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Ship Speed Estimation using Wireless Sensor Networks: Three and Five Sensors Formulation

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Abstract

Intrusion detection on the sea is an important surveillance problem for harbor protection, border security, and commercial facilities such as oil platforms, fisheries facilities and other marine wealth. Widely used methods for ship detection are using radar or satellite which is very expensive. Besides the high cost, the satellite image is easy affected by the cloud. And it is difficult to detect small boats or ships on the sea with marine radar due to the noise or clutters generated by the uneven sea surface. In this paper, we propose ship speed estimation by taking advantage of ship-generated wave's characteristics with Wireless Sensor Network (WSN). We use a grid fashion for sensor node deployment that can be clustered into three and five sensors. We propose the ship speed formulation for each type of claster. We use three sensors, we may expect to improve energy efficiency by involving small number of sensor for detection. We use five sensors, we may expect to improve accuracy of detection. We also propose an algorithm for detection by incorporating individual sensor detection. The individual sensor detection produces a time stamp that records the ship-generated waves intruding the sensors.

Keywords*: Harbor protection; Wireless sensor network (WSN); Ship speed detection; Three sensors, Five sensors*

1. Introduction

Indonesia is the largest archipelago in the world with 13.466 islands, with a coastline of approximately 81.900 kilometers, land area of 1.922.570 km^2 and marine area 3.257.483 km^2 (marine area is three times the land area). Sea border area with Malaysia, Australia, Singapore, Thailand, Philippines, Vietnam and Timor Leste.The border region is one important area that must be protected and monitored properly, therefore the intrusion detection on the sea is an important surveillance issue for commercial facilities protection (e.g oil mining, fisheries and other marine wealth).

Widely used methods for ship detection are using radar or satellites which are very expensive. Besides the high cost, the satellite image is easily affected by the cloud. And it is difficult to detect small boats or ships on the sea with marine radar due to the noise or clutters generated by the uneven sea surface. Therefore the use of Wireless Sensor Networks (WSN) can reduce the implementation costs compared with using radar or satellite.

Terrestrial intrusion detection with WSN have recently been developed using magnetometers, thermal sensors, and acoustic sensors. The main challenge to deploy sensors on the sea, they are not static and move randomly because of the ocean waves influence. The random movement of the node makes it difficult for most sensors to detect an intrusion. To overcome this difficulties, the ship detection carried out by detecting the waves formed by the ship (ship-generated waves) using WSN [1],[2]. To improve area of detection, sensor can be designed using array antenna applying compressive sensing [3],[4]. Based on the four sensors, the ship location can be estimated using cooperative signal processing [5].

The previous WSN research [1],[2] have deployed an experimental WSN to detect ships by using three-axis accelerometer sensors with iMote2 on buoys on the sea surface with 4 nodes sensors for detection. The research results show the relationship between the ship speed with the detection success ratio. Increasing ship speed also increases detection success ratio

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because the higher speed ship cause higher waves energy, it can improve the detection probability. It also showed that the increase in the distance between the sensor nodes cause the detection success ratio declined sharply. Overall, the error estimation of detection process are not more than 20% of the actual ship speed.

In this paper we propose formulation of ship detection using three and five sensors, instead of four sensors [1],[2]. Motivation of using three sensor is to improve energy efficiecy globablly. We can expect using the less number of sensors involves for detection, we can save energy the rest of sensors. Moreover, motivation of using five sensor is to improve detection accuracy. We have five time stamps that can be computed using our propose formula based on the trogonometry principles.

2. Ship Generated Waves

2.1. Ship Wave Patterns

When a ship moves across a surface of water, it generates waves which comprise divergent and transverse waves as shown in Figure 1. Kelvin found that V-shaped patterns were formed by two locus of cusps whose angle with the sailing line is 19^{o}28' in deep water [6], and the angle between the sailing line and the diverging wave crest lines at the cusp locus line should be 54^{o}44' [1]. Note that this pattern is independent of the size and velocity of the ship.

