

# Beamforming for Wireless Communications Between Buoys

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**Abstract**—The marine environment monitoring based on buoys is one of the main methods in marine monitoring. The distance of wireless communications between buoys is critical for oceanographic monitoring. In this paper, a new technique is presented to improve the distance of marine wireless communication using beamforming. An inertial measurement unit (IMU) which consists of tri-axis gyroscopes and accelerometers is installed on the buoy node to track the realtime attitude of the antenna array. The realtime attitude of the antenna array is calculated with a filter scheme. With the result, the relative direction of the destination node to the antenna array is obtained. Then a corresponding algorithm is selected to control phased array antenna beamforming parameters, directing the beam at the destination node. In addition, the solution is simulated under the condition of regular waves. The results reveal that the beamforming technique provides significant power gains and improve the distance between two communicating nodes effectively.

## I. INTRODUCTION

The wireless communications for oceanographic monitoring typically include satellite communications [1], commercial cellular network access, e.g. 3G [2], and approaches designed for wireless sensor networks (WSNs), e.g. ZigBee [2], [3]. Satellite communications are relatively expensive solution with limited capacity and the commercial cellular network only covers offshore areas. WSNs are flexible in network extension and cost-effective in data collection, but suffer from a large number of relay buoys caused by limited point-to-point communication distance. As a result, the distance of wireless communications between buoys becomes critical for oceanographic monitoring.

Beamforming directs the majority of signal energy transmitted from a group of transmit antennas in a chosen angular direction, and effectively extends the communication distance [4] between nodes. For now, beamforming technology has not been widely applied in wireless communications between buoys. The main reason is that the beamforming direction changes as the buoy moves and rotates with the wave. For the current beamforming technology, transmission side requires the channel information [5], [6]. The channel information is obtained by channel estimation from the receiver and then is feed back to the sender. In condition of long-range and low signal to noise ratio (SNR), channel estimation is not easy and the feedback link from the receiver to sender is hard to establish.

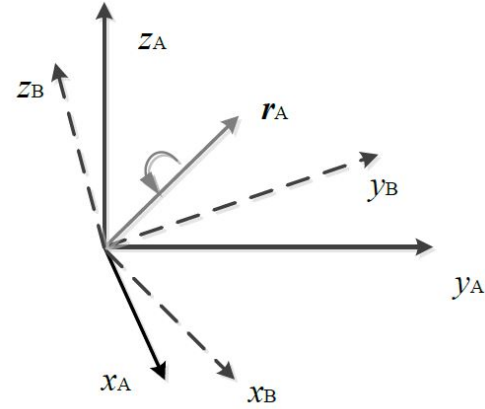


Fig. 1: The orientation of frame  $B$  is achieved by a rotation, from alignment with frame  $A$ , of angle  $\vartheta$  around the axis  $\mathbf{r}_A$ .

This paper presents a beamforming scheme between buoys without channel estimation and feedback from receiver. The investigation is performed by installing an IMU on the buoy to track the rotational and translational movements of the buoy. The realtime attitude of the transmit antenna array, which is fixed on the buoy, is calculated using the orientation filter [7]. After calculating the realtime posture of the antenna, the relative direction of the target node to the transmit antenna array is gained. As a result, the beam can be steered directly to the target node without channel information. Then a corresponding algorithm [4], [8], [9] is selected to control beamforming parameters of phased array antennas, directing the beam at the target node. To verify the effect of the scheme mentioned above, simulations are performed.

This paper is organized as follows. Theory about quaternion representation is presented in Section II. The measurement of orientation of the antenna array and beamforming method is presented in Section III. In Section IV, the pattern of the antenna array and the movement of the buoy are both simulated. By tracking the movement of the buoy, beamforming is performed and the power gain is obtained. Finally, summarizing remarks are given in Section V.

