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*Published in:*  
Nihon Kokai Gakkai Ronbunshu

*Publication date:*  
2015

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*Citation (APA):*  
Nielsen, U. D., & Iseki, T. (2015). Study on Short-term Variability of Ship Responses in Waves. Nihon Kokai Gakkai Ronbunshu, 132, 51-57.

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# Study on Short-term Variability of Ship Responses in Waves

Toshio Iseki<sup>1</sup> • Ulrik Dam Nielsen<sup>2,3</sup>

## Abstract

Short-term variability of ship responses is investigated by cross-spectrum analysis. In a steady state condition, it is well known that a certain length of sampled data is required for stable results of the spectral analysis. However, the phase lag between responses, in terms of the phase angle of the cross-spectra, has not been discussed in detail. Using long stationary time series, the transition of amplitudes and relative phase angles of the cross-spectra has been investigated by iterative analyzes with a few seconds of time shifting. In the results, the short-term variability of the relative phase angle was observed. In effect, the variability may compromise the accuracy of the wave buoy analogy.

**Keywords :** *Seakeeping, wave buoy analogy, aleatory uncertainty, Fourier transform, relative phase.*

## 1. Introduction

The authors of the present paper are advocates of the wave buoy analogy. In this analogy, measured responses from an advancing ship are used together with corresponding transfer functions to obtain estimates of the sea state at the exact position of the ship<sup>(1), (2), (3)</sup>. In general, results of the wave buoy analogy compare reasonably well with results of other means for wave estimation<sup>(4),(5)</sup> but observations with poor agreement are also found; not to mention which means are the most accurate. This brings into question how much variation, due to aleatory uncertainty<sup>(6)</sup>, the sea state itself may exhibit on a short-term scale in 2-5 minutes period.

A direct measure for the aleatory short-term variation of a sea state in time and position could be obtained on the basis of results by the wave buoy analogy. However, an indirect approach is to estimate the sea state variation in terms of measured ship responses, since any change in sea state will be observable in the wave-induced responses of a ship; assuming other operational parameters (speed, heading, etc.) to be constant and neglecting the fact that a ship, to some degree, is a wave filter. The

advantage by this indirect approach is that modelling uncertainties, of the wave buoy analogy or other similar means for wave measurement, will not influence results. In case of the wave buoy analogy, notably uncertainty related to the transfer functions of the ship could influence results. ‘Modelling uncertainties’ may, in this sense, be viewed as a kind of epistemic uncertainty<sup>(6)</sup>.

In this study, full-scale responses measured on a training ship were analyzed by the ordinary Fourier transform technique, with the purpose to examine any short-term variation in the data. The responses were investigated by iterative cross-spectral analysis with a short time shifting. The transition of amplitudes and relative phase angles of the cross-spectra was monitored precisely and some uncertainties were observed. The short-term variability of the relative phase angle is illustrated and the problems encountered are discussed.

## 2. Analysis method

The studied full-scale data is analyzed by the discrete Fourier transform method.

If the measured ship response is expressed

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by  $x(n)$  ( $n=0,1,2,\dots,N-1$ ), the discrete Fourier transform is defined by the following equation,

$$X_N(f) = \sum_{n=0}^{N-1} x(n) \exp(-i2\pi fn\Delta t) \dots\dots\dots(1)$$

$$= X_{NR}(f) + iX_{NI}(f)$$

where  $f$  is the frequency (of encounter),  $\Delta t$  the sampling time,  $X_{NR}(f)$  and  $X_{NI}(f)$  the real part and the imaginary part, respectively, of the Fourier transform.

Using the Fourier transform expressed by eq. (1), the power spectrum is defined by the following form.

$$S_{xx}(f) = \frac{\Delta t}{N} X_N(f) \overline{X_N(f)}$$

$$= \frac{\Delta t}{N} (X_{NR}(f)^2 + X_{NI}(f)^2) \dots\dots(2)$$

Considering that the Fourier transform is complex-valued, phase angle (i.e. the argument) of the Fourier transform can be defined as follows;

$$P_{xx}(f) = \text{Arg}(X_N(f))$$

$$= \tan^{-1} \left( \frac{X_{NI}(f)}{X_{NR}(f)} \right) \dots\dots\dots(3)$$

The phase angle depends on the beginning time of measurement and does not have much physical importance.

