or cinematic) has been used for motion analysis of fish [48], but with swimming rate or body motion as the measured parameters.

4.3.2 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. 4.14) to avoid extra stress on the test subjects.

4.3.2.1 Animal Care and Ethics

These experiments were authorized by an Institutional Animal Use and Care Committee and conducted in accordance with an approved protocol (UHM IACUC #10-912).

4.3.2.2 Subjects

Siberian sturgeon (*A. baerii*) were used as test subjects for these experiments. The first test subject can be seen in Fig. 4.13 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.

4.3.2.3 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 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. 4.15.

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 the vertical component of gill motion.

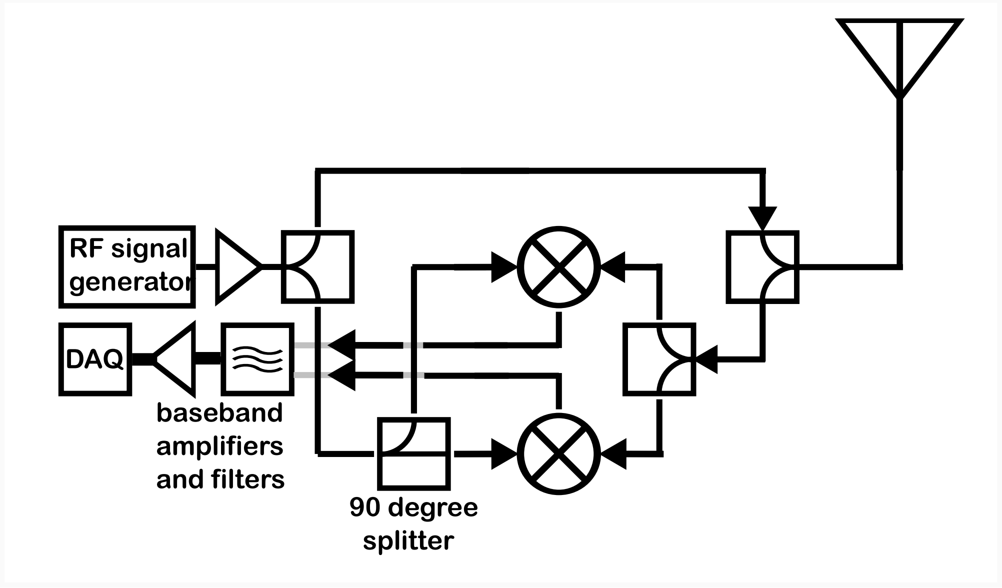


Figure 4.15: Block diagram of radar system used for these experiments. The RF blocks (splitters, mixers, antenna) are each indicated in this schematic while the two SR560 amplifiers (one for per channel) used for baseband signal conditioning are noted as a single unit before the computer based data acquisition.

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 a rate of 1000 Samples/s. Data was collected using software written in LabVIEW, with a live display for instant feedback and traces stored as for off-line analysis.

4.3.2.4 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.

4.3.2.5 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.

4.3.3 Analysis

4.3.3.1 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. 4.16 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. 4.17. This same data (from a 24 s excerpt) is plotted over frequency in Fig. 4.18 overlaid with data from the radar sensor, showing good agreement between the two methods for ventilation rate (in this case 115 BPM). As the

Figure 4.16: 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 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 pleasingly less surgically traumatic option.

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. 4.19 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.

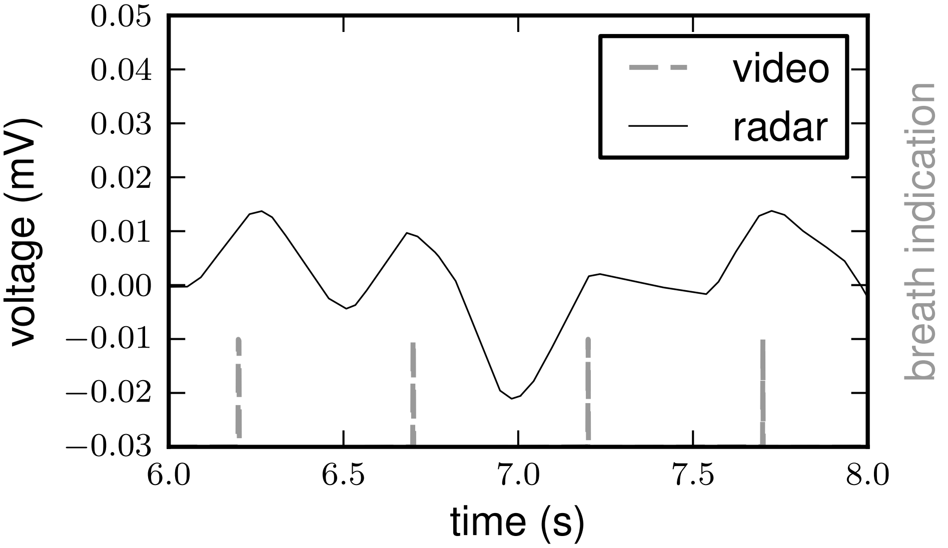


Figure 4.17: Plot of simultaneously recorded radar and video data showing the radar output varying in sync with the breathing cycles extracted from the video. Voltage scale is for radar only, with unitless vertical spikes indicating timing for each breath in the video trace.

