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SLAM – Based Approach to Dynamic Ship Positioning

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ABSTRACT: Dynamically positioned vessels, used by offshore industry, use not only satellite navigation but also different positioning systems, often referred to as 'reference' systems. Most of them use multiple technical devices located outside the vessel which creates some problems with their accessibility and performance. In this paper, a basic concept of reference system independent from any external device is presented, basing on hydroacoustics and Simultaneous Localization and Mapping (SLAM) method. Theoretical analysis of its operability is also performed.

1 DYNAMICALLY POSITIONED UNITS AND THEIR APPLICATIONS

Fast growth of demand for fossil fuels and inability to meet it only from land-based reservoirs created a need to start exploiting offshore oilfields. To do so, however, special positioning technology was needed, allowing drilling ships to maintain position in most hydro- and meteorological conditions. That is how dynamic positioning systems were invented. Det Norske Veritas (DNV, now DNV-GL after merging with Germanischer Lloyd) provides following definition of dynamically positioned (DP) vessel (DNV, 2013):

'A vessel which automatically maintains its position and heading (...) exlusively by means of thruster force'

DP vessels are used by offshore industry, mainly for:
- maintaining position of drilling ships if anchoring is found to be impractical;
- keeping pipe-laying vessels exactly over the predetermined track of the pipeline;
- maintaining safe distance between two units during cargo or crew transshipment from one to another;
- other operations, where stable position or heading is crucial.

To ensure safety of operations, redundancy is introduced. For each part of equipment, a backup devices must be ensured to guarantee proper functioning of the system even if some devices fail to operate. DP systems are divided into classes from DP-1 (no redundancy, failure of single device can cause the whole system to collapse) to DP-3 (system continues to work even if one engine room is under fire or flooded). Decision on which class of the equipment shall the vessel possess to perform her task is made by operator according to required level of reliability. It must be underlined, however, that DP systems are recommended to support offshore operation only when no failure is detected. When it occurs, the operation should be suspended – DP system's (no matter its class) objective is to ensure safe withdrawal from the operation (IMO, 1994).

Vessel's position and heading is constantly monitored and controlled by dynamic positioning system, consisting of sensors, displays, operator panels, thrusters etc. A very important part of DP system is also a positioning reference system.

2 REFERENCE SYSTEMS

Precision and accuracy of systems widely used by merchant marine is insufficient for dynamic positioning purposes. Therefore, some special reference systems must be introduced and the most important and frequently used of them will now be briefly described:

- Satellite navigation – global navigation satellite systems are based on receiving data from satellite units and processing it by the receiver in order to compute global-referenced position and other parameters, like heading for instance. Errors produced by ionospheric disturbances, inaccuracies in satellites' constellation measurements etc., can be reduced by using differential corrections (calculated by shore-based stations and transmitted either by them or by commercial satellites). Costs of obtaining highly-precise corrections prove to be too high for shipping but negligible in offshore industry. Global coverage is the biggest advantage of such systems;
- Hydroacoustic – those systems' working principle is based on using sound wave emitters and receivers, located both on the seabed (referred to as 'transponders') and ship's hull ('transducers'). Transponders serve as objects, distances or bearings towards which can be determined. The biggest advantage of using hydroacoustic navigation systems is that precision of navigation is higher than in dead reckoning and can be as high as 5 millimeters (Rowiński, 2008). On the other hand, the biggest limitation of such systems is that transponders must be precisely placed on the bottom of the sea before even operations can start and that makes them suitable only for long-term operations performed in a relatively small area. Moreover, the transponders shall be raised to the sea surface periodically in order to clean it from algae and other marine organisms (Rutkowski, 2013);
- Taut wire – in those systems, a clumpweight is lowered to the seabed. By measuring the amount of wire paid out and the angle between wire and vertical, position can be calculated in relation to position where the weight was initially lowered. Accuracy decreases with depth of water as ocean current may curve the wire. Horizontal taut wires can also be applied, measuring position in relation to fixed structure;
- Microwave – those systems' working principle is based on determining vessel's position in reference to fixed structure by using radar. In various systems, this can be achieved in many ways, like for example by detecting the difference from parallel that the two antennas are one to another and using the signal to drive two coupled servo motors to move the antenna on the station, bringing it parallel to the counter station's one (Artemis) or determining distance between interrogating antenna and transponder attached to the fixed object together with angle between line normal to the interrogator and transducer's direction e.g. by measuring the phase shift (RADius, RadaScan);
- Laser – infrared laser beams can be used to determine the distance between two objects by measuring time in which light is produced by vessel's rotating antenna, reflected and received. Special reflectors must be placed on the latter object to make this possible. Mutual orientation of those two is determined by sensing the angle between laser and ship's hull's plane of symmetry together with her heading: Fanbeam, CyScan (Rutkowski, 2013).

