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Vessel attitude estimation by camera sensors

S. Del Pizzo[1], S. Gaglione[1], A. Angrisano[2], G. Salvi[1], S. Troisi[1]
[1] Department of Science and Technology, Parthenope University of Naples, Centro Direzionale di Napoli, Is. C4 80143, Napoli, Italy.
[2] G. Fortunato University, via R. Delcogliano 12, Benevento, Italy

Abstract –

Vessel attitude is one of the most sensitive information in important operation. For instance, during ship cargo loading or discharge operation an un-accurate estimation of vessel attitude could compromise the safety of the procedure. Ship pith and roll parameters are directly measured by traditional sensors (bubble levels) or indirectly estimated from ship motion monitoring. Also inertial sensors, that provide a continuous attitude information, are actually used in offshore riser monitoring and dynamic positioning systems but not spread in all commercial ships. The aim of the proposed study is to provide vessel roll and pith using a cheap technology just widespread in shipping. This work presents the project of an embedded solution that uses visual information, captured by a consumer camera that "looks" the horizon. The camera system is constrained to the ship hull, while a computer unit is able to detect and track the horizon line, that fall within the image bounds. The paper describes how the horizon's movements provide pitch and roll angles, furthermore, in order to perform an accuracy analysis, several static tests were carried out.

I. INTRODUCTION

The information on a vessel "ego-motion", its position and attitude, is of great interest for mariners in different ship operation and scenarios such as open sea, congested harbors and waterways. The knowledge of vessel attitude is important, for example, during cargo loading and discharging, and could ensure the safety conclusion of operation. Reliable estimation of the state of a 6-Dregree of Freedom body is a fundamental task in several disciplines; many authors employ Vision Navigation System (VNS) in their applications, even if this approach is still a challenging problem with several aspects to be explored. Specifically, the use of horizon detection for attitude determination is an old idea: Todorovic et al. [1] implement a computer vision solution, based on horizon tracking, for flight stability and autonomy of MAVs (Micro Air Vehicles).

Other research groups, as well as single authors, have ongoing worked to this topic. Numerous approaches are able to detect the horizon with unsupervised systems. One of such approaches is based on the clustering of the image in two parts: the ground (or sea) and sky regions. The horizon line can be computed optimizing the clustering with statistical hypothesis [2-5]; another method uses a circular mask applied on the image that is invariant to the angles between horizon and x- axis of the image [6]. Another approach detects the horizon from a set of straight lines attained through the use of a pre-processed image followed by the Hough transform [7-9].

The recent developments in computer vision and wide availability of low cost hardware, that is getting smaller and smaller, are a consolidate team able to occupy a main role in any scientific and technologic field, from medicine to engineer. The navigation is not an exception, indeed, even if the technology is not completely ready, it's getting to start the employ of artificial vision systems to support the traditional navigation systems e.g. in indoor navigation for mobile autonomous robot [10, 11], in terrestrial navigation [11] and aerial navigation [1, 7]. Such vision-based systems are very lightweight so suitable to equip unmanned aerial vehicle, whose typical payload is extremely low.

In this work, a new methodology is proposed to estimate the roll and pitch angles between a reference and a generic attitude. In such methodology the single frame of a video is considered as a central projection.

The new approach is suitable for marine and aerial application:

- safety purposes, the data can be included in a classical black-box recorder;
- near-shore single-beam hydrographic survey performed with low cost systems, the attitude obtained can be used to correct the unavoidable errors due to roll and pitch angles;
- augmented reality purposes, the horizon detection and the obtained roll and pitch can be overlaid on the display system to provide extensive information.

Furthermore, the paper describes the system setup used to evaluate the performance and reliability of the methodology, comparing the obtained results with the solutions of two external systems: photogrammetric and INS ones.