On the other hand, if another ship response is expressed as  $y(n)$  ( $n=0,1,2,\dots,N-1$ ), definitions of the power spectrum and the phase angle mentioned above can be extended to a cross-spectrum.

$$S_{xy}(f) = \frac{\Delta t}{N} X_N(f) \overline{Y_N(f)}$$

$$= \frac{\Delta t}{N} \{ (X_{NR}(f)Y_{NR}(f) + X_{NI}(f)Y_{NI}(f))$$

$$+ i(-X_{NR}(f)Y_{NI}(f) + X_{NI}(f)Y_{NR}(f)) \}$$

.....(4)

$$P_{xy}(f) = \text{Arg}(S_{xy}(f))$$

$$= \tan^{-1} \left( \frac{-X_{NR}(f)Y_{NI}(f) + X_{NI}(f)Y_{NR}(f)}{X_{NR}(f)Y_{NR}(f) + X_{NI}(f)Y_{NI}(f)} \right)$$

.....(5)

In this case, the cross-power spectrum takes complex number while eq. (2), i.e. the “auto-spectrum”, is real-valued. Furthermore, the phase angle represents the phase difference between the two responses and has indeed importance, especially focus is on the wave buoy analogy. Therefore, the phase angle of the cross-spectrum is denoted the “relative phase angle” in this paper.

The Fourier analysis is applied to the time series, which are assumed to be stationary. The concrete application is illustrated in Figure 1. The top blue colored bar denotes the measured steady state time series of a ship response. The Fourier analysis is applied to the time series of constant time span and iterated many times with constant time shifting. Each shorter bar in the figure indicates a single Fourier analysis. Based on the assumption of the stationary time series, therefore, all the results of the Fourier analysis must coincide with each other. An investigation of the aleatory short-term variation of the results is the core objective of this study.

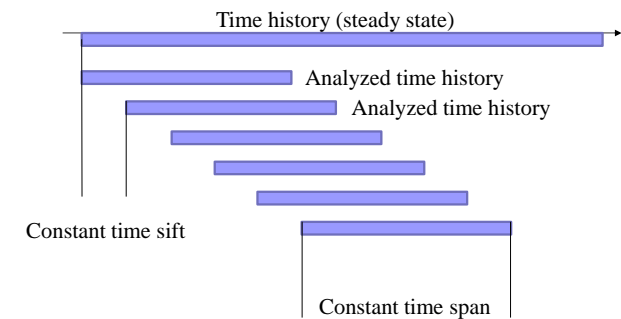


Figure 1 Concrete procedure of the Fourier analysis of stationary time series.

### 3. Full Scale Ship Experiment

The full scale ship experiment was carried out on October 17th 2013 using the training ship Shioji-maru of Tokyo University of Marine Science and Technology. The principal particulars and a photo of the ship are shown in Table 1 and Figure 2, respectively. The location of the experimental area was off Sunosaki cape in Chiba Prefecture, Japan. Ship motions and the position were measured using a fiber optic gyro and a GPS system. The data was sampled every 0.1s (10Hz) and recorded in the hard disk of a notebook PC through the RS-232C port.

Table 1 Principal particulars of T.S. Shioji-maru

|                            |                                      |
|----------------------------|--------------------------------------|
| Length (P.P.)              | 46.00(m)                             |
| Breadth (M <sub>LD</sub> ) | 10.00(m)                             |
| Depth (M <sub>LD</sub> )   | 6.10(m)                              |
| Draught (M <sub>LD</sub> ) | 2.65(m)                              |
| Displacement               | 659.4(t)                             |
| Main engine                | 4 cycle diesel<br>1,030 kw × 700 rpm |



Figure 2 The training ship Shioji-maru.