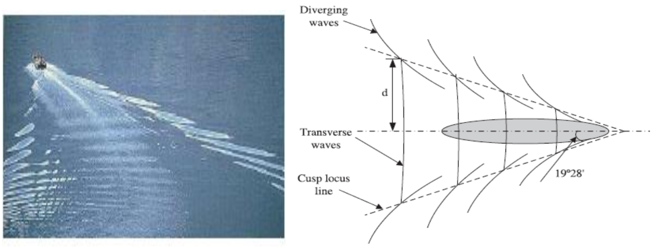

Figure 1. Ship-generated wave model. [1][2]

When the ship's waves spread out sideways and propagate from the sailing line, both the height and energy of the waves decrease. The research in [7] pointed out that the transverse waves decrease inversely proportional to the cube root of the distance from the vessel, which means that transverse waves decline much faster than divergent waves. Only divergent waves can be observed far from the vessel. In addition, when we observe ship-generated waves at a fixed spatial point, the ship-generated wave train has a limited duration [1],[2]. The maximum wave height H_m at distance d from the sailing line can be expressed as the following equation:

$$H_m = cd^{-\frac{1}{3}} \quad (1)$$

Where c is a parameter related to the speed of the passing ship. We can see that height of the ship-generated wave decreases exponentially respect to the distance. Otherwise, the ship wave increases when the ship speed increases. In other words, we see that the ship foot print is easy to be detected when the ship travels quickly.

2.2. Ship Wave Characteristics

The previous method of observing ship-generated waves is how measure the pressure fluctuations at some elevation points in the water column, then transform the pressure into wave height. However, this method requires expensive equipment. In addition, it is difficult to deploy the devices underwater [1],[2].

We can use accelerometer to measure the actual surface movement of ship-generated waves. When the accelerometer is used in an ocean environment, the buoy and the accelerometer undergo a generally oscillatory, sinusoidal-like vertical acceleration due to wave action. Because the sensor changes direction randomly in the ocean, we can only consider the z-accelerometer readings which last for a period of 250 seconds.

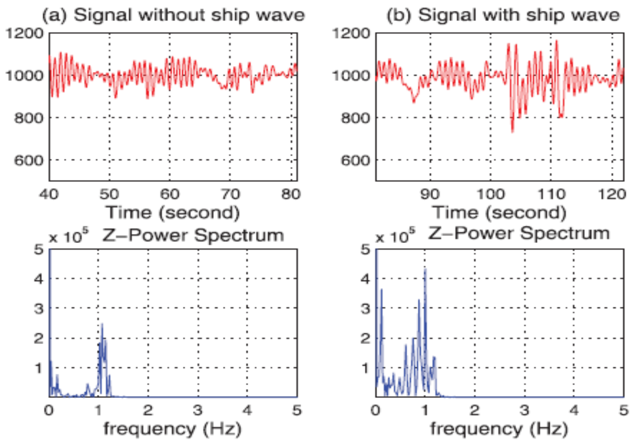

Figure 2. Z- Power Spectrum (a) Signal without ships and its spectrum. (b) Signal with ships and its spectrum [1],[2].

As shown in Figure 2, we can see that the ship waves mainly focus on the low frequency spectrum. Figure 2a shows ocean waves without ship waves. The spectrum has a high, single peak concentration around a characteristic period around 1 Hz. Otherwise, the spectrum of the ocean waves combined with the ship waves, as shown in Figure 2b, has multiple peaks and wide crests without distinct peaks (from 0 -1 Hz).

2.3. Grid Sensor Model

When a ship travels through a monitored area, the ship continuously disturbs a succession of small areas. As shown in Figure 3, when a ship travels through the sensor networks, the waves generated by the passing ship disturb the sensor areas i=1,i=2,i=3 in a sequential manner. These areas have spatial and temporal correlations. By exploiting these correlations, we can improve the reliability of the detection system.

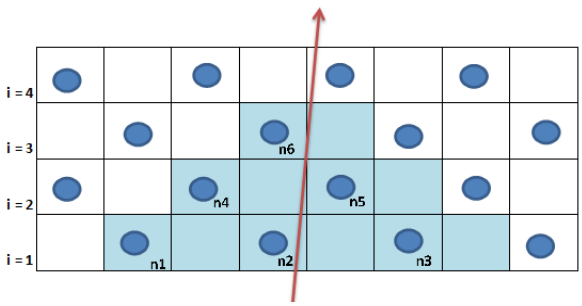

Figure 3. Grid-Based Sensor Node Deployment Design.

3. Ship Speed Estimation using Multiple Sensors

As described in Section 2, the angle between the locus of cusps and the sailing line is a fixed constant, $19^{o}28'$. Using this characteristic, we can estimate the speed of the intruding ship. In this section, we derive three formulation for ship speed estimation, i.e.: four, three, and five sensors. For four sensors formulation, we slightly differ with [1],[2] in terms of sensor deployment. We form a parallelogram instead of square. However, we arrive at the same formulation as square form.

