Underwater Interferometric Radar Sensor for Distance and Vibration Measurement

Michael Sporer [1], Fabian Lurz [1], Eberhard Schluecker [2], Robert Weigel [1] and Alexander Koelpin [1]

[1]Institute for Electronics Engineering, [2]Institute of Process Technology and Machinery
University of Erlangen-Nuremberg, Erlangen, 91058, Germany

***Abstract*— With the growing application of autonomous underwater vehicles (AUV) and underwater construction, i.e. robotic manipulator and maintenance systems, there is an increasing demand on precise underwater distance sensors. In this paper we present a low–cost, short–range and contactless sensor which uses electromagnetical (EM) waves for measuring distances underwater. The measurement system is based on interferometric radar applying a six–port interferometer and using EM waves at a frequency of 2.4 GHz. Measurement series in fresh water have been carried out showing an precision of below 100 µm up to a distance of 35 mm with only 8 dBm of transmit power. Due to the high measurement rate the system can also be employed for vibration analysis. Additionally, by connecting a commercial 2.4 GHz data transceiver, it is imaginable for the system to be simultaneously used for high data rate communication between e.g. AUV and unmanned underwater platforms (UUP).**

I. Introduction

Recently, increased research in the field of underwater sensor technology and autonomous underwater vehicles (AUV) can be noticed. The reasons are various, ranging from scientific exploration of the oceans and the deep–sea to growing economic demands like localization and exploitation of natural resources hidden underwater. Additionally, the effort and complexity of maintenance, upkeep and repair of the existing underwater infrastructure i.e. oil and gas pipelines and fibre–optic networks are expected to rise in the future.

For controlling and monitoring tools and instruments precise underwater proximity and distance sensors are needed. Typically, optical and acoustic sensors are employed. However, although providing high–precision, optical sensors are costly and they suffer from water turbidity. Acoustic sensors benefit from the relatively low attenuation of acoustic waves in water and therefore offer long–range coverage. The main drawbacks are disturbances in short ranges due to multipath effects, low measurement rate and relatively low distance resolution (cm to mm range) [1], [2]. In order to achieve higher resolution especially in short–range applications high–frequency electromagnetic (EM) waves can be utilized but due to the increasing attenuation of EM waves in water with rising frequency a trade–off between accuracy and range must be considered. In this paper a high–resolution, low–cost and contactless underwater distance and vibration sensor is presented based on radar interferometry using EM waves at 2.4 GHz. The sensor consists of a radar frontend for signal conditioning, an underwater antenna and a six–port interferometer [3] allowing precision phase and thus distance measurements.

A. Properties of EM Waves in Water

Due to the distinct dipole character of water molecules, fluid water shows strong polarizability and therefore a relatively high dielectric permittivity. The permittivity is strongly dependent on frequency f, temperature T (in °C) and conductivity σ of additives like salt (concentration S in ppt). It can be approximated by the second–order Debye model

$$\varepsilon_r(T,S,f) = \frac{\varepsilon_s(T,S) - \varepsilon_1(T,S)}{1 + jf/f_1(T,S)} + \frac{\varepsilon_1(T,S) - \varepsilon_\infty(T,S)}{1 + jf/f_2(T,S)} + \varepsilon_\infty(T,S) + j \cdot \frac{\sigma(T,S)}{2\pi\varepsilon_0 f} = \varepsilon_r' - j\varepsilon_r'' \quad (1)$$

with the vacuum, static, immediate and asymptotic dielectric permittivities ε_0, ε_s, ε_1, ε_∞ and the first and second Debye relaxation frequencies f_1 and f_2. Using empirical values given in [4] the real (ε') and imaginary (ε'') part of the relative permittivity of water can be calculated.