Other reference systems' working principles are based on using inertial navigation together with other navigational devices. To ensure proper redundancy and reliability of position fixing, at least three (voting 2 of 3) reference systems of different working principles should be used in a time.

One of the greatest disadvantages of above-listed reference systems (except for taut wire) is that they require special off-vessel devices or infrastructure to operate. This creates a risk of failures the vessel's crew could not cope with or need of distributing e.g. hydroacoustic navigation systems' transponders prior to operation which can be found economically ineffective for short-time activities. The solution of this problem is finding a fixed objects, which navigational parameters can be measured at open seas. Sailors in 18th or even 15th century would claim celestial bodies to meet the requirements, but the precision and accuracy of celestial navigation is insufficient for today's applications. An only fixed object to determine a fix to appears to be a seabed.

Vessel's velocity in relation to seabed can be measured by Doppler Velocity Logs (DVL). However, their precision and accuracy is highly dependent on sound's speed in water, which in turn changes with depth (temperature and salinity to be more precise). Errors created by this effect disqualify DVLs from being used in highly-precise dynamic positioning. There is, however, a theoretical possibility of determining vessel's motion components by using other hydroacoustic devices, initially designed for different purposes, like for instance imaging sonar. Here, a pulse of sound is directed downwards, reflected by the seabed and received by the rotating transducer (Figures 1 and 2). The signal is then divided into a number of beams by highly sophisticated algorithms and converted into water depth values, creating 3D image of the seabed (Marine Electronics, 2014). To achieve high resolution, a hydroacoustic wave should be of a high frequency (200 through 400 kHz) and low beamwidth. Unfortunately, such a high frequency causes sea water to disperse sound wave pretty quickly and for that reason, transceivers must be placed relatively close to the seabed (up to 500 meters in best case). This method is suitable especially for low speed over ground or when the vessel is to maintain her position which circumstances are common in offshore industry.

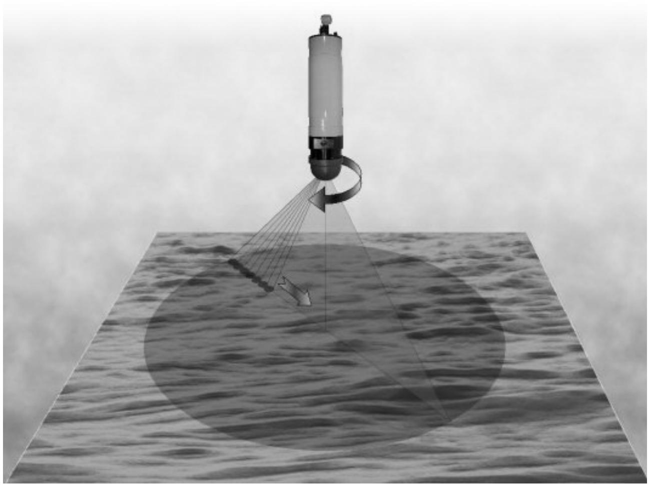

Figure 1: Imaging sonar working principle (Marine Electronics, 2014)

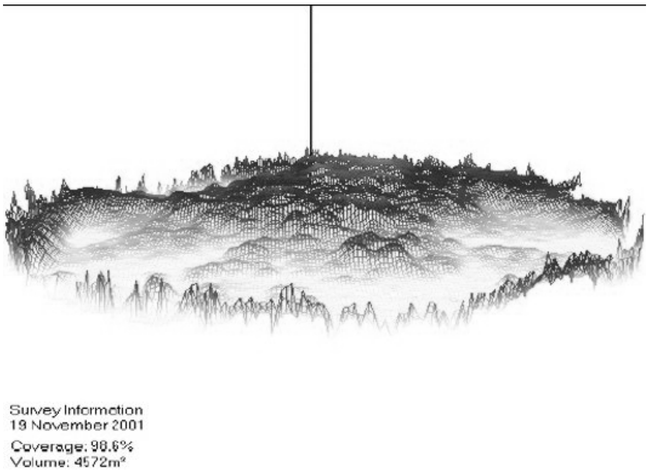

Figure 2: Imaging sonar 3D survey results (Marine Electronics, 2014)