4.3.3.2 Radar

The data was analyzed using small programs in Python [49] with additional libraries for data processing [50] and visualization [51] customized for these experiments. The baseband analog filtering removed some noise and drift, but not all. Digital filtering helped clean the signals during the off-line analysis. Matching ventilation rates can be seen in Fig. 4.18, 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. 4.19 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

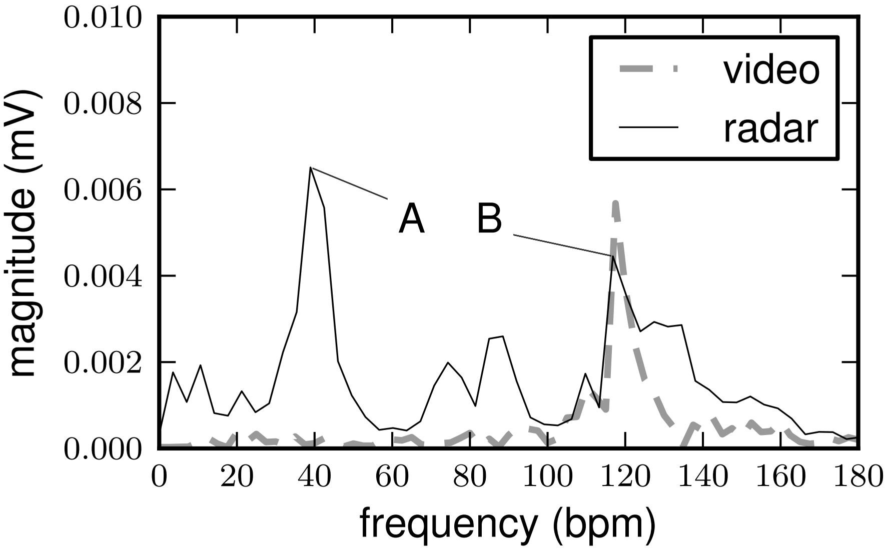


Figure 4.18: Plot of ventilation over frequency for both radar and video showing good agreement between the two for ventilation. Two peaks in the radar trace are indicated with A and B (heart and gill, respectively) indicating detected physiological motion with the ventilation matching that from the video reference and the heart rate shown only in the radar trace due to trouble with monitoring heart motion in the video recording.

video reference. Both frequency plots were generated using 24 s long windows of data.

4.3.4 Results

The results show the radar capable of monitoring both gill and heart motion without antenna–subject contact. Due to problems with reference heart measurements, sequential radar and reference measurements were required to check heart motion sensing.

Simultaneous radar and reference measurements were possible for respiration rate (gill motion). Time domain Data showing gill motion sensing can be seen

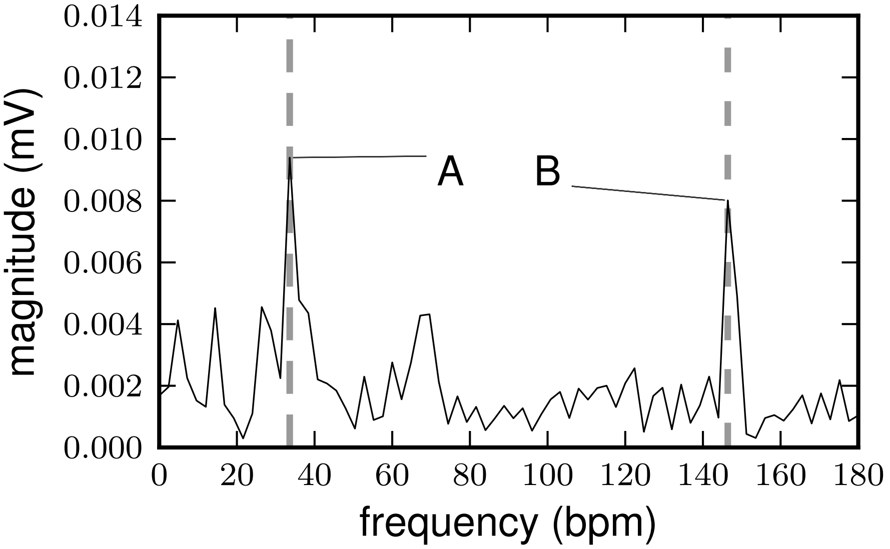


Figure 4.19: Plot of radar sensed motion over frequency with heart and ventilation (A, B) motion marked. Radar and reference agreement can be seen in the overlap between the indicated peaks and the dashed vertical lines.

in Fig. 4.17 with the same results shown over frequency in Fig. 4.18.

In the results from this experiment, video and radar indicate 115 BPM (Breaths Per Minute), and radar indicates repetitive motion (probably heart) close to 40 BPM (Beats Per Minute). The video, recorded simultaneously with the radar, did not provide heart rate information.

The reference video was unable to provide heart rate information when the sturgeons were oriented upright and over the radar antenna. To compare the radar reported motion with information from the reference, heart related motion was first recorded with the video reference and then the motion was recorded with the radar system immediately after the end of the video recording The data for the radar and reference are shown in Fig. 4.19 — neither the heart rate nor the respiration rate changed significantly in the time between the radar and reference measurements. Because the radar and reference measured different signals (varying over time), direct time domain comparisons would be difficult. The physiological rates visible in the frequency plot are stable enough to show the radar detection of heart motion, and additionally the steady heart and respiration rates. The results of this experiment show agreement between radar and video for heart and ventilation with a heart rate of about 35 BPM and a ventilation rate of about 145 BPM.

In addition to this pair of experiments showing radar detection of gill and heart motion, other experiments provide data showing the repeatability of these results. The rates as reported by the radar and reference measurements are shown in Tab. 4.2 along with the differences between them.