Assuming a permeability of water equal to the vacuum permeability μ_0 the wavenumber k becomes

$$k = \beta - j\alpha = 2\pi f \sqrt{\mu_0 \varepsilon_0 (\varepsilon_r' - j\varepsilon_r'')} \quad (2)$$

with the phase and attenuation constant β and α [5]. Thus, the power attenuation A_{dB} of a plane wave propagating a distance z and its wavelength λ are

$$A_{dB} = 20\log_{10}(e)\alpha z \quad (3)$$

$$\lambda = \frac{2\pi}{\beta} \quad (4)$$

Fig. 1 shows the attenuation of an underwater EM wave in a frequency range between 10 MHz and 100 GHz for different salinities S and temperatures T. Both, attenuation and wavelength are strongly dependent on frequency. Increasing the temperature decreases the attenuation whereas rising salinity leads to a significant increase in attenuation especially at frequencies below a few GHz.

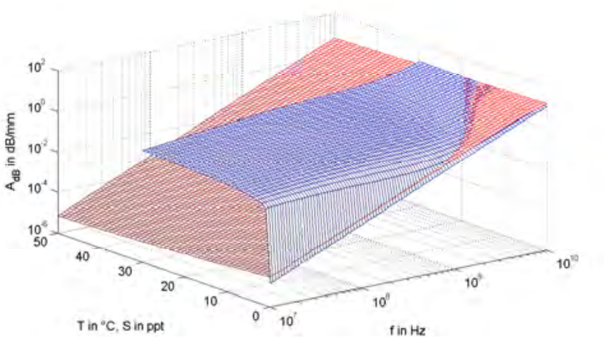


Fig. 1. Attenuation of a plane EM wave in water for $f = 0.01 - 10\,\text{GHz}$. The red surface shows the dependence on temperature with $S = 0$. The blue surface shows the dependence on salinity at $T = 20°$.

B. Underwater Radar Interferometry

Interferometer based position measurement systems provide precise distance information by measuring the phase difference between two coherent signals, one of which is transmitted by a radar antenna to the target, backscattered by this target and again received by the antenna. The distance d between target and antenna is calculated from the measured phase difference $\Delta\varphi$ as

$$d = \frac{\Delta\varphi}{4\pi} \cdot \lambda + \frac{n}{2} \cdot \lambda \tag{5}$$

with $n = 0, 1, 2, \ldots$ denoting the phase ambiguities. Relative distances can only be measured unambiguously in a range of $\lambda/2$. However, Fig. 1 suggests that if the strong signal attenuation is considered, i.e. the power of the received signal is used for coarse distance measurement like in [6], the ambiquity issue can be resolved, thus allowing absolute distance measurements.

Distance resolution is limited by the phase resolution of the interferometer and the wavelength λ of the transmitted signal in the surrounding medium (Equ. 5). Regarding Fig. 1 and Equ. 4 there is a trade–off between high distance resolution (small wavelength) and high range (low signal attenuation).

For this short–range sensor we decided to use a frequency of 2.4 GHz (Industry, Scientific and Medical (ISM) radio band) which allows the use of low-cost standard components. Additionally, the impact of salinity is relatively low at this frequency.

C. Underwater Distance Measurement System

Fig. 2 shows a block diagram of the proposed system consisting of a radar frontend, an underwater antenna, a directional coupler and a six–port interferometer presented in [7]. The transmit signal is generated by a frequency synthesizer and fed through a directional coupler into an underwater radar antenna where it is radiated towards the target (transmit power 8 dBm). A part of the transmit signal, the reference signal, is coupled to one port of the interferometer. The received backscattered signal (test signal) is decoupled, bandpass filtered and finally fed into the other interferometer port. Both, transmit and receive paths, contain amplifiers which may be individually switched on or off in oder to increase the dynamic range. The four baseband output signals of the six–port interferometer are low–pass filtered for antialiasing (3 kHz cut–off frequency), then recorded by the internal 10–bit analog–to–digital converter (ADC) of a microcontroller (µC) and finally transferred to a PC for evaluation. The frontend contains a second input port for optionally connecting an additional antenna in order to calibrate the system if required. The applied underwater antenna [8] is based on an open–ended dielectric–filled waveguide and therefore provides high directivity allowing to focus the radiated field on the target. In order to evaluate the performance of the system a target has been moved linearly along the antenna axis by means of a computer controlled high–precision linear stage. Antenna and target have been placed in a tank filled with fresh water at room temperature as shown in Fig. 3.