## II. BASIC THEORETICAL FOUNDATION

### Quaternion representation

A quaternion is a four-dimensional complex number that can be used to represent the orientation of a rigid body or coordinate frame in three-dimensional space [7]. An arbitrary orientation of frame  $B$  relative to frame  $A$  can be achieved through a rotation of angle  $\vartheta$  around an axis  $\mathbf{r}_A$  defined in frame  $A$ . This is represented graphically in Fig. 1, where the mutually orthogonal unit vectors  $\mathbf{x}_A$ ,  $\mathbf{y}_A$  and  $\mathbf{z}_A$ , and  $\mathbf{x}_B$ ,  $\mathbf{y}_B$  and  $\mathbf{z}_B$  define the principle axis of coordinate frames  $A$  and  $B$  respectively. The quaternion describing this orientation,  $\mathbf{q}$ , is defined by

$$\mathbf{q} = [q_1, q_2, q_3, q_4]^T$$

$$= \left[ \cos \frac{\vartheta}{2}, -r_x \sin \frac{\vartheta}{2}, -r_y \sin \frac{\vartheta}{2}, -r_z \sin \frac{\vartheta}{2} \right]^T, \quad (1)$$

where  $r_x$ ,  $r_y$  and  $r_z$  define the components of the unit vector  $\mathbf{r}_A$  in the  $x$ ,  $y$  and  $z$  axes of frame  $A$  respectively.

Euler angles  $\psi$ ,  $\theta$  and  $\phi$  describe an orientation of frame  $B$  achieved by the sequential rotations, from alignment with frame  $A$ , of  $\psi$  around  $\mathbf{z}_A$ ,  $\theta$  around  $\mathbf{y}_A$ ,  $\phi$  around  $\mathbf{x}_A$ .  $\psi$  is defined by

$$\psi = \arctan \frac{2q_2q_3 - 2q_1q_4}{2q_1^2 + 2q_2^2 - 1}. \quad (2)$$

$\theta$  is defined by

$$\theta = -\arcsin(2q_2q_4 + 2q_1q_3). \quad (3)$$

$\phi$  is defined by

$$\phi = \arctan \frac{2q_3q_4 - 2q_1q_2}{2q_1^2 + 2q_4^2 - 1}. \quad (4)$$

## III. METHOD

The scheme consists of two steps. 1) The relative direction of the destination node to the transmitting antenna array is calculated. 2) Beamforming is performed. In order to get the direction of the target node relative to the antenna array, the realtime attitude of the buoy should be obtained firstly. Thus, a tracking algorithm is selected to calculate the realtime attitude of the buoy by installing accelerometers and gyroscopes on the buoy. Knowing the relative direction of the target node to the antenna array, beamforming is then performed, directing the beam at the target node.

### A. Measurement of Orientation

To ensure the accurate measurement of orientation of the buoy, this paper adopts the orientation filter presented by [7] to track the movement of the buoys. The filter employs a quaternion representation of orientation to describe the realtime posture. In this paper, the filter is directly adopted (as shown in Fig. 2) to track the movement of antenna array. The complete derivation and empirical evaluation of the filter can be seen in [7]. The relative parameters and their significance are shown in Table I.

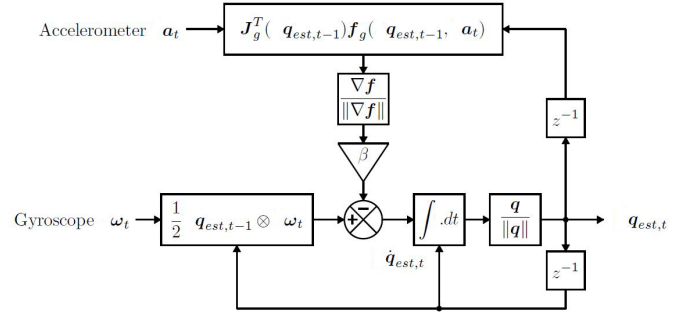


Fig. 2: Block diagram representation of the complete orientation filter for an IMU implementation.

TABLE I: The related parameters of the block diagram.

| Parameter                                 | Significance                                         |
|-------------------------------------------|------------------------------------------------------|
| $\mathbf{a}_t$                            | normalized accelerometer measurement                 |
| $\boldsymbol{\omega}_t$                   | angular rate vector                                  |
| $\mathbf{q}_{est,t-1}$                    | estimate of orientation at time (t-1)                |
| $\mathbf{q}_{est,t}$                      | estimate of orientation at time t                    |
| $\dot{\mathbf{q}}_{est,t}$                | the change rate of estimate of orientation at time t |
| $f_g(\mathbf{q}_{est,t-1}, \mathbf{a}_t)$ | the objective function                               |
| $J_g^T(\mathbf{q}_{est,t-1})$             | the Jacobian of the objective function               |
| $\beta$                                   | the magnitude of the gyroscope measurement error     |