3 SLAM DESCRIPTION

Simultaneous Localization and Mapping (SLAM) is a set of methods enabling navigation of autonomous robots in an unknown environment. Here, a robot (or any other vehicle, a dynamically positioned vessel for instance) itself uses onboard sensors to create a map of area in which it operates and navigates using this map. To achieve that, probabilistic methods are used to determine the spatial relationships between characteristic points of – in underwater case – seabed topography. Those points are then referred to as 'landmarks'. *A priori* knowledge regarding the area of operation is not required.

A vehicle is moving through an unknown environment, taking observations of an unknown landmarks by using sensors (imaging sonar, multibeam echosounder etc., Figure 3). At a time *k*, following parameters are defined:

- x_k – the state vector, describing the location and orientation of the vehicle;
- u_k – the control vector, applied at a time *k-1* to drive the vehicle to a state x_k;
- m_i – a vector, describing the location of the i^{th} landmark whose true location is assumed time invariant;
- z_{ik} – an observation taken from the vehicle of the location of the i^{th} landmark in time *k*.

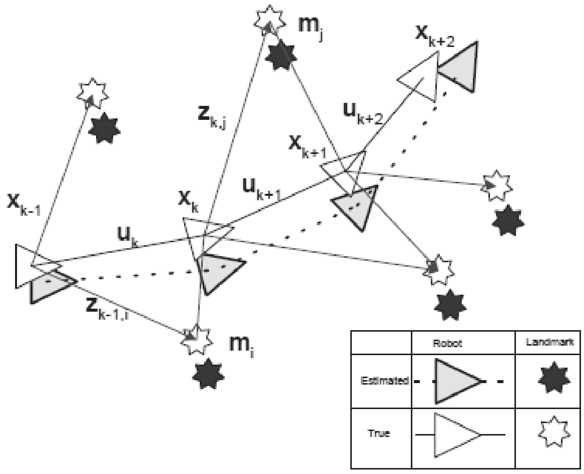

Figure 3: SLAM method principle (Durrant-Whyte & Bailey, 2006)

In addition to that, the history of vehicle locations ($x_{0:k}$) and control inputs ($u_{0:k}$), set of all landmarks (*m*) and set of all landmark observations ($z_{0:k}$) are created. In a probabilistic approach to SLAM problem, a probability distribution:

$$P(x_k, m \mid z_{0:k}, u_{0:k}, x_{0:k}) \quad (1)$$

is calculated for all times *k*. By that, relative locations of landmarks $m_{0:k}$ are determined. The accuracy of landmarks observations increases together with their number, as the observations can be considered as nearly-independent. Even if landmark m_i observed from position x_k is not visible from position x_{k+1}, its location is corrected in time *k+1*, because its relation to other objects remains known. Some errors are introduced by sensors imperfections and inaccuracy of x_k vector determination (Durrant-Whyte & Bailey, 2006). After a map of landmarks is created, a position of the vehicle itself can be determined in relation to them – a fix is obtained by methods of old-fashioned pilot navigation. *Ergo*, position and orientation of the vehicle is determined in relation to a grid of landmarks. Furthermore, exact global referenced positions (latitude and longitude) of landmarks need not to be known as a vessel can navigate and operate in local set of coordinates from the time *k*. In this case, however, coordinates of all infrastructure elements must be known in relation to landmarks' grid besides or rather than being known in global set of coordinates.

Consider DP vessel equipped with imaging sonar, proceeding on sea surface over the seabed. Its orientation is heading measured by gyrocompass and position – latitude and longitude measured by GNSS (x_k). At time *k*, relative positions of landmarks are measured by sounding and then processed into a map of spatial relationships between landmarks themselves. Relative position in this case means three distances from transducer: to port/starboard side, ahead/astern (by measuring respective beam angles) and vertical (by measuring time of sound wave travelling in water). As the transducer is fixed to ship's hull, those distances and angles change only when ship's position or heading change (or, if the transducer is rotating, its angle of rotation must be taken into account). In other words, by measuring change of those angles and distances in k and $k+p$, the change of ship's orientation and position in relation to landmarks' grid can be determined. GNSS fixing or other reference systems can be used in order to compare results or as a backup.