Table 4.2: Data for sturgeon respiration rates over multiple experiments.

experiment identification	respiration rate (bpm)		
	radar	reference	difference
t1m	123.7	120.0	3.7
t1n	117.7	117.5	0.2
t2a	122.7	121.8	0.9
t2d	122.8	126.2	-3.4
t3b	70.7	69.4	1.3
t3c	70.7	70.3	0.4

4.3.5 Discussion

The radar and reference reported ventilation rates matched quite well and the reported heart rates also showed good agreement. Both the radar and video showed the variation in ventilation rate over time in the course of testing. The video reference, however was not able to provide heart rate information (at all without intervention) and even ventilation was difficult to determine from some the recordings (when the subject moved or when the tank wall started to fog up. The radar worked at short ranges (1 to 5 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) [52] or blind source separation (BSS) [3]. 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 [53]. 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.

CHAPTER 5

Transitional and Future Work

All experiments to date have involved short ranges (from 20 cm down to subject–antenna contact). For systems usable in other situations, for example aquaculture, controlling the antenna–subject range may be simpler than using a more capable system, but more capable sensors can ease this task. One facet of this is sensing at longer ranges, another is separating multiple sources of motion (heart, gill, fin, body motion from one fish, or heart motion for more than one fish, or a combination of these). Both longer range/larger volume sensing and motion separation require increases in hardware capabilities. After outlining sensing improvements possible with more capable radar sensors, I will describe some miniaturization efforts and work on a path towards creating more capable radar sensor systems.

5.1 Radar Sensing at Longer Ranges

There are a few straightforward extensions from the radar systems used for these experiments and more capable (and complicated) systems that can monitor a non-stationary subject.

- single radar system that tracks the subject location and uses minimal RF power
- multiple radar systems at multiple locations across the volume
- single radar system with multiple antennas (MIMO, SIMO, switch one radio through multiple antennas)

5.1.1 Tracking Radar

Air search radar systems typically sweep a radio beam through an area of interest and calculate target location through antenna angle and time from transmit to receipt of signal. Tracking radar systems typically aim a small beam at a target and maintain radar contact with it by monitoring the Off-Boresight Angle and altering the beam angle to minimize this. For monitoring a single fish in a tank, a non-directional antenna presents limitations only in power efficiency. For monitoring multiple subjects in a tank (or volume of sea), scanning a beam across them can separate the motion from each, allowing signal processing on one fish at a time, rather than requiring the radar system to analyse the motion of all the fish with each other. For both these cases, the system should vary the transmitted power to use the minimum necessary — this will make the radar seem safer, improve energy efficiency, and exclude clutter motion stemming from sources further away from the radar system.

5.1.2 Multiple Independent Radar Systems

Air traffic control centers sometimes require multiple radar systems to cover the airspace assigned to them. This results in a large amount of data being available to the controller. To address this, automation systems have been designed that consolidate the radar data for the controller. This consolidation includes eliminating duplicate radar returns, ensuring the best radar for each geographical area is providing the data [54–57]. Like the network of radar systems used for tracking air traffic, multiple radar sensors can be located in an enclosure with algorithms selecting which one to use as a subject swims past the antennas. This could be a network of simple radar systems with non-directional antennas, each similar to those currently used in experiments, but with additional signal processing for fusing the outputs of the sensors together to form a coherent picture of the subject activity.

A system like this might not require a separate radar system for each antenna location. An RF switching matrix could route the signals between a single radar tranceiver and the antennas in sequence. The major drawbacks to such a switched antenna approach are sampling rate/throughput and RF transmission lines. Using a single radar system limits the number of antennas (N_{ant}) and sampling rate of the system (SR_{sys})

$$SR_{ADC} \geq SR_{sys} \times N_{ant} \tag{5.1}$$

because every sample from every antenna must be processed by the same radar (and baseband) hardware (SR_{ADC}). The ADC sample rate is not the only limitation of throughput, but simply a representative example. RF transmission lines are expensive, and difficult to use in water.

Using a radar system switched between multiple antennas sidesteps problems with calibrating multiple RF front-ends and baseband channels, and provides a simple path for the signals.

5.1.3 Multiple Antenna Radar System

Similar to using multiple radar systems, multiple antennas can configured as a MIMO [58–60] (multiple transmit and multiple receive antenna) or SIMO [3, 5, 60] (single transmit and multiple receive antenna) system with algorithms to separately combine the components of the received signals for each subject or source of motion. Because this processing can be performed in the digital domain, the antennas can be placed throughout the tank or enclosure with local signal processing and simple digital communication lines (or wireless data links) connecting the parts of the system together.

5.2 Future Work: Signal Processing Improvements

The signal processing and analysis used for these experiments with fish have been relatively simple and straightforward. Improved analysis of data is a prerequisite for monitoring in less controlled conditions.

5.2.1 Unrestrained Monitoring

monitor heart or gill motion without unreasonable restriction on body motion

Some challenges:

- larger tank,
- variable antenna–subject range,
- changing angle of subject (head on, tail on, broadside, ...)
- alternate periods swimming and hovering
- monitoring with continually swimming subject
- identifying or classifying heart and gill motion with radar data alone

Some of these challenges fall into the domain of the hardware, firmware, or low level signal processing. For varying antenna–subject range (especially in a larger tank), the radar system needs to modulate the transmit power: lower when the subject is close to the antenna and higher when the subject is farther away. Identifying heart or gill motion without the use of a reference can be considered a separate class of data analysis and will be covered in the next section.