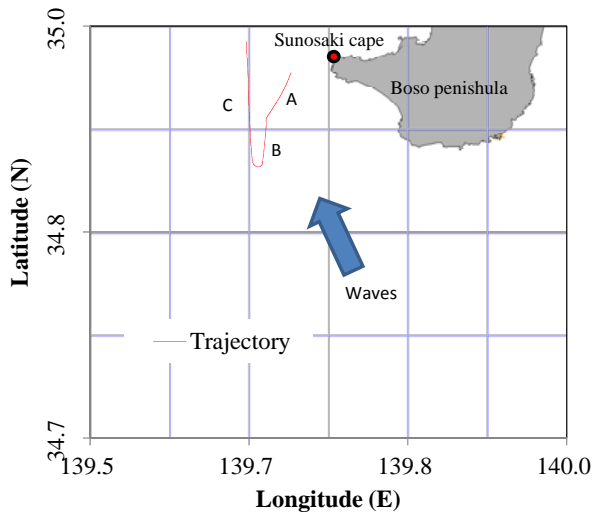


Figure 3 The experimental area at off Sunosaki cape and the ship trajectory.

Figure 3 shows the trajectory of the T.S. Shioji-maru during the experiment. In order to measure changes in ship motions with respect to the encounter angle of waves, the propeller pitch angle was set to 15 degrees. Measurement was carried out for 60 minutes involving three straight sections and changes in course. The sections A and B have 10 minutes duration and the section C has 20 minutes duration. The wave direction was SE as reported by Japan Meteorological Agency.

Table 2 Ship course and the sea conditions

| Run | Ship course (deg) | Ship speed (knot) | Duration (min) | Wind dir. | Wind speed (m/s) |
|-----|-------------------|-------------------|----------------|-----------|------------------|
| A   | 200               | 11.0              | 10             | NNE       | 3.0              |
| B   | 180               | 11.0              | 10             | NNE       | 3.0              |
| C   | 0                 | 10.5              | 20             | NNE       | 5.0              |

Table 2 shows the ship courses and the mean speeds-through-water, measurement duration, true wind directions and wind speeds are also summarized. During the experiment, the observed waves were: height 1.0-1.5m, directions 150-160 and 335-350 degrees (mixed sea condition).

#### 4. Results of the analyzes

The computer software, which can continuously estimate auto and cross-spectra with constant time (data points) shifting, has been developed for the present research work. A screenshot of graphical results produced by the software is shown in Figure 4. In the right part of the screen, the ship course and the

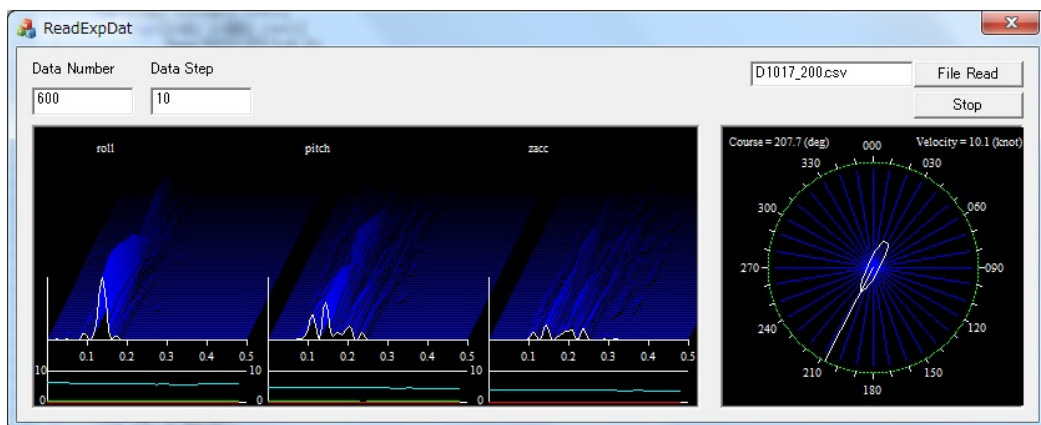


Figure 4 Screen shot of the developed software (run A).

speed are indicated and the three components of the power spectra are shown in the left part of the dialog box. The most recent spectra are plotted by white color and the past spectra are drawn by blue color. In this example, the 600 data points of time series are analyzed by Fourier transform with tapered cosine bell type data window and the analysis was iterated with 1s (10 data points) time shifting. It can be seen that the shape of spectra change with rather short period. Theoretically, shapes of spectra are not changed under the stationary sea condition. It can be considered that the change of spectra appears due to lack of the motion cycles (the number of ship oscillations). In case of model testing in irregular waves, it is recommended that 200 cycles of motions should be involved in the time series to estimate spectra accurately<sup>(7)</sup>. If the mean period of motions is 10s, 20,000 data points (2,000s) are required with 0.1s sampling time. Therefore, this concludes that the 600 data points are not sufficient for analyzing the time series even if the data can be considered as a stationary time series.