4 ANALYSIS OF INITIAL CONDITIONS OF APPLYING SLAM AS A REFERENCE SYSTEM

Ability to determine vessel's position in relation to fixed objects with increasing precision (in opposite to decreasing precision as in dead reckoning) makes SLAM one of solutions to problem of positioning vessels without relying on external sources of information. Due to requirement of ensuring redundancy in DP operations, SLAM can only be one of at least three positioning systems. Either way, there are some conditions to make this method applicable:

- Sensors accuracy and precision – sensors used by the system must be of highest quality available on the market to ensure satisfying precision and accuracy of landmarks' relative position measurements. The most important technical parameters of the sensors would be their pulse length (and by that – altitude resolution), number of beams and maximum range. Resolution of today's hydroacoustic sensors can be as high as 1.5 centimeters which enables good positioning precision. Specific requirements regarding sensors' performance and precision in bathymetric surveys can be found in (IHO, 2008). The more beams of smaller beamwidth are used, the higher horizontal resolution can be achieved;
- Depth of water – as it was mentioned before, using high frequency sound wave causes problems with wave dispersion by sea water. The longer distance the sound travels in water, the less accurate the soundings become. Modern imaging sonars have maximum range of some 400 meters and this can be the most serious limitation of described system's operational performance. However, the devices are still being developed and this disadvantage's significance can be reduced in future, for example by progress in field of parametric hydroacoutics. Loss of precision characteristics in waters deeper than preferable as per sonar's technical specification can be determined by inspection and may be a subject of further study;
- Fix rate – assuming sound speed in seawater to be approximately 1500 mps and depth of water of 400 meters, sound wave would require more than 0.5 seconds to cover the distance from transducer to landmark and back. Next pulse shall not be transmitted sooner to avoid identification and interference issues. Thus, position can be obtained not more often than this (plus the time the transducer might require to rotate in angle enabling sufficient number of landmarks to be located), decreasing proportionally as depth of water in area of operation increases;
- Topography of the seabed – SLAM requires some distinguishable points ('landmarks') to determine vessel's position in relation to them – the very operational principle of the system is based on isolating specific points from the background (seabed) and identifying them using e.g. their shapes. To do so, the system's processing unit must find points of depth significantly different than those in vicinity and then identify them as either i^{th} or $i+1^{th}$ landmark. This would require the seabed in operational area to be pleated enough to isolate and then properly identify landmarks. The more objects can be isolated from seabed's image, the better precision can be achieved. It should be noted that underwater infrastructure of oilfield, such as pipelines or manifolds, can serve as landmarks. To improve probability of finding proper objects, the swath area can be increased by using sensors of greater or adjustable swath width (up to 200 deg.);
- System's design – reference system based on SLAM method can be divided into hardware (sensor measuring relative position of landmarks) and software – a processing unit. This would not only convert data regarding soundings into vessel's position, speed and heading, but also take other factors into account in process of data fusion including angle of heel and trim. Another function of processing unit could be adjusting the sensor's operating parameters like pulse length depending on the depth of water.

5 SLAM-DP ADVANTAGES AND DISADVANTAGES

Hereby presented system using SLAM methods would have some advantages and disadvantages, listed in Table 1.

Table 1. Advantages and disadvantages of SLAM application in dynamic positioning

Advantages	Disadvantages
autonomous operations (not dependant on external devices); ship's mobility not limited by anchors etc.; constant or even increasing precision; enables data regarding both position and heading; position relative to point of interest (manifold etc.) – no need to know its global-referenced position.	maximum depth of water limit; inaccurate when flat seabed; possibility of interferences from hydroacoustic navigation systems; system's precision and accuracy can be found poorer than those of satellite systems, making it unsuitable for DP; ability of proper system maintenance reduced by sensor's location under the waterline.

6 SUMMARY

Preliminary concept of positioning reference system based on depth sounding and SLAM post-processing has been presented. The described system eliminates some limitations of today's reference systems such as dependence on external data sources. However, it has its own disadvantages as listed in the paper. Further research is required to determine whether the desired precision can be achieved using this method and if its performance can meet the requirements of dynamic positioning process.

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