For monitoring ventilation rate or heart rate of unrestrained subjects, algorithms must either extract these rates from radar signals with large amounts of clutter (from the swimming) or determine when the subject is moving and when it is resting and provide ventilation and heart rates during these still periods. Such algorithms can be adapted from those used for extracting cardiopulmonary signals from moving human subjects.

5.2.2 Improved Signal Processing

For a single subject, random swimming may result in differing subject aspects facing the radar antenna. Though additional work would demonstrate fish specific ramifications of this, work on human heart rate sensing for multiple subject angles [61] shows this should be feasible. While a single subject should have only one heart beat, separating heart and gill motion through frequency filtering alone may prove insufficient — algorithms for blind separation of signals from multiple sources may translate from human heart and lung motion [5] and help with heart and gill motion as well.

Single subject monitoring is much easier than physiological monitoring for many subjects or even monitoring a single subject with the motion of nearby individuals creating clutter. Research into separating the signals from multiple motion sources (specifically human heart beats) either for two nearby subjects with similar signal power [3], or with one subject more distant [62].

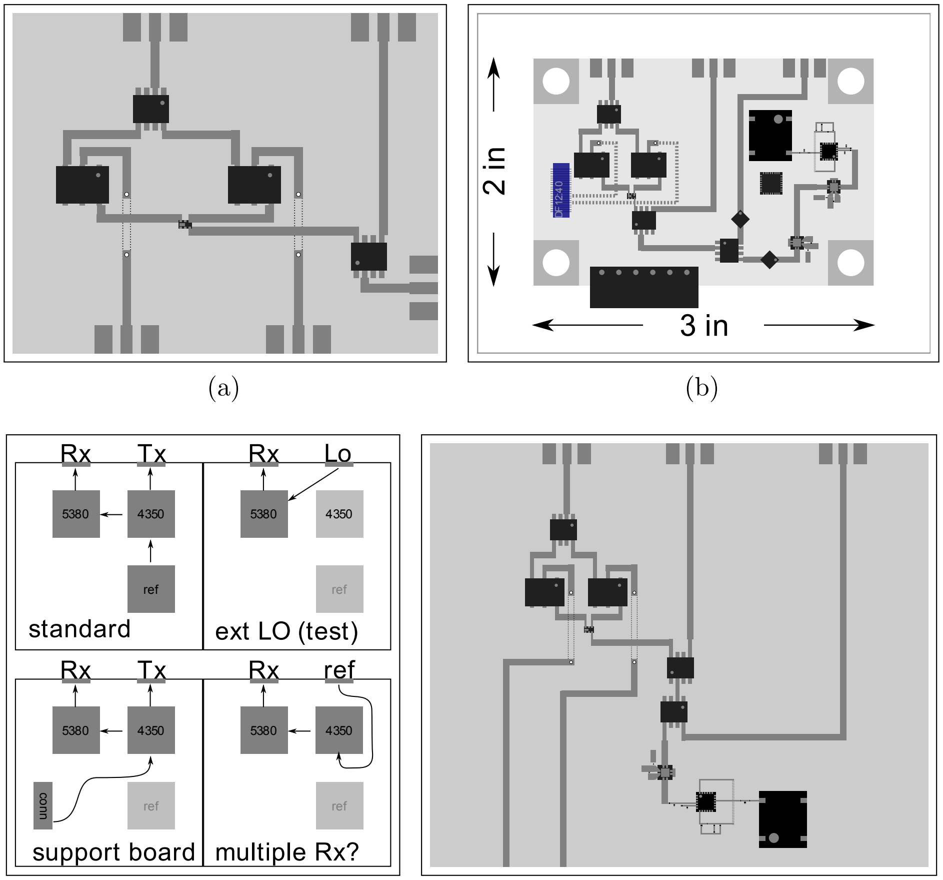
5.2.3 Physiological Motion Identification without Reference

Physiological monitoring of fish requires identification of subject heart-, gill-, fin-, and body motion. For experiments with low numbers of subjects, checking the radar and reference reported motion from an early experiment can provide a good idea of the expected, e.g. ventilation, motion parameters for similar conditions. In experiments with similar subjects, after classifying motion, these results can be checked against the reference measurements. In non-experimental situations, the radar (or data analysis algorithms working with radar data) will have to classify signals and provide information about physiological motion without reference measurements. This will require identifying heart- and gill-motion especially.

Algorithms to classify motion sensed by radar are not available specifically for use with fish, but can be adapted from those available for human use. Heart rate (and HRV) monitoring in sleeping subjects with indication when body motion interferes with the heart motion sensing [63] is one example of data analysis that can be ported to fish monitoring. Another example that may help with identifying heart motion and differentiating it from gill motion is estimation of the radar cross section (RCS) [64] of the motion source.

5.3 Printed Circuit Radar Miniaturization

Current equipment for radar experiments is bulky, expensive, and fragile. The components assembled into the radar systems used for the fish monitoring experiments could be used for the more complicated systems, but this could be problematic and costly. Problems stemming from the low level of integration and large size could prevent effective operation. Troubleshooting such a system could be more than burdensome — verifying correctness of operation for any given experiment can prevent the collection of usable results. Reducing the expense of the current radar systems and system blocks of equivalent complexity could help with some of the reliability questions (allow for swapping whole blocks to eliminate faults). Since some sensor system advances are dependent on a larger set of hardware, cost reduction can bring them into the range of feasibility. A different problem facing laboratory sized systems is difficulty



(a) (b)

(c) (d)

Figure 5.1: Diagrams of concepts for miniaturization starting from (a) direct translation of existing radar systems to printed circuit boards; continuing through (b) small stackable modules; and also (d) larger single-board integrated designs with some of the connector configurations illustrated in (c).

transporting the hardware for on-site or field experiments.

