Wave Height Measurement Using a Short-range FMCW Radar for Unmanned Surface Craft

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Abstract—**This paper describes a radar system designed for deployment on an unmanned surface craft under development in the Autonomous Ocean Systems Laboratory of Memorial University. The radar system includes two sub-systems: one a long-range radar that detects sea-surface objects a few kilometers away, the other a short-range frequency modulated continuous wave radar. This short-range radar not only detects the near obstacles but also senses the sea state to enhance the navigation safety of the unmanned surface craft. The short-range radar provides a useful complement to the blind zone of the long-range radar and largely determines the survival of the unmanned surface craft in oceans. The design of the short-range system and the experimental results obtained from both wave tank and sea-surface tests are presented. The results show that the short-range radar are able to estimate the sea-state by measuring wave height.**

I. INTRODUCTION

The Unmanned Surface Craft (USC) SeaDragon [1] is under development in the Autonomous Ocean Systems Lab (AOSL) of Memorial University. It is an intelligent marine environment monitoring platform on which sensors and instruments including a weather station, radar, LIDAR, sonar, camera and GPS are installed, to collect oceanographic data and monitor icebergs. It is designed to be capable of navigating at sea for extended period of time. The radar system of the USC detects objects at the surface and estimate sea-state information to enhance navigational safety. Many techniques and instruments have been developed to estimate sea state. Wave rider buoy monitors the sea state [2]; satellite-borne Synthetic Aperture Radar (SAR) can retrieve sea state through analyzing radar images [3] and land-based radar can extract properties of coastal wave fields [4]. The information on sea state provided by these systems cannot meet, however, the requirement of USC which requires local sea state information in real-time. It is necessary, therefore, to develop a small-scale, short-range radar system for deployment on the USC. Usually wave height is used to describe the sea state [5]. This short-range radar system for the USC is designed and developed to measure wave height.

II. RADAR SYSTEM OF USC

The radar system of the USC consists of a Long-Range Radar System (LRRS) and a Short-Range Radar System (SRRS). They will be mounted on the deck of the USC. The LRRS undertakes a single task to detect the range and azimuth of large-scale objects such as vessels, icebergs and islands. It is powered at all times as the USC navigates on the sea-surface. The information on targets at the sea-surface is transmitted to the USC Navigator which is the central control and management unit. The navigator determines observation targets and develops navigation course using the information. However the LRRS cannot provide information on nearby dangerous objects, for collision avoidance because of its blind zone. The SRRS is assigned more than one task and the first one is to track the objects which threaten the navigation safety. The SRRS should be able to measure the distance, velocity, and moving direction of objects within its scanning area. Distance to Closest Point of Approach (DCPA) and Time to Closest Point of Approach (TCPA) [6] will be provided to the USC Navigator in real-time to make decision for collision avoidance. The other task is to estimate sea state information which is another important factor strongly related to the navigational safety of the USC. The USC usually uses wave height to measure sea state. Therefore the SRRS is required to estimate the wave height with the reflected radar signals from near sea-surface, and then send the wave height to USC navigator to evaluate navigation safety.

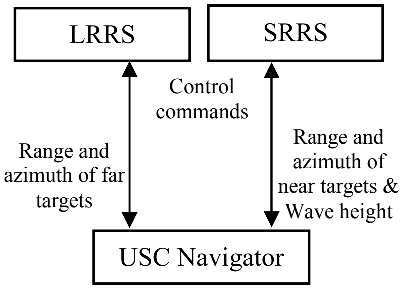

Fig. 1. Relation of two radar sub-systems and USC navigator.

In Figure 1, the LRRS and SRRS communicate with Navigator separately. The navigator receives the information on targets and sea state from the radar system, and meanwhile it also sends control commands to the radar system to switch different operating modes. In consideration of the measurement requirements, the LRRS and SRRS are all Frequency Modulated Continuous Wave (FMCW) radars with which distance and velocity can be measured [7]. These two radars

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operate at X-band and K-band frequencies, to avoid mutual interference.