As shown in Fig. 2, the orientation quaternion of the buoy  $\mathbf{q}_{est,t}$  can be calculated by the input  $\mathbf{a}_t$  from accelerometer and  $\boldsymbol{\omega}_t$  from gyroscope. Then the euler angles  $\psi$ ,  $\theta$  and  $\phi$  are obtained by equation (2), (3) and (4) respectively. Therefore the buoy's realtime orientation is known at all times.

### B. Beamforming Implementation

After obtaining the relative direction of the target node to the antenna array, beamforming can be performed to direct the beam at the target node. Several schemes can be used to perform beamforming [10], [11]. This paper takes the uniform rectangular array (URA) as an example, as shown in Fig. 3.

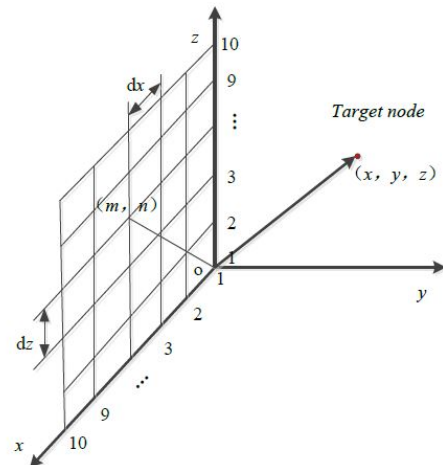


Fig. 3: Phased array coordinate schematic diagram.

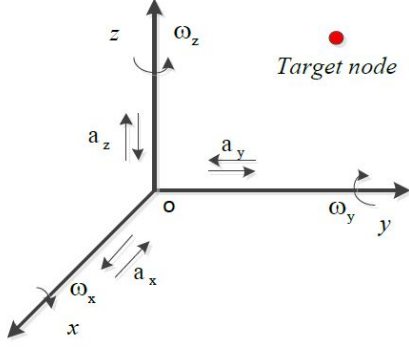


Fig. 4: Inertial sensor coordinate frame

Array elements are distributed in the  $xz$ -plane.  $dx$  and  $dz$  are shown in Fig. 3, representing the spacing of the adjacent units of  $(x, z)$  axes respectively. When using a digital phase shifter to perform beamforming, the phase value of the cell  $(x_m, z_n)$  relative to the cell  $(0, 0)$  are expressed as:

$$\varphi(x_m, z_n) = m\varphi_{x_0} + n\varphi_{z_0}, \quad (5)$$

where

$$\varphi_{x_0} = \left( \frac{2\pi dx}{\lambda} \cos \varphi_x \right) / \left( \frac{2\pi}{2K} \right), \quad (6)$$

$$\varphi_{z_0} = \left( \frac{2\pi dz}{\lambda} \cos \varphi_z \right) / \left( \frac{2\pi}{2K} \right), \quad (7)$$

where  $(\varphi_{x_0}, \varphi_{z_0})$  represents the initial vector,  $(\varphi_x, \varphi_z)$  represent the angle of the beamforming direction and planar array coordinates  $(x, z)$  axes,  $K$  represents the number of digital phase shifter bits [4], [8], [9].

#### IV. SIMULATION

In order to verify the effect of the scheme proposed in this paper, simulations are performed under the condition of regular waves. Under regular waves, the movement of the buoy is assumed to be the sway along  $y$ -axis, the heave along  $z$ -axis, and the rotation around  $x$ -axis, as shown in Fig. 4. The simulation steps are as follows. Firstly, the movement of the buoy is simulated under the influence of regular waves, as shown in Fig. 6, and then the parameters measured by gyroscopes and accelerometers are determined. Secondly, the parameters gained in the previous step are taken as the input to the system, and then the Euler parameters  $\psi$ ,  $\theta$  and  $\phi$  are obtained using the oriental filter. Finally, knowing the error of the attitude and the antenna array pattern after beamforming, the power gain over the time is obtained.