3.1. Ship Speed Estimation Model with 4 Sensor Nodes [1],[2]

Based on the research [1],[2], it is assumed that the network is implemented manually as shown in Figure 3. It is also assumed that the cruise line makes an angle α to the line 2 node as shown in Figure 4. At point A, the wave of the ship detected by sensor Si at time t1. When the ship arrived at point C, the waves are detected by sensors S'i at time $t3$. So the ship sailed from point A to point C during $t3$ - $t1$. We assume that ship speed is V.

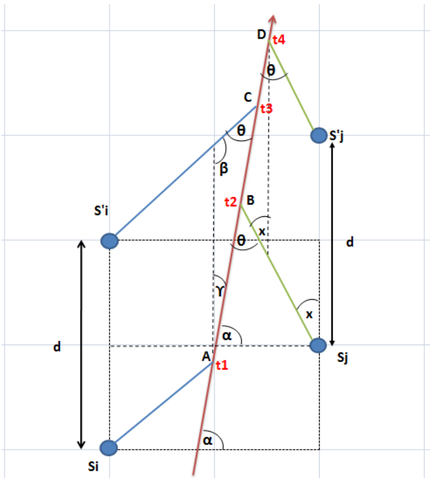

Figure 4. Ship Speed Estimation Model with 4 Sensor Node.

By using 4 sensor nodes resulting the ship speed and direction estimation as the following equation [1],[2] :

$$\gamma = 90° - \alpha \quad (2)$$

$$\theta = 20° \quad (3)$$

$$\begin{aligned}\beta &= 180° - (20° + 90° - \alpha) \\ &= 180° - 110° + \alpha \\ &= \alpha + 70°\end{aligned} \quad (4)$$

$$\begin{aligned}x &= 90° - (180° - \alpha - \theta) \\ &= 90° - 180° + \alpha + 20° \\ &= \alpha - 70°\end{aligned} \quad (5)$$

$$\frac{|AC|}{\sin\beta} = \frac{d}{\sin\theta} \quad (6)$$

$$\frac{|BD|}{\sin x} = \frac{d}{\sin\theta} \quad (7)$$

$$\begin{aligned}V_{AC} &= \frac{|AC|}{t3 - t1} \\ &= \frac{d\sin\beta}{(t3 - t1)\sin\theta} \\ &= \frac{d\sin(\alpha + 70°)}{(t3 - t1)\sin\theta}\end{aligned} \quad (8)$$

$$V_{BD} = \frac{|BD|}{t4 - t2} \quad (9)$$

$$= \frac{d \sin x}{(t4 - t2) \sin \theta}$$
$$= \frac{d \sin(\alpha - 70°)}{(t4 - t2) \sin \theta}$$

Ship crossing angle α is defined as follow :

$$\alpha = arc\ \tan\left(\frac{(t4 + t3 - t2 - t1)}{(t2 + t3 - t4 - t1)} \tan 70°\right) \tag{10}$$

3.2 Ship Speed Estimation Model with 3 Sensor Nodes

We further remove one sensor the top one in Figure 4 as we can see in Figure 5 shows the model to estimate the ship speed and direction using three sensors.

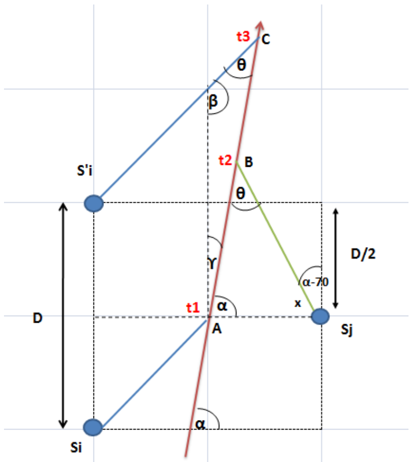

Figure 5. Ship Speed Estimation Model with 3 Sensor Nodes.