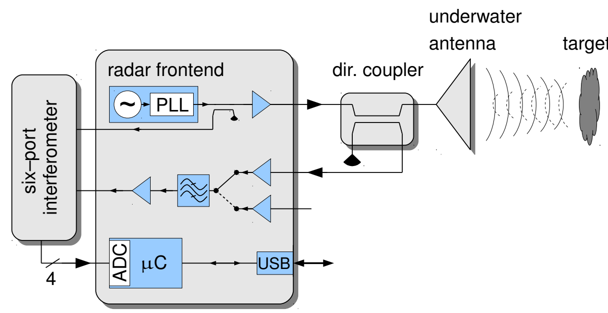


Fig. 2. Block diagram of the underwater distance meas. system

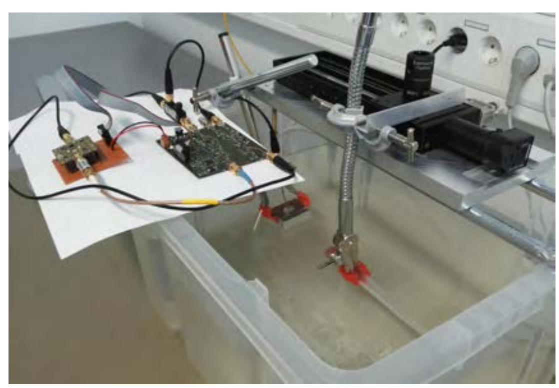


Fig. 3. Measurement setup showing radar frontend, six–port interferometer, directional coupler, underwater antenna and target mounted on a linear stage

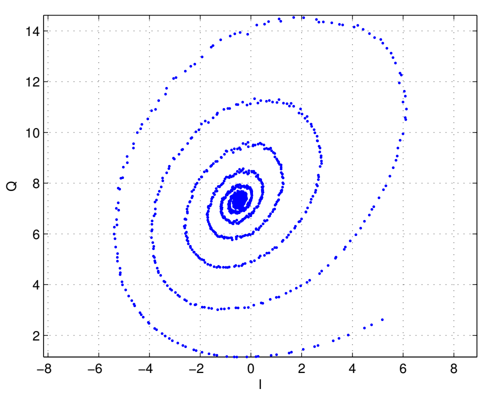
The target is a stick of 15 mm diameter covered with copper foil at the front face. We have performed a measurement series for recording the six–port baseband signals of 10 identical sweeps. During each sweep the target has been moved in 50 µm steps over a distance of 1 mm to 60 mm from the antenna. After each step the mean value of 16 consecutive ADC samples is transferred to the PC.

D. Data Analysis

The four measured baseband signals of the six–port represent a complex vector $Z = I + jQ$ whose real (I) and imaginary (Q) parts can be computed by subtracting the according two baseband data pairs [3]. The phase difference $\Delta\varphi$ between reference and test signal is the argument of Z, i.e.

$$\Delta\varphi = \arg\{Z\} = \tan^{-1}\left(\frac{Q}{I}\right) \tag{6}$$

Fig. 4 shows the recorded data vector Z of one exemplary sweep. The logarithmically decreasing amplitude of Z with increasing distance to the antenna (Equ. 3) produces a logarithmic spiral in complex representation. Note the distinct spiral arm. This allows to distinguish measurement points with phases φ and $\varphi + n \cdot 2\pi$ solving the ambiguity problem. Offset and gain distortions of I and Q values



2

Fig. 4. I and Q values of one measurement sweep

due to parasitic reflexions and nonidealities of the six–port interferometer are obvious. However, these static errors can be removed by calibration. For this purpose, a logarithmic spiral is fitted into the measured data points of one calibration sweep. The thereby obtained offset and gain errors are subsequently used to calibrate the remaining measurement sweeps. After calibration the distance is computed using Equ. 5 and 6.