#### 4.1 Auto-spectral analysis

Figure 5 shows the transition of the pitching variances with respect to the “constant time shifting”. The data was measured on the “run C” and can be considered as a stationary time series. Theoretically speaking, therefore, the variance must take constant value regardless of the time shifting. The total number of data points is 15000 (i.e., duration is 25 minutes) and the variances were calculated as the area of pitching auto-spectra. The horizontal axis denotes the shifted time in second. The six colored lines indicate results based on the time span of the analysis, for instance, the blue line “1 min.” was evaluated by 1 minute time span (600 data points). On the contrary, the green line “6 min.” was evaluated by 6 minutes time span (3600 data points). It can be seen that there are some large fluctuations of pitching motion around 500s and the longer time span provides the smoother line. It can be considered that the smoother line is quite reasonable and successfully estimated under stationary conditions.

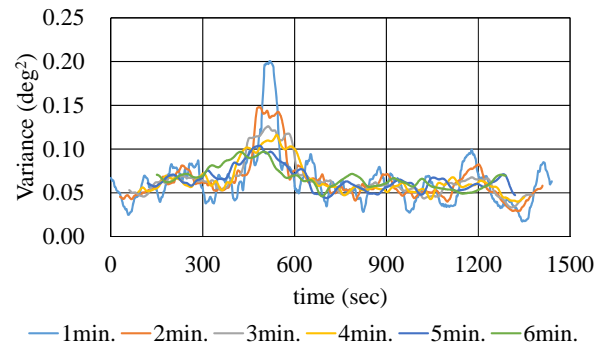


Figure 5 Transition of the pitching variance for each time spans (run C).

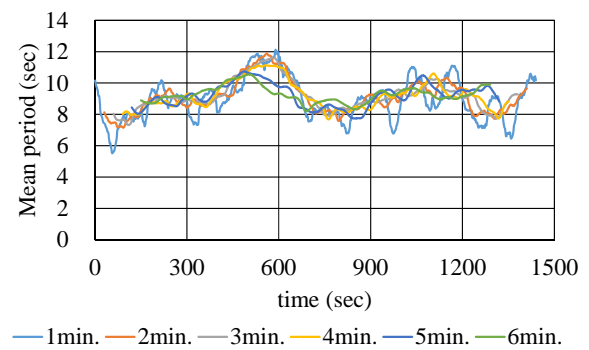


Figure 6 Transition of the mean period of pitching motion for each time span (run C).

Figure 6 shows the transition of the mean period  $T_{01}$  of the pitching motion. In this result, the periods were calculated by dividing the spectral area (0<sup>th</sup> order moment) by the 1<sup>st</sup> order moment. In other words,  $T_{01}$  indicates the center of the spectral area. Therefore, the transition of the mean period represents the frequency-shift of the center of the spectrum. In the same way as observed from figure 5, it can be seen that the longer time span gives the better result. From Figure 6, it is inferred that the encounter period of the waves is around 10 seconds, and 5 minutes time span must be required at least.

#### 4.2 Cross-spectral analysis

In general, a cross-spectrum is complex-valued representing the composite amplitude and the relative phase angle of the measurements. In this study, cross-spectra of the ‘rolling - pitching’ and ‘pitching - vertical acceleration (in short, v.acc)’ were investigated by the method described in the previous section.

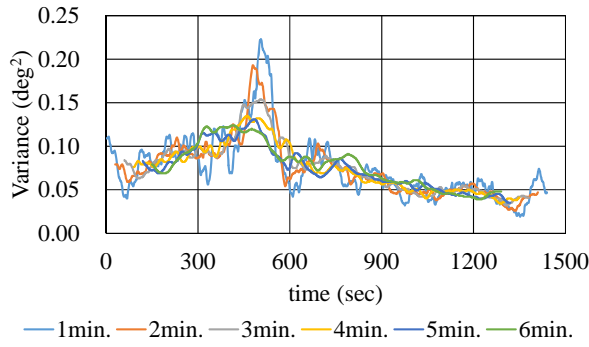


Figure 7 Transition of the amplitudes of roll-pitch cross-spectra for each time span (run C).