##### A. Antenna Array Pattern

This paper takes a  $10 \times 10$  URA as an example, as shown in Fig. 3. Array elements are distributed in the  $xz$ -plane with the array look direction along the positive  $y$ -axis. Assume the carrier frequency of the incoming narrow band sources is 300 MHz. Use a rectangular lattice, with the default spacing of

half wavelength along both the row and column dimensions of the array. Each element is an isotropic antenna element.

The antenna array pattern at the direction of any degrees azimuth and any degrees elevation are available through simulation. The antenna array pattern at the target direction of 30 degrees azimuth and 50 degrees elevation is shown in Fig. 5. Fig. 5 shows that the biggest normalized power gain after beamforming is at the direction of 30 degrees azimuth and 50 degrees elevation.

##### B. The Movement of Buoy under the Condition of Regular Waves

Numerical wave tank (NWT) has been presented for the investigation of hydrodynamic characteristics of floating structures. Compared with traditional physical tests, NWT provides more detailed flow field information with smaller scale effect and lower cost. Wave-generating boundary method that defining the particle velocity and wave height on inlet boundary is introduced in this paper. The  $x$ -direction velocity is

$$u = \frac{\pi H}{T} \frac{\cosh k(y+d)}{\sinh kd} \cos(kx - \omega t) + \frac{3\pi H}{4} \left( \frac{\pi H}{L} \right) \frac{\cosh 2k(y+d)}{\sinh^4 kd} \cos 2(kx - \omega t), \quad (8)$$

the  $y$ -direction velocity is

$$v = \frac{\pi H}{T} \frac{\sinh k(y+d)}{\sinh kd} \sin(kx - \omega t) + \frac{3\pi H}{4} \left( \frac{\pi H}{L} \right) \frac{\sinh 2k(y+d)}{\sinh^4 kd} \sin 2(kx - \omega t), \quad (9)$$

the particle's vertical displacement is

$$\eta(x, t) = \frac{H}{2} \cos(kx - \omega t) + \frac{H}{8} \left( \frac{\pi H}{L} \right) \frac{\cosh kd}{\sinh^3 kd} (\cosh 2kd + 2) \cos 2(kx - \omega t), \quad (10)$$

where  $T$  represents wave period,  $k$  represents wave number,  $H$  represents wave height,  $d$  represents water depth,  $\omega$  represents circular frequency,  $t$  represents time,  $x$  represents particle horizontal coordinates,  $y$  represents particle vertical coordinates [12].

This paper simulates the wave using wave-generating boundary method and the Fluent user-defined function. The buoy is assumed to be a floating cylinder. The fluid volume function is adopted to track the free surface of the fluid and the movement of the buoy over the time. The parameters of the regular wave and the buoy are shown in Table II.

Based on the simulation results, the movement of the buoy is presented in Fig. 6. As shown in Fig. 6, the blue trace represents the vertical displacement  $s_z$ , the red one represents the horizontal displacement  $s_y$  and the black one represents the angular rotation  $\phi$ .