III. WAVE HEIGHT MEASUREMENT METHOD

The SRRS estimates sea state level through measuring wave height. It cannot measure wave height directly, but as an FMCW radar it can sense movements of water particles and measure their velocities which are related to wave height. The relationship between wave height H and velocities of water particles in a wave is expressed as [8],

$$u = \frac{\pi H}{T}\left[\frac{\cosh k(d+z)}{\sinh kd}\right]\cos(kx - \sigma t) \tag{1}$$

$$w = \frac{\pi H}{T}\left[\frac{\sinh k(d+z)}{\sinh kd}\right]\sin(kx - \sigma t) \tag{2}$$

where,

u: horizontal component of velocity

w: vertical component of velocity

d: water depth

T: wave period

k: wave number

σ: wave angular frequency

x: horizontal coordinate of water particle

z: vertical coordinate of water particle

As the wave propagates in deep or shallow water, water particles excise different obits. The horizontal and vertical components of velocity become

for deep water:

$$u = \frac{\pi H}{T} e^{kz}\cos(kx - \sigma t) \tag{3}$$

$$w = \frac{\pi H}{T} e^{kz}\sin(kx - \sigma t) \tag{4}$$

for shallow water:

$$u = \frac{\pi H}{T}\left(\frac{1}{kd}\right)\cos(kx - \sigma t) \tag{5}$$

$$w = \frac{\pi H}{T}\left(1 + \frac{z}{d}\right)\sin(kx - \sigma t) \tag{6}$$

By setting,

H: 0.5 meter

T: 10 second

k: 2π/30

σ: 2π/10

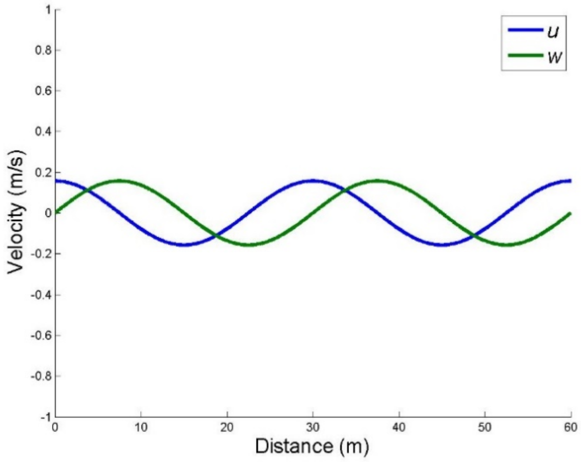

Fig. 2. Velocity components u and w in deep water

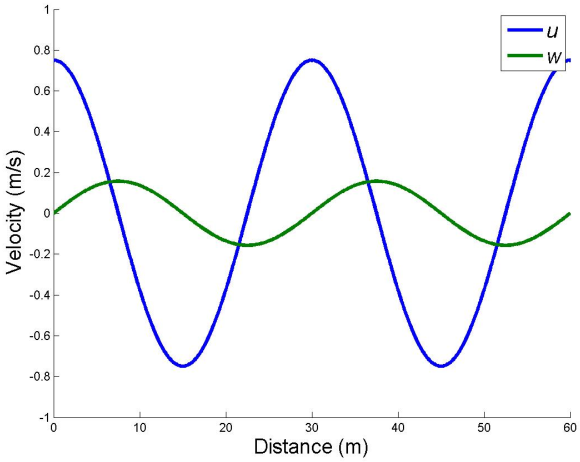

Fig. 3. Velocity components u and w in shallow water (depth : 1 m)

Figures 2 and 3 show the velocity components u and w in deep and shallow water, respectively. The vertical components of the water particle velocity w in deep and shallow water are same because the wave height and period are same for both cases. However the horizontal component u is largely accelerated in shallow water. That is the reason why the orbit of water particle becomes elliptical. Typically the SRRS mounted on USC is close to sea-surface so that it is sensitive to the horizontal component u. If the maximum value u_M of the horizontal component u can be measured, the wave height can be calculated with the following equation for,

deep water:

$$H = \frac{u_M T e^{\left(\frac{kH}{2}\right)}}{\pi} \tag{7}$$

and for shallow water:

$$H = \frac{u_M T k d}{\pi} \tag{8}$$

In Equation (7), the components $e^{\left(\frac{kH}{2}\right)}$ is usually omitted because it approximately equals to 1 when the wave has a low steepness. Consequently, the SRRS is developed to measure the velocity of water particle to calculate wave height based on the above equations.

IV. SYSTEM DEVELOPMENT

The SRRS is made of three components, a radar transceiver, a controller and an enclosure, as shown in Figure 4. The radar transceiver is composed of the transmitter and receiver antennae with which the FMCW is generated, transmitted and received; the radar controller is used to manage multiple tasks, such as generating frequency modulation voltage, processing radar signals, communicating with navigator of USC and driving the stepper motor.