Fig. 5 shows the standard deviation of the measurement error of all sweeps. The measurement error rises with increasing distance due to the strong signal attenuation in water. For $d < 35\,\mathrm{mm}$ the standard deviation is lower than 100 µm, for $d < 25\,\mathrm{mm}$ even 50 µm can be achieved. Note that, after calibration, the measurement rate is mainly limited on sample rate of the ADC and processing speed in the digital domain. In [9] e.g. an update rate of 50 kHz has been reached.

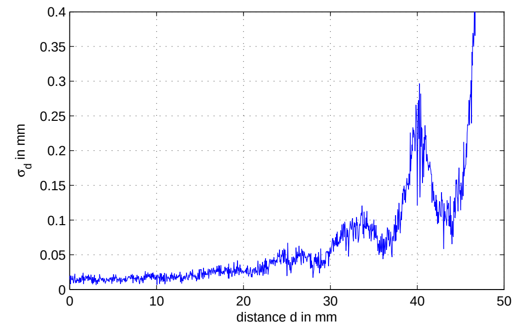


Fig. 5. Standard deviation σ_d of the dist. meas. error (10 sweeps)

II. Conclusion

In this paper we present a low–cost underwater distance measurement system based on interferometer radar using EM waves at 2.4 GHz. Due to the strong signal attenuation in water the system is mainly intended for short–range applications where high resolution is required. It can therefore be employed as an extension and assistance for long–range acoustic–based sensors. Thanks to the high measurement rates the system can also be used for vibration analysis. Furthermore, due to the use of high–frequency EM waves it is imaginable to connect a common data transceiver stage to the radar frontend in order to enable simultaneous high–datarate communication.

References

[1] L. Whitcomb, D. Yoerger, H. Singh, D. Mindell, and D. M. Zx, "Towards precision robotic maneuvering, survey, and manipulation in unstructured undersea environments," in *in Robotics Research - The Eighth International Symposium*. Springer-Verlag, 1998, pp. 45–54.

[2] C.-C. Chang, C. Y. Chang, and Y. T. Cheng, "Distance measurement technology development at remotely teleoperated robotic manipulator system for underwater constructions," in *Underwater Technology, 2004. UT '04. 2004 International Symposium on*, April 2004, pp. 333–338.

[3] A. Koelpin, G. Vinci, S. Lindner, S. Mann, F. Barbon, S. Linz, F. Oesterle, and R. Weigel, "Six-port technology for precise geometrical measurement applications - an overview," in *Microwave Conference (EuMC), 2013 European*, Oct 2013, pp. 1587–1590.

[4] T. Meissner and F. Wentz, "The complex dielectric constant of pure and sea water from microwave satellite observations," *Geoscience and Remote Sensing, IEEE Transactions on*, vol. 42, no. 9, pp. 1836–1849, Sept 2004.

[5] S. J. Orfanidis, *Electromagnetic waves and antennas*. ECE Department, Rutgers University, August 25, 2013.

[6] D. Park, K. Kwak, W. K. Chung, and J. Kim, "Development of underwater distance sensor using em wave attenuation," in *Robotics and Automation (ICRA), 2013 IEEE International Conference on*, May 2013, pp. 5125–5130.

[7] F. Lurz, S. Lindner, S. Mann, S. Linz, F. Barbon, R. Weigel, and A. Koelpin, "A low-cost 2.4 GHz frequency measurement system for microsecond time domain pulses based on six-port technology," in *Microwave Conference (EuMC), 2014 European*, to be published.

[8] M. Sporer, R. Weigel, and A. Koelpin, "Open–ended dielectric–filled waveguide antenna for underwater usage," in *Microwave Conference (EuMC), 2014 European*, to be published.

[9] F. Barbon, G. Vinci, S. Lindner, R. Weigel, and A. Koelpin, "A six-port interferometer based micrometer-accuracy displacement and vibration measurement radar," in *Microwave Symposium Digest (MTT), 2012 IEEE MTT-S International*, June 2012, pp. 1–3.