II. HORIZON DETECTION

The Inertial Measurement Units (IMU, accelerometers and gyroscope) are the most common sensors to compute attitude, they have the advantages of high-rate and relatively small latency but can be subject to significant drift. On a ship is not requested the high-rate attitude information so the proposed vision system, that allows the extraction of a low frame-rate, precise and stable solution, is fully satisfactory.

The visual system is composed by a consumer frame camera that is constrained to the ship and looks toward the horizon. In the method described below we assume that the images have been already corrected to take into account the geometric distortions of the camera.

The proposed methodology can be separated into two distinct phases:

1. Automatic Horizon detection;
2. Roll and Pitch computation.

In the first phase, the algorithm finds a straight line in the image relative to the marine horizon, by employing methods and procedures well-known in computer vision. The roll and pitch angles between a reference horizon and target horizon are evaluated in the second phase. Many horizon line detection methods for any scenario are known [12, 13], they can be divided into three categories:

- Segmentation and Classification based algorithm;
- 1D Edge Detection and Least Square based algorithm;
- 2D Edge Detection and Hough transform based algorithm.

The first category includes all the algorithms that employ a clustering method to find two zones within the image: sky-ground or sky-sea separated by a line, which will be considered the detected horizon line.

In 1D Edge Detection and Least Square method the edge detection is the fundamental phase, indeed this approach finds the position of the maximal local edge for each image column. The optimal horizon line passes through the maximal local edges detected, and can be identified using the least-square method [13]. This method has a low computational complexity but many false maximal can generate wrong solutions.

In marine scenario, the horizon line is usually straightforward, so the Hough transform allows to detect it in the image. The 2D Edge Detection and Hough transform method is based on sequential process that can be summarized in two basic steps:

1) edge detection [14] on pre-processed image;
2) application of the Hough transform [15] to edges map.

The entire computational complexity of the method is strictly correlated to the density of Hough space. The approach described in this work is an enhanced version of a method already described [16] that employs a customized version of 2D edge detection and Hough transform.

In the first step, the image captured by the camera, whose optical axis can be supposed parallel to the longitudinal axis of the ship, is submitted to a series of transformations and filtering by means of computer vision algorithms.

The result is a black and white image called "edge map" (figure 1)

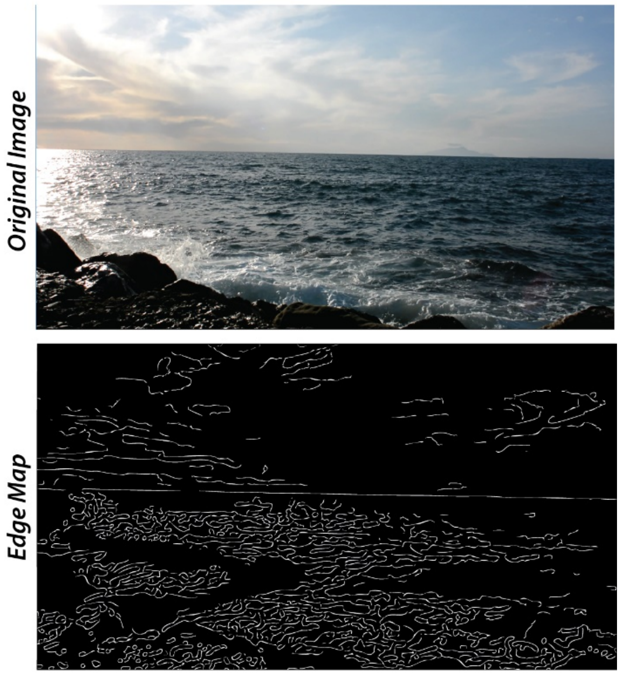

Fig. 1. On the top the original image, while on the bottom its edge map.

The Hough transform algorithm is applied in the second step to detect the longest straight line in the scene that should represent the instantaneous horizon. But in marine scenario several obstacles could be present in the images (like other ships or an irregular skyline due to coastline); these circumstances can create false horizons.