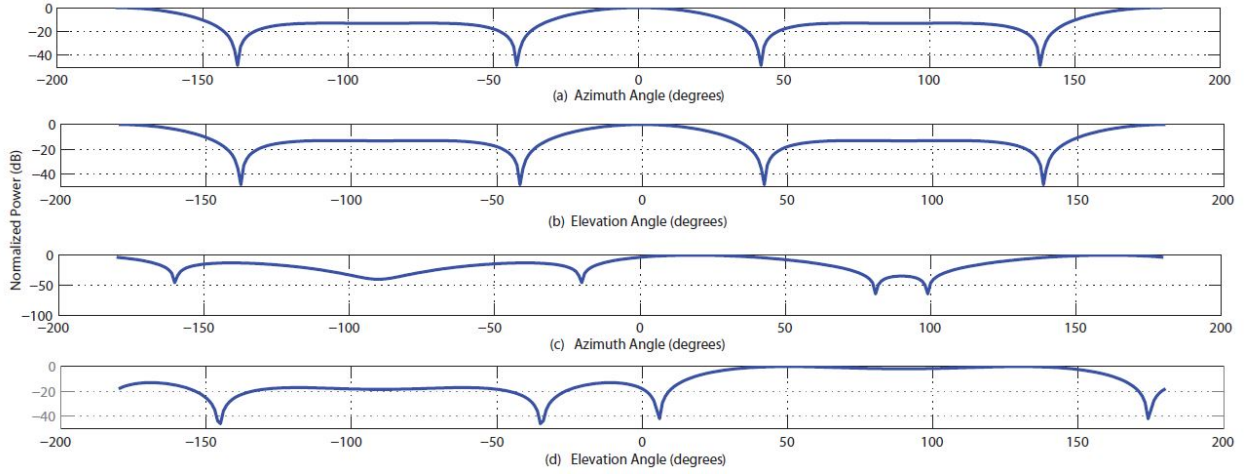


Fig. 5: The beam pattern before and after beamforming, (a) and (b) are before beamforming, (c) and (d) are after beamforming.

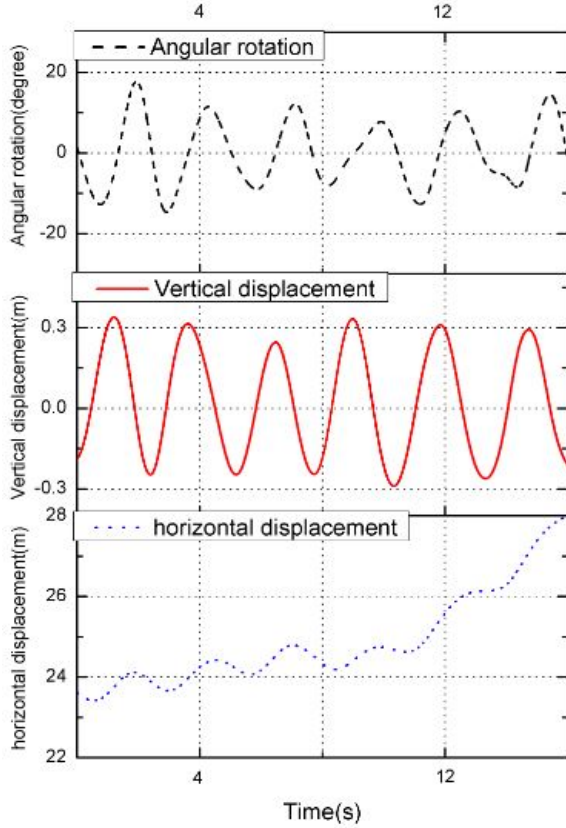


Fig. 6: The buoy's movement

### C. Beamforming

With the movement parameters  $s_z$ ,  $s_y$ ,  $\phi$  of the buoy, the system input  $\mathbf{a}_t$  is given by

$$\mathbf{a}_t = [0, a_y, a_z]^T, \quad (11)$$

TABLE II: The parameters of regular wave and buoy.

| Parameter                     | Magnitude             |
|-------------------------------|-----------------------|
| wave length                   | 10 m                  |
| wave height                   | 0.8 m                 |
| acceleration of gravity       | 9.81 m/s <sup>2</sup> |
| depth of water                | 3 m                   |
| the diameter of floating body | 1 m                   |
| the height of floating body   | 0.5 m                 |
| the density of floating body  | 0.5 kg/m <sup>3</sup> |

where

$$a_y = \frac{d^2 s_z}{dt^2} * \sin(\phi) + \frac{d^2 s_y}{dt^2} * \cos(\phi) + \frac{d^2 \phi}{dt^2} * \pi/180, \quad (12)$$

$$a_z = \frac{d^2 s_z}{dt^2} * \cos(\phi) - \frac{d^2 s_y}{dt^2} * \sin(\phi) - \left(\frac{d\phi}{dt}\right)^2 * \pi^2/180^2, \quad (13)$$

and  $\omega_t$  is expressed as

$$\omega_t = [\omega_x, 0, 0]^T, \quad (14)$$

where

$$\omega_x = \frac{d\phi}{dt}, \quad (15)$$

which are used as the input of the system. Therefore, the realtime attitude is tracked using the filter mentioned above by calculating  $\mathbf{q}_{est,t}$ . The sampling period is assumed to be 2 ms, while the gyroscope measurement error is assumed to be 5 deg/s. Euler parameters  $\psi$ ,  $\theta$  and  $\phi$  are computed directly from quaternion data using equations (2), (3) and (4). Knowing the realtime attitude of the antenna array and the initial position of the two buoys, beamforming is performed using the scheme mentioned above.