5.3.1 Planning

With the connectorized radar systems as a starting point, miniaturization concepts started by directly transferring these to printed circuit equivalents. The board ideas transformed over time to more integrated systems combining the function of the equipment needed for experiments into a small package.

The conceptual designs led to prototype designs implemented as printed circuits. The first prototype, rather than a direct translation from coaxial to printed circuit components, used more highly integrated parts: an AD8347 mixer and an ADF4350 frequency synthesizer. The second prototype built on the success of the first prototype design and the lessons learned from it. Simpler and less costly parts, and additional support circuitry for easier operation were some of the updates.

5.3.1.1 Use Cases

I considered a few scenarios to illuminate the design space. These include the current work with experiments conducted in the lab with connectorized radar systems, portable experiments with fish or other animals in field conditions, portable experiments in hospitals, and interesting techniques that might need specific features.

1. Lab Experiments: Single radar system with a single antenna for both transmit and receive or two antennas – one for each. The radio source used would only need to generate the desired frequency without any need to match other clocks or signals. As with the current hardware, this system would provide analog baseband signals and operate for long periods of time with mains power.
2. Portable work:
    a) Field experiments require small radar systems with minimal dependences on external resources. A radar system for these types

of experiments would need a single antenna connector for various antennas, depending on the specifics of each experiment. Like a lab radar system, an internally generated reference frequency and analog baseband outputs would be fine. The main constraints would relate to portability — the system would need to be small and self-sufficient, thus requiring both integrated power supplies and signal processing. Sunlight readable indicators or displays would greatly enhance the usability of the system, and battery powered operation for a day of experiments is reasonable. While integrated digital conversion, storage, and display for the radar output would be useful, these features can be adequately provided by discrete hardware.

    b) Clinic or Hospital experiments would create similar requirements to field experiments, but with more emphasis on configurable signal processing and less frequent, but longer experiments.

3. Interesting Sensing Techniques:
    a) Harmonic radar tags operate by receiving energy at one radio frequency and then using that energy to transmit energy at a multiple of the original signal. A radar system using such tags would need to generate two related frequencies internally, or use two antenna connectors and external radio components for the harmonic conversion.
    b) Current homodyne Doppler radar systems generate baseband outputs by using the transmitted signal to directly convert the received reflections to baseband signals. A superheterodyne receiver could

offer performance benefits with respect to noise, DC offset in output signals, software defined radio (SDR) signal processing. Generating two LO frequencies for a single radar system can be accomplished with a pair of LO sources on a single radar board or with one LO source on each of two radar boards with a shared reference frequency for coherent operation.

c) Multiple Input, Multiple Output (MIMO) radar systems or single input (SIMO) systems need multiple channels operating on a single frequency. Multiple radar boards configured for generating individual LO signals based off a shared frequency reference can form the hardware platform for such a system. Experiments would not initially require extended run-times, or other special considerations.

5.3.2 Development Prototype Details

I sequentially created two prototype printed circuit designs as proof of concept tests. Neither of these was intended as an end goal, but rather as a step on the path to hardware systems that offer higher reliability and greater ease of use at lower cost than those currently used. These boards, rather than prototyping hardware for a single type of radar system or mode of operation, provide a simple base to build towards multiple possible system designs, such as: (a) basic hardware block to replace or augment current connectorized systems; (b) minimal, low power system for a wearable sensor; (c) small, self contained nodes of a sensor network; (d) multichannel system for MIMO, SIMO, monopulse or phased array sensing; depending on the constraints of the environment or experiment.

The first design tested initial feasibility concepts, including FR4 as a substrate for RF transmission lines, highly integrated commercial radio components, and manual assembly techniques. To this end, the design included not only a pair of RFICs: one frequency synthesizer (ADF4350) and one quadrature demodulator (AD8347) with supporting circuitry, but it also included a set of transmission lines connecting pairs of coaxial connectors.

The second prototype design built on the successes of the first prototype with modifications based on the problems encountered. It also included higher system integration, with on-board power, configuration, and baseband processing circuit sections.

While the second iteration has a useful set of features, there are gaps that a productized system would need to cover. Some of those are evident on inspection, others will become apparent in the course of using the current design for experiments and finding problematic limitations.

For both of the prototype designs, conservative design choices and modular circuit design help increase the likelyhood of success. Commercial-off-the-shelf integrated circuits (rather than research prototypes) and circuits modeled off vendor examples reduce the design complexity. Clear links between major circuit sections on the board allow for easy separation of functional blocks for troubleshooting or repurposed use. Some of these links are surface mount jumpers, some are traces on outer layers, and power connections are surface mount ferrite beads.

While all the components on the radar boards are commercially available, and specifically intended to be easy to source, the design overall is customized to the specific goal of providing a widely usable miniaturized radar system at low cost. These designs are intended to be used as radar hardware in experiments and provide repeatability in performance, both through sufficiently low cost to dedicate radar systems to individual experiments and through consistent unit-to-unit performance.

5.3.2.1 First Prototype Design

The first prototype design (Fig. 5.2) was a success for feasibility testing. In addition to demonstrating the feasibility of transmission lines on a FR4 substrate, this design provided valuable feedback regarding board assembly techniques, external connectivity, and radio frequency integrated circuits.