To reduce the possibility of false-horizon detection an ad-hoc custom filter is applied to the edge-map". Furthermore, all the horizon lines are usually characterized by a great image gradient magnitude and especially by a constant value of its direction along the entire line. For these reasons, the proposed algorithm chooses the line with the less variation of image gradient angle, among twenty possible candidate lines.

Moreover, a mask image is used to specify the areas, on the camera frame, where components of vehicle like fuselage or hull are visible. Such parts could generate strong and straight edges on the image inducing false horizons. During the edge detection, the masked areas are rejected.

III. PITCH AND ROLL COMPUTATION

The image processing presented in the previous sub-section detects the horizon line within the image. This can be considered like a sensor front-end: the measure obtained by the "sensor" needs to be related to the camera roll and pitch angles and hence of the vessel attitude.

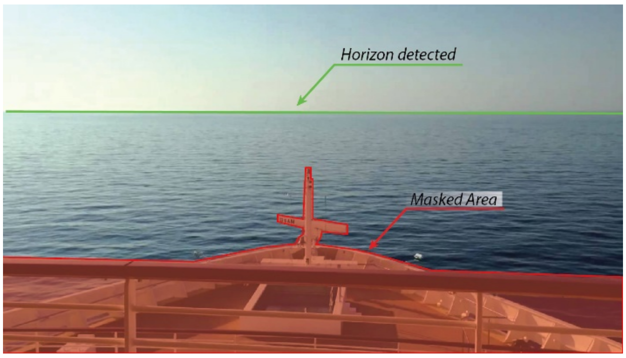

Fig. 2. An example of image masking during the video recording acquired on a ship. The red area is not processed.

Of course, if the camera optical axis is parallel to the vessel longitudinal axis, a rotation of the horizon in the image is connected with roll movements. On the other hand a simple vertical shift is related with pitch movements; but both parameters cannot to be directly measured on the image. The developed algorithm needs to define a reference horizon, which corresponds to a ship reference attitude. The roll and pitch angles are computed as the attitude difference between a reference horizon to any other.

The Euclidean geometry describes the world using a 3 coordinates by three-dimensional vector $X = [x, y, z]$, as well as an image describes it as bi-dimensional representation: $x = [u, v]$.

The mapping between the world space and image space is described by the pinhole camera model and its equation:

$$\mathbf{x} = \mathbf{PX} \tag{1}$$

where P is known as projection matrix, while the vector x and X are the coordinates of a generic point respectively in the image and world reference system, expressed into projective space. When a camera captures a picture, it performs such transformation. Of course, the transformation between two spaces is related to camera features, specifically, extrinsic and intrinsic parameters. The former is the orientation of the camera in the world space, is made up by the camera position and attitude, while the second one depends on internal camera parameters, such as the focal length and the pixel size; both are contained into the projection matrix [17]

Further parameters have to be taking into account, as well, such as the image distortion caused by lens. Specifically, in this work the distortion parameters are previous determined by procedures of self-calibration [18]. Therefore, the algorithm employs such parameters in order to computes undistorted images. This latter step allows to preserve straight lines, between the world space and image one, and it helps the horizon detection. Indeed, the image is a bi-dimensional projective representation of real world, it preserves straight lines but not the angles (principal point excluded) [19], for this reason it's not possible measure the angle directly on the image.

In the first version of the system it was used an approach where the image is regarded as gnomonic azimuthal map. In this work, a rigorous and faster approach has been employed; it provides results with a significantly lower number of operations. Such approach is based on the analysis of the direction cosines.

Let's considerer the pinhole camera model, composed by camera frame and perspective center, the distance between the plane's frame and perspective center is the calibrated focal length as shown in figure 3.