The results are shown in Fig. 7 and Fig. 8. In Fig. 7, the 2 traces represent the actual angles and the estimated angles respectively. In Fig. 8, the trace represents the calculated error in the estimated angles. From Fig. 7 and Fig. 8, we find that the trace representing the filter estimated angles closely tracks the

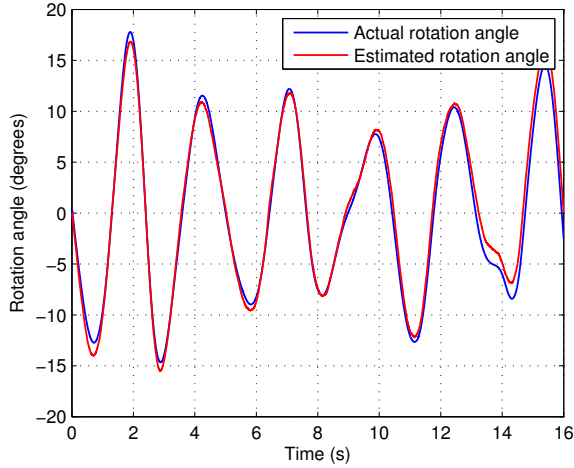


Fig. 7: Typical results for actual and estimated angle  $\phi$ .

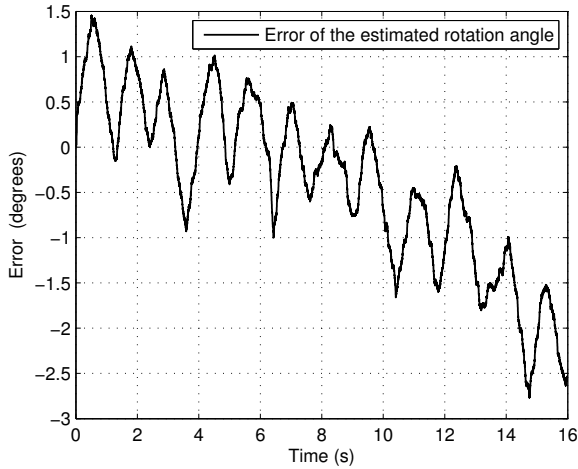


Fig. 8: Typical results for error.

trace representing the actual angles, and the error is between -3 and 1.5 degrees. Fig. 9 shows theoretical value and the simulative result of the power gain. Simulative results reveal that the beamforming technique provides significant power gains effectively. Fig. 9 indicates that the antenna gain, ranges from 19.93 to 20 dB, is obviously higher than that of antenna without beamforming.

## V. CONCLUSIONS

A novel beamforming scheme between buoys has been demonstrated in this paper. Accelerator and gyroscope are installed on the buoy to track its movement. With the realtime attitude calculated by a certain scheme, the relative direction of the target node to the antenna array is obtained. Then a method is selected to perform beamforming. Finally, the scheme is tested and verified under the condition of regular waves. The results show that the beamforming effectively improve the antenna gain. Innovative aspects of the this paper is that this paper employs a method to get the relative direction of target

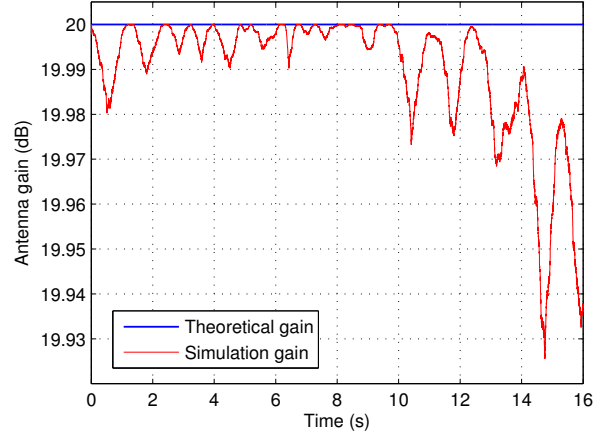


Fig. 9: Typical results for power gain

node to the antenna array by installing an IMU on the buoy, and then performs beamforming without channel estimation.

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