Summary: Some of the details successfully tested with this board included: transmission lines, frequency synthesizer programming with a microcontroller, on-board LO generation, quadrature demodulator. Some aspects of the board were less successful: leadless packages, manual reflow assembly, part sourcing, external connectivity.

Assembly: Leadless packages, specifically the fine pitch quad flat no-lead (QFN) used for the frequency synthesizer are difficult to align to the pcb footprint and require careful solder dispensing to avoid bridging adjacent pins or failing to connect a pin to its pad.

Manual reflow assembly was slow, but mostly successful. The two largest problems related to the finer pitch components: the two integrated circuits

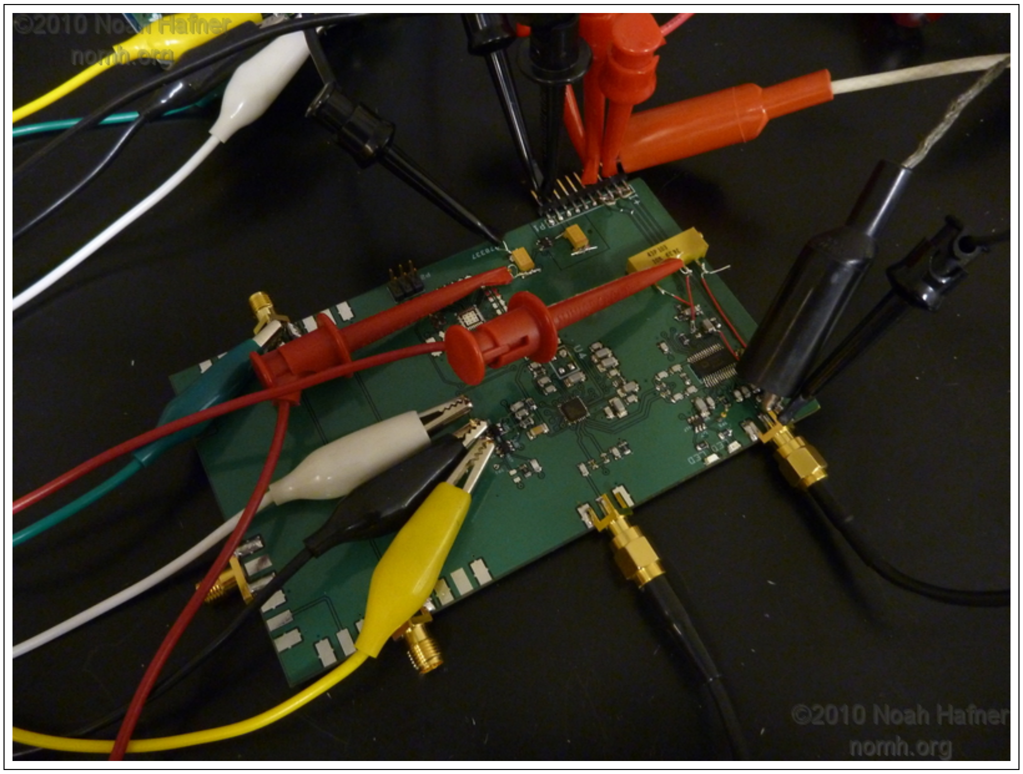


Figure 5.2: Photo of first miniaturization prototype board during testing. The connections in the upper corner are the analog output signals. Frequency synthesizer programming signals use the white/black/yellow connections near the center of the board. Power is supplied near the upper edge (by the outputs) to either side of a yellow-orange capacitor. The connections by the receiver section of the board (right SMA connector) are for debugging and investigating the operation of the mixer offset adjustment.

(ICs) providing the radio functions. Correctly dispensing solder paste required careful attention for all the parts, but special care was needed for the ICs. After reflow, the mixer required manual rework to separate shorted pins or connect floating pins to the pads on the board. The frequency synthesizer failed after a few hours of operation. This is likely due to high thermal resistance between the exposed pad and the pcb ground plane.

Component Availability Part sourcing was troublesome for some of the parts, though generally straightforward for the majority. The frequency synthesizer IC (ADF4350) was only available in prototype quantities from Analog Devices as samples. The microcontroller (ATMega328, 32 QFN package) was unexpectedly difficult to source. Test points simplified connecting a similar microcontroller on a separate board to program the frequency synthesizer, but while this helped test microcontroller–synthesizer communication, it did not help investigate programming a microcontroller on the radar board.

Board I/O External connectivity had positive and educational points. The end-launch SMA connectors were easy to work with and mounted securely to the board. The remaining connectors were troublesome, with the planned pin header both failing to fit the board and proving troublesome as a connector. The closely spaced individual pins were difficult for attaching clips. The test point pins for the programming bus and the pins adding during rework for the mixer debugging were useful, if delicate.

Testing: This prototype board offered some useful indications during tests, but was only used for informal tests. Part of the problem stemmed from the large number of connections to the board from various pieces of equipment, the rest was simply the failure of the onboard LO source shortly after the board started to provide useful output signals. One of the successful tests was FR4 transmission lines, tests showed high loss, but adequate performance for short lines. This points to a need for minimal distance between the radio components on the board. Using an AVR to program the ADF4350 frequency synthesizer was not complicated for simple results. The process involves a series of multi-byte transfers over SPI to load the configuration registers of the synthesizer. More involved code would be required to allow interactive programming for some of the synthesizer settings, as an example, allowing RF output frequency specification in Hz. While the microcontroller used for synthesizer programming was capable of running off a 3.3 V supply, the microcontroller board supplied 5 V. As a precaution for situations like this, buffers were added to the data lines running to the synthesizer. With 7 V safe inputs and 3.3 V outputs, these buffers were successful at protecting the synthesizer from high voltages and greatly eased interfacing the off-board microcontroller.