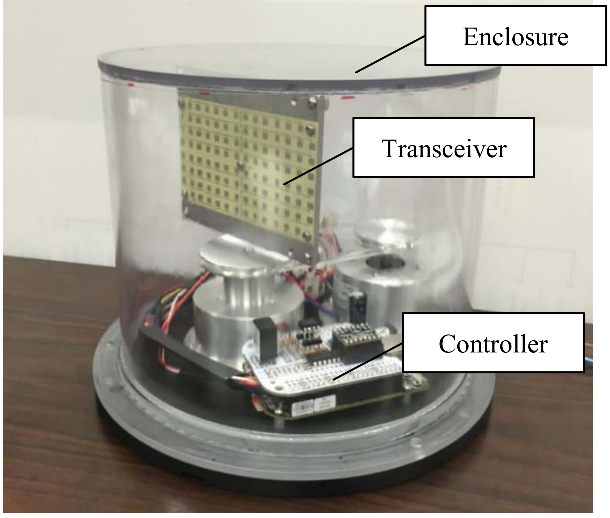

Fig. 4. Short-rang radar system of the USC.

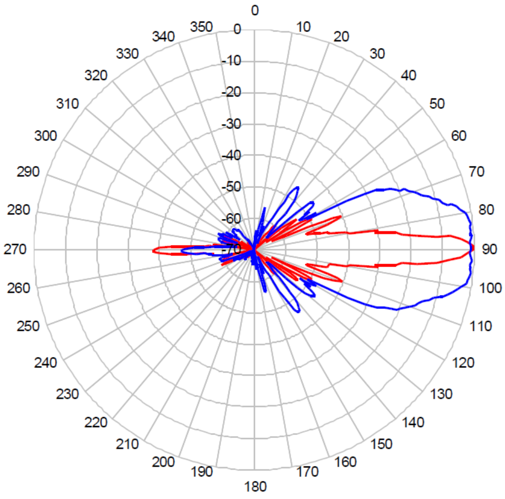

Fig. 5. Antenna patterns of short-range radar transceiver.

The radar transceiver for the USC should be designed to have a narrow beam width in the azimuth direction, high range resolution and low power consumption. In addition, low weight and small dimension are also preferred. Consequently the Traffic Supervision 24 GHz radar transceiver module K-MC3 manufactured by RFbeam Microwave GmbH is selected for our application. Figure 5 shows the antenna patterns for the azimuthal and elevation planes which are denoted with a red and blue curves, respectively. The beam widths are 7-degree in azimuth and 25-degree in elevation. The narrow beam width in the azimuthal direction ensures enough azimuthal resolution to the applications on the USC. The K-MC3 radar transceiver can achieve a 0.83-meter range resolution with 180 MHz modulation depth with a power consumption of less than 0.5 Watts.

The radar controller should manage the transceiver, enclosure and signals in real-time because the USC requires enough time to avoid obstacles and awareness of the present sea state. We use BeagleBone Black, which is an embedded Linux single-board computer working with high-speed processor and large memory as the controller. The radar controller drives a digital-to-analogue converter (DAC) to generate frequency modulation voltage for the transceiver. It also exchanges information with the USC through CAN bus, especially the direction, range and velocity of targets and the characteristics of ocean waves. The radar enclosure is built to protect the transceiver, controller and other related devices. The dimension of the test enclosure is 21×21×19 cm^3 which is a compact design for the application on USC. The dome of the enclosure is made of polycarbonate nearly transparent for the 24 GHz microwave.

V. EXPERIMENTS AND RESULTS

The SRRS has been tested in a wave tank and on the ocean to measure wave height respectively.

A. *Wave Tank Experiment*

Figure 6 shows the wave tank of fluids laboratory of Memorial University. Its length and width are 50 m and 4.5 m respectively. The water depth is 1.8 m. The SRRS was mounted on the towing carriage 1.5 m above the tank. The generated wave period was 4 seconds and the height was 0.12 m.

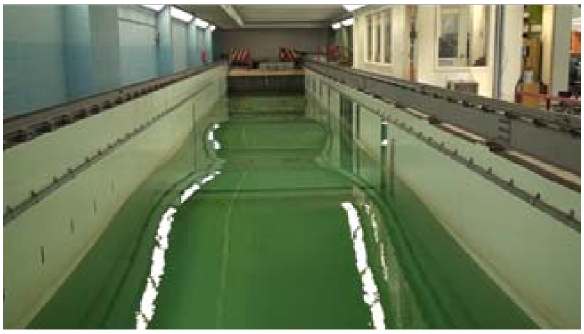

Fig. 6. Waves generated in tank.

The water surface reflected radar signals back to the K-MC3 radar transceiver of the SRRS where the Doppler frequency was measured and stored. The output signal is analyzed by the Beaglebone Black and its spectrogram is obtained. The horizontal component of the water particle velocity can be calculated with the following Equation [9]

$$v = \frac{f_d C_0}{2 \times F_c} \tag{9}$$

where f_d is the Doppler frequency, C_0 is the light speed and Fc is the center frequency of radar signal, i.e. 24 GHz. Figure 7 shows the absolute values of the measured velocities collected in 20-seconds. The wave tank generated a single frequency wave in the wave tank so that the reflected signals from wave can be clearly identified. The maximum value of the horizontal component of the water particle velocity is found to be 0.097 m/s. The wave height is estimated to be 0.116 meter using Equation (8). This result is very close to the generated wave height of 0.12 m.