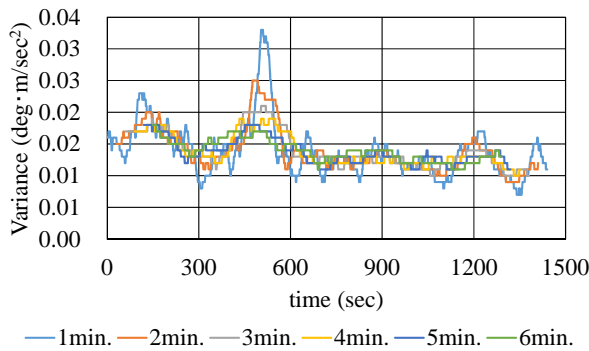


Figure 8 Transition of the amplitude of pitch-v.acc cross-spectra for each time span (run C).

Figure 7 and 8 show, respectively, the transition of the rolling-pitching and pitching-v.acc variances that were calculated as the composite amplitude of the cross-spectra. The shapes of the transitions are almost the same as those seen in Figure 5. This concludes that there is little difference in the influence of the time span between auto-spectra and cross-spectra.

The relative phase angle of a cross-spectrum defined by eq.(5) can be evaluated at each frequency. Therefore, an index based on the concept of standard deviation is defined to evaluate the total movement of phase movement (in short, P.M.) at the  $n$  shifted time. The definition is expressed as follows;

$$I_{PM}(n) = \sqrt{\frac{1}{N_f} \sum_{i=0}^{N_f} \{P_{xy}(f_i; n) - P_{xy}(f_i; n-1)\}^2} \quad \dots\dots\dots(6)$$

where  $N_f$  denotes the total number of discrete frequencies and  $P_{xy}(f_i; n)$  represents the relative phase spectrum at the  $n$  shifted time.

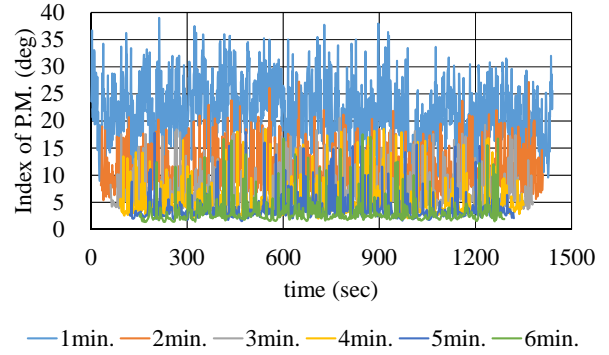


Figure 9 Transition of  $I_{PM}(n)$  of roll-pitch cross-spectra for each time span (course 0deg).

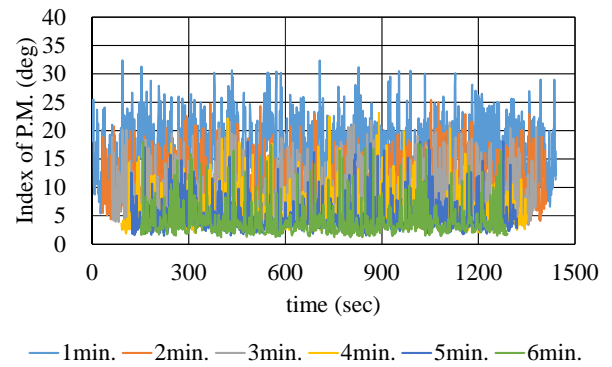


Figure 10 Transition of  $I_{PM}(n)$  of pitch-v.acc cross-spectra for each time span (course 0deg).

Figure 9 and 10 show the transition of the index  $I_{PM}(n)$  of rolling-pitching and pitching-v.acc, respectively. Looking at these figures, rough fluctuation of the index  $I_{PM}(n)$  and no periodic transition can be seen. It can be observed that the longer time span degrades the level of the index but it cannot remove the fluctuation itself. Moreover, it can be estimated that the  $I_{PM}(n)$  takes large value when the cross-spectrum has low power, because a low power means weak signals which may have much noise and uncertainty. Therefore, the fluctuation of the index can be interpreted as the short-term variability of the relative phase angle.