Lessons Learned: Educational points from the first prototype board cover design techniques, usability, and functionality. Some components can be surprisingly difficult to source, this can be alleviated by selecting parts available from multiple suppliers (or distributors if there is a single manufacturer). For more common parts, such as operational amplifiers or resistors, using components with standard pinouts and packages can ease the task of finding replacements if needed. The AD8347 mixer/demodulator was selected for a few of its features: leaded package, integrated baseband amplifiers, offset control, gain control, 2.7 to 5.5 V supply. Of these, the offset and gain control were not useful for physiological sensing — this demodulator is intended for communications receivers and the automatic offset and gain functions are designed for higher bandwidth waveforms. The leaded TSSOP package was much easier to work with than the leadless QFN ADF4350 package. Both the a slightly larger pin step of 0.65 mm and exposed leads made the mixer package much easier to work with than the 0.5 mm spaced lands under the synthesizer package. Using regulated power from off-board is a dangerous operating mode. Similarly using external signal for sensitive control inputs on the board opens risks of ESD or accidental high voltage signals destroying on-board components. In addition to the danger of damage, the connections add another possible point of failure and the lab equipment adds considerable weight, volume, and cost to the radar system. For these reasons, higher levels of integration are important. This board had multiple test points and other debugging aids incorporated into its design. More complicated designs should have more points to insert or extract signal for testing purposes or adapting the design for new tasks. In addition to optional signal connections, modular design with easily separable circuit sections for various functions can reduce the work required to locate problems and also to reuse parts of the design in subsequent iterations.

5.3.2.2 Second Prototype Design

The second iteration prototype design incorporated knowledge gained from the first design expanded the scope from just feasibility to a useful piece of equipment. This version was designed to build on the previous version with additional features to allow it to serve as a USB connected peripheral that needs only an antenna for radar measurements. With some board components only available in leadless packages, the board assembly for the initial boards moved away from in-lab board assembly. Two assembled examples of this design can be seen in Fig. 5.3. These boards will be ready for testing, characterization, and use in experiments after the addition of a few more components and appropriate

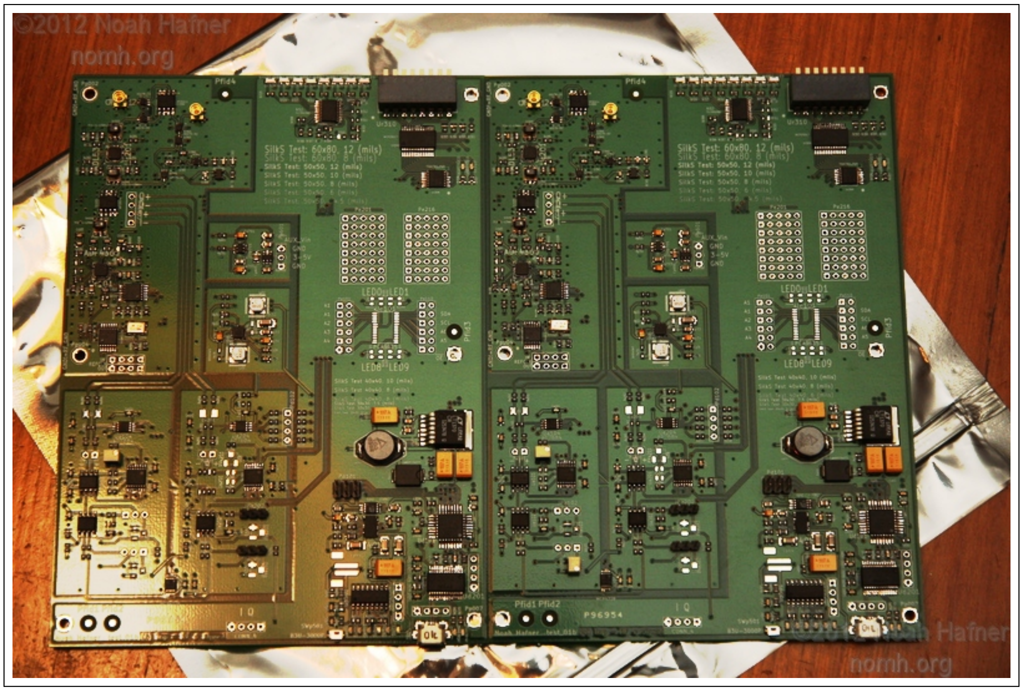


Figure 5.3: Two examples of the second radar board design. These boards have, in addition to the RF source and mixer, baseband signal processing, power, user selected configuration, and digital interface blocks.

firmware.

Purpose: The purpose of this board design was to reuse as much of the previous design as possible and provide integrated replacements for external equipment that would be otherwise needed for use in radar experiments. The goal is a highly integrated radar hardware design usable both in support of experimental work and for verifying circuit implementations. A successful design would also serve as a launching point for specialized systems for wearable, portable, or underwater radar sensors.