Using the same way, the ship speed and crossing angle equation can be expressed as follows:

$$\begin{aligned} \beta &= 180° - (20° + 90° - \alpha) \\ &= 180° - 110° + \alpha \\ &= \alpha + 70° \end{aligned} \tag{11}$$

$$\begin{aligned} x &= 180° - \alpha - \theta \\ &= 180° - \alpha - 20° \\ &= 160° - \alpha \end{aligned} \tag{12}$$

$$\frac{|AC|}{\sin \beta} = \frac{d}{\sin \theta} \tag{13}$$

$$\frac{|BD|}{\sin x} = \frac{d}{\sin \theta} \tag{14}$$

$$V_{AC} = \frac{|AC|}{t3 - t1}$$
$$= \frac{d \sin \beta}{(t3 - t1) \sin \theta}$$
$$= \frac{d \sin(\alpha + 70°)}{(t3 - t1) \sin \theta} \tag{15}$$

$$V_{AB} = \frac{|AB|}{t2 - t1} = \frac{\frac{d}{2}\sin x}{(\mathrm{t2} - \mathrm{t1})\sin\theta} = \frac{d\sin(160° - \alpha)}{2\,(\mathrm{t2} - \mathrm{t1})\sin\theta} \quad (16)$$

Ship crossing angle α is defined as follow:

$$\alpha = \arctan\left(\frac{(t3 - t1) - 2(t2 - t1)\tan 70°}{2(t2 - t1) - (t3 - t1)\tan 70°}\right) \quad (17)$$

3.3. Ship Speed Estimation Model with 5 Sensor Nodes

We use 5 sensors by adding one sensor from 4 sensors model. From Figure 6, we can see that we can gather more time stamp by increasing the number of sensor. Figure 6 is a model to estimate the ship speed and direction using 5 sensor nodes

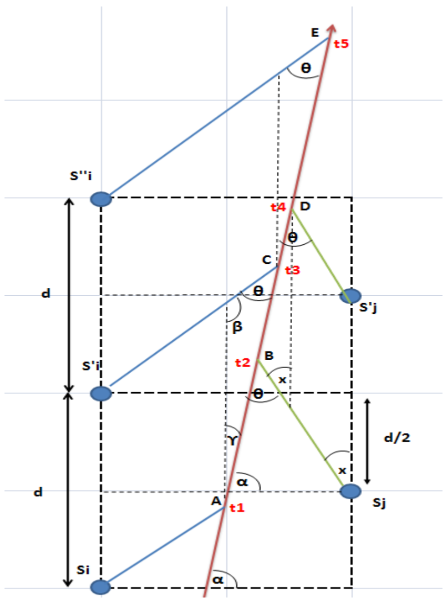

Figure 6. Ship Speed Estimation Model with 5 Sensor Node

Using the same way with 3 sensors model, the ship speed and crossing angle equation are written as follows:

$$V_{BD} = \frac{d\sin(\alpha - 70°)}{(\mathrm{t4} - \mathrm{t2})\sin\theta} \quad (18)$$

Ship crossing angle α is defined as follow:

$$\alpha = arc\ \tan\left(\frac{(2(\mathrm{t3} - \mathrm{t1})(\mathrm{t5} - \mathrm{t3}) + (t4 - t2)(t5 - t1))}{(2(\mathrm{t3} - \mathrm{t1})(\mathrm{t5} - \mathrm{t3}) - (t4 - t2)(t5 - t1))}\tan 70°\right) \quad (19)$$

3.4. The Algorithm

The ship speed estimation process can use algorithm with 3, 4 and 5 sensor nodes involved in the detection process.

```
Ship Speed Detection Algorithm
Procedure Initialization
        Grid topology initialization
        Set D
        SetUpCluster ()
End procedure

Procedur SetUpCluster
        N = number of sensor node
        If N=3 then
          set neighbor 3 node
          CalculateShipSpeed3Node()
        Else if  N=4 then
          set neighbor 4 node
          CalculateShipSpeed4Node()
        Else if  N=5 then
          set neighbor 5 node
          CalculateShipSpeed 5Node()
        End if
End procedure

Procedure CalculateShipSpeed3Node
        Set θ, t1,t2,t3
        Speed Calculation with equation (16)
        Return v,α
End procedure

Procedure CalculateShipSpeed4Node
        Set θ, t1,t2,t3,t4
        Speed Calculation with equation (9)
        Return v,α
End procedure

Procedure CalculateShipSpeed5Node
        Set θ, t1,t2,t3,t4,t5
        Speed Calculation with equation (18)
        Return v,α
End procedure
```

4. Conclusion

Ship detection system with Wireless Sensor Network (WSN) is designed using grid-based topology involving three nodes, four nodes and five nodes deployment. The ship speed estimation for three variation of the nodes deployment carried by the ship generated wave (V-Shaped wave). Ship crossing angle is assumed to move in a straight line at a constant speed in the monitoring area. We derive formulation for three and five node deployment. We consider three sensor formulation because when system detection involve less number of sensor, WSN conserves one sensor to improve energy efficiency. Otherwise, we consider five sensors, we may expect improvement of detection accuracy.

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