In order to remove the short-term variability, a weighted index is introduced on trial. The weighted index is defined by introducing the power of cross-spectra. The definition is expressed as follows;

$$I_{WPM}(n) = \sqrt{\frac{1}{N_f} \sum_{i=0}^{N_f} \frac{|S_{xy}(f_i; n)|}{|S_{xy}(n)|_{\max}} \{P_{xy}(f_i; n) - P_{xy}(f_i; n-1)\}^2} \quad \dots\dots\dots(7)$$



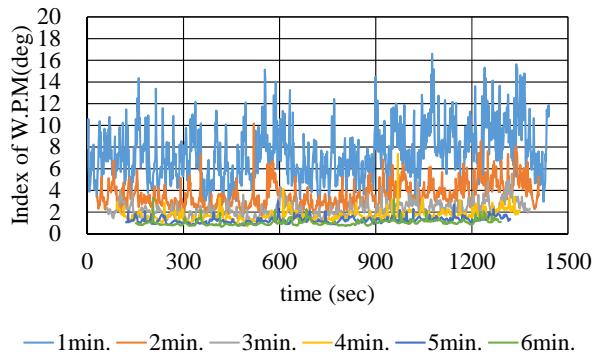


Figure 11 Transition of  $I_{WPM}(n)$  of roll- pitch cross-spectra for each time span (course 0deg).

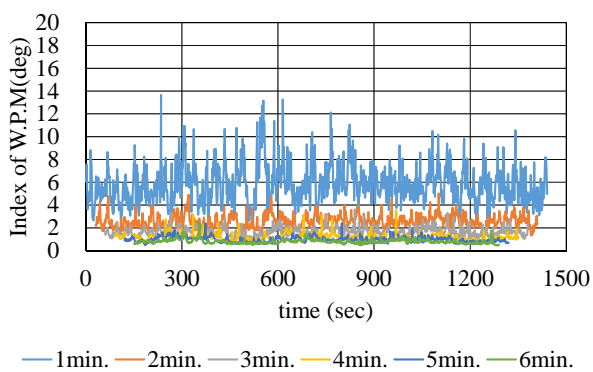


Figure 12 Transition of  $I_{WPM}(n)$  of pitch- v.acc cross-spectra for each time span (course 0deg).

Figure 11 and 12 show the transition of the index  $I_{WPM}(n)$  of rolling-pitching and pitching-v.acc, respectively. Comparing to Figure 9 and 10, a certain level of improvement can be seen. This concludes that measures can be considered and introduced to avoid the short-term variability.

As mentioned in Section 2, the relative phase angle of the cross-spectra involves directional information of waves because the phase lag between the ship motions is induced by the encounter wave angle. Therefore, short-term variability of the relative phase angle between ship responses is very harmful when it comes to sea state estimation using the wave buoy analogy, which relies completely on measured ship responses. Therefore, if we can effectively reduce the influence of short-term variability in cross-spectral analysis, the causal relationship between ship motions and waves can be taken into account accurately and the directional estimation of the wave buoy analogy will be improved.

## 5. Conclusions

In this study, short-term variability of ship responses is investigated by cross-spectrum analysis. Using stationary time series of measured full-scale ship responses, details of the transition of the variance and relative phase angles of the cross-spectra have been investigated precisely with time shifting. The results obtained in this report are summarized below:

- ① In analyzes of (statistical) variance, common sense of stationary spectral analysis is confirmed; that is, “the longer time span, the better result”.
- ② Short-term variability of the relative phase angle is observed and the tendency is completely different to that of statistical variance.
- ③ The level of the short-term variability can be reduced by taking the signal strength into account.

The short-term variability of the relative phase angle is very harmful to sea state estimation by the wave buoy analogy. Hence, in future work, the characteristics of the short-term variability should be investigated more precisely.

## 6. Acknowledgements

This work is partly supported by Grant-in-Aid for Scientific Research of the Japan Society for Promotion of Science (No. 26420822). The authors express sincere gratitude to Capt. Yoshinori Manabe and crew of the training ship T.S. Shioji-maru, Mr. Tatsuya Koike and Mr. Satoru Hamada, Tokyo University of Marine Science and Technology.

Part of this work is directly related to the Centre for Autonomous Marine Operations and Systems (AMOS), and the second author would like to thank AMOS for economical support. The Norwegian Research Council is acknowledged as the main sponsor of AMOS through the Centres of Excellence funding scheme, Project number 223254-AMOS.

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