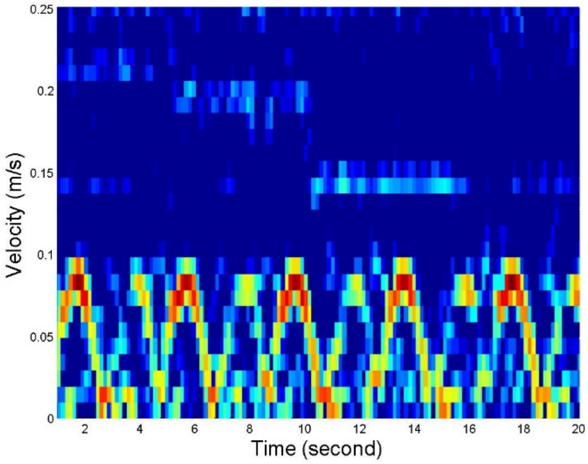

Fig. 7. Velocities of water particles in wave tank.

B. Sea-surface Experiment

A land-based experiment was carried out in Broad Cove, St. Phillips, Newfoundland Canada. Figure 8 represents a snapshot of the wave. 10-second swells were propagating from the open sea. The SRRS was placed on a stationary platform to look in the wave direction toward the sea-surface. The SRRS was about 1.5 m above sea-surface.

The received signals are processed in the same way as wave tank experiment. The horizontal components of water particle velocity is shown in Figure 9. Eight velocity peaks can be seen, and the time difference of two adjacent peaks is about 10 seconds. Because the swell propagates toward the beach, the SRRS measured the horizontal component of the water particle velocity. The measured velocities of eight peaks from left to right are listed in Table 1.

Fig. 8. Sea state with 10 seconds swell.

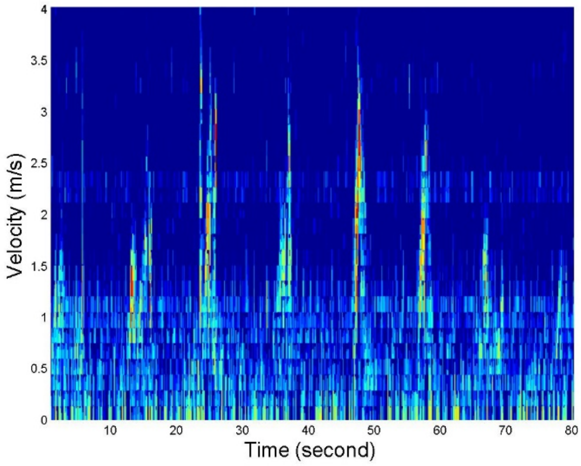

Fig. 9. Velocities of water particles on sea-surface.

TABLE I. MEASURED VELOCITIES

Peak No	1	2	3	4	5	6	7	8
Velocity (m/s)	1.4	1.5	2.1	2.7	3.1	2.6	1.8	1.4

The averaged velocity is 2.08 m/s from which the wave height of the swell can be calculated accoring to the Equation (8). But the wavelength λ is unknown. The wave speed C can be estimated using the dispersion relation for shallow water waves [10],

$$C = \sqrt{gd} \tag{10}$$

where, g is the acceleration of gravity (9.8m/s^2) and d is the average water depth (5.6 m, provided by Navionics.com) near the shore of the Broad Cove. Consequently, the wavelength λ is equal to the multiplication of C and wave period T, and then the λ is calculated to be 74.1 m. It is used to calcualte the wave number k. The wave velocity becames maximun when the wave is very close to SRRS. The average water depth of 1 m associated with the maximum velocity is used to calculate wave height. According to Equation (8), the estimated wave height is calculated to be 0.56 m which is very close to the value estimated by observation.

CONCLUSION

A 24GHz short-range FMCW radar transceiver for detecting sea-surface targets and estimating sea state information to enhance the navigational safety of a USC is designed. Wave height is estimated through measuring the velocity of water particles. Two experiments were carried out to test the capability of the short-range radar system. The spectrograms of the received signals can demonstrate the velocity variation of water particles, and the wave height can be calculated based on the relationship of wave height and water particle velocity. The wave height estimated in the wave tank is close to the known value; although not being evaluated using ground-truth, the wave height result obtained from sea-surface experiment agrees with those estimated by observation. Further validation experiments will be carried out on at sea in the future.

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