Some of the design features are aimed at supporting easy reconfiguration between some common hardware configurations: a configurable path from LO generator to antenna connectors and from antenna(s) to the mixer, switchable gain in the baseband signal processing, firmware mediated user interface through dip switches and LEDs. Other aspects of the design are intended to expand its flexibility: redundant baseband signal paths (discrete ADCs for directly digitizing mixer outputs, and microcontroller-integrated ADCs for digitizing the baseband signals after analog conditioning, analog outputs to external data converters and data transmission via USB), components with leaded packages in the analog conditioning sections to ease rework or custom assembly, optional import/export for frequency reference signal, firmware mediated configuration for host computer controlled configuration modification, or simple configuration selection via dip switches, external antenna connectors mounted to enclosure and wired to board. Fully functioning radar boards will be able to aid in data collection for a wide range of experiments.

These new functions would also be tested on these radar boards and their suitability for future designs judged; an example of this is the integrated baseband signal processing circuit sections and discrete ADCs connected to the mixer outputs.

Status: Of the two assembled boards, both require both a small number of additional components and firmware to control the board. Some of the circuits in this design have been simulated, others were instead copied from part data sheets or design examples.

Initial firmware to test microcontroller programming and host communication via USB will be simpler than later firmware variants with greater capability. Subsequent test required firmware additions will include frequency synthesizer configuration, RF signal path configuration, baseband signal acquisition from discrete ADCs, baseband signal acquisition from board analog outputs using integrated ADCs, and communication with user interface circuitry.

Positive Details: Through the design process and assembly, some details of the boards proved helpful. Modular circuit design was sometime troublesome, requiring a single part in multiple conflicting locations, but greatly helped organize discrete sections of the board. Working through most of the layout in separate blocks sized to the floor plan dimensions allowed easy reorganization to accommodate modifications to the overall board size and relative locations of functional blocks. Board assembly showed some minor problems with documentation and communication, stemming from differing assembly techniques. With those problems fixed, this design can be easily manufactured in low volumes.

Negative Details: Some problems with the implementation or support work have already shown themselves. Some were unavoidable while others can be used as negative examples for future work. Leadless packages, as noted earlier, are difficult to use. Some of the components on this board are available only in leadless packages. Of these components, some had no functional alternatives (frequency synthesizer) or the alternatives would have been more problematic than the package mounting. Other components were replaced with larger alternatives or passed over in the initial stages of part selection. Only the baseband signal processing blocks shared similarities with any of the other functional blocks on the radar board. While the basic layout of these was shared, external control signals routed from other parts of the board introduced differences and were not sharable between the two baseband blocks. Related to this, some control signals required cross-board routing. Some of the circuit elements used for controlling the signal routing switches were shared between multiple circuit blocks. This design choice reduced the number of components on the board and separated most digital signals from the radio and analog sections of the board. The cost of this choice was long runs from one side of the board to the other, presenting difficulties in fitting the needed traces without blocking other lines or components. I noticed that the ADF4360 frequency synthesizer on this board outputs lower RF power than the ADF4350 on the previous board. I had originally chosen to use the ADF4350 on this board as well, but difficulties sourcing the part led me to change away from it. For continuous wave radar, the switch to an integer-N only synthesizer is not a major concern, but in addition to lacking the auxiliary RF output, the ADF4360 output power is limited to the range -13 to -6.5 dBm rather than the -4 to 5 dBm range from the ADF4350. An issue that became more problematic over time was managing the bill of materials (BoM). Initial creation of a component list from the schematic was straightforward. Selecting parts to use for the list was more difficult — not all parts are available in prototype quantities. During some delays following the initial part selection, some of the selected parts became harder to find and had to be replaced with functional equivalents with compatible footprints. Tracking these changes along with some later refinements in the circuit became much more work intensive. Minimizing the number of different parts used can help with some of this; maintaining a database of available parts with unique identifiers and then linking those to the schematic, netlist, and layout.

Lessons Learned: Educational points from the second prototype board include limiting the long signal runs, additional planning check points, and more structured BoM management. Separate pairs of buses (SPI, I^2C) for static configuration and data transfer, and additional I/O expanders can simplify cross-board signal routing to just those buses and power. Both using a parts database and a smaller BoM can help with changing requirements or part availability. Features that could improve the usability or resiliency of the board over the current design would also be valuable additions. Examples of these features are power sequencing, internal signal clamping, transient protection for external connections, and local storage. Soft power control to various sections of the board and an external power switch may be nice, but are not critical. Similarly, an improved user interface may help in some situations, but may be superfluous with users preferring a software interface on a computer with a large screen.

CHAPTER 6

Closing

The monitoring vital signs for fish is critical for advancing the study of trophic and energetic strategies, distributions and behavior, environmental impact, and aquaculture approaches. Presented here is a new approach for monitoring fish metabolic rate without the trauma and stress associated with capture, surgical ECG, or other implanted sensing system.

Tests comprised 130 experiments involving pre-test checks, mechanical phantoms, and live fish. The live subjects in these experiments were: 10 tilapia, 3 sturgeon, 1 hammerhead, 1 pacu, and 1 catfish — all of whom survived.

Radar sensor configuration varies with operating conditions. Body attached sensors required only sufficient range to sense heart motion from the skin, while stand-off sensors need to detect small motions with water separating the antenna and the subject. This, with the experimental results showing reduced performance at higher frequencys for longer ranges would lead to lower frequencies of operation for non-contact sensor systems, while contact radar would benefit from smaller antennas with less propagation drawbacks of higher radio frequencies. Radar motion sensing in freshwater shows improved range over saltwater operation and for both saltwater and freshwater, Doppler radar exhibits less susceptibility to environmental noise and clutter motion.

Continuing development of analysis techniques, hardware, and system miniaturization will still be required for easily usable sensor systems. Such sensors can aid in monitoring fish populations in aquaculture and in data gathering for research on wild populations.

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