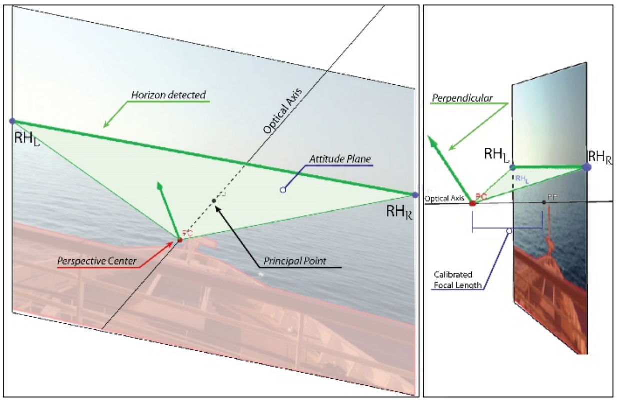

Fig. 3. Two view of pinhole camera model in 3D. The distance between the Perspective Center and the image frame is the calibrated focal length. In green is marked the detected horizon and the respective attitude plane.

Let's assume a horizon, detected on image, as reference horizon (in figure 3 is colored in green), such line intersects the camera frame boundary in two points (RH_R and RH_L). The plane which passes through such points and the perspective center establish the reference attitude of the camera and therefore of the ship.

A generic horizon, detected on image, intersects the camera frame boundary in two points as well, and therefore identifies the correspondent plane of attitude. Each plane can be expressed by the direction cosine of its perpendicular unit vector: the angle between the two perpendicular is a spatial angle that provides the attitude variation (figure 4).

Supposing that the camera frame is located perpendicular to the longitudinal axis of the ship, the spatial angle can be easily divided into roll and pitch angles.

IV. EXPERIMENTAL TRIALS

For the assessment of the proposed approach, several static trials have been carried out in order to validate the method and to estimate the achievable accuracies and precisions.

The analysis on the quality of the results has been carried out by the comparison with a precise methodology (photogrammetry) and with a low-cost INS. The INS solution has been used as an alternative to the suggested horizon solution, investigating their characteristics and hypothesizing their integration.

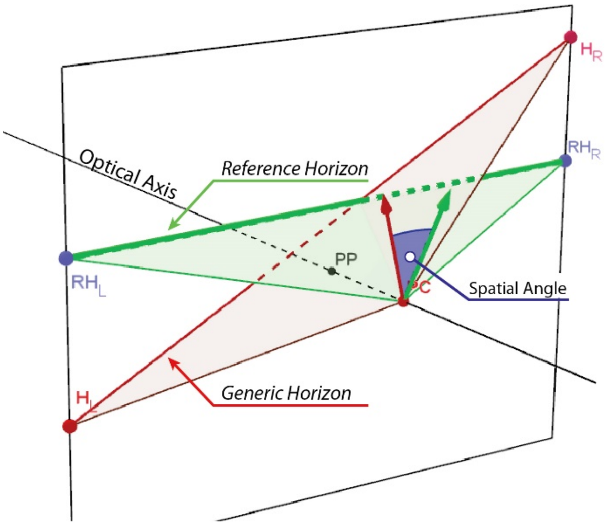

Fig. 4. Spatial angle between the two unit vectors perpendicular to the horizon planes.

A. Testfield description

The equipment used to evaluate the performances of proposed method is constituted by two plates with a set of photogrammetric circular targets. The lower plate is fixed whereas the high plate is movable (figure 5). The lower static plate supplies the photogrammetric reference system. The upper plate can assume several attitudes by means of a locking device that blocks it in a specific position, allowing the observation of the sensors on it.

On top of upper plate were placed: a camera Nikon D7100 for recording a video of the horizon, an X-Sens MTi-G used as low-cost sensor for INS measurements and a steel calibrated bar. A laptop was used for the time synchronization of instruments, for data acquisition and video recording.

In the first trial, the attitude angles between the fixed plate and the upper one, were detected by above-mentioned methodologies. Such angles are considered as reference for the subsequent trials. Afterwards, the upper plate was rotated and locked in different casual positions forming considerable angles of roll and pitch with respect to reference position.

The photogrammetric technique was employed to determine the precise coordinates of the circular target attached on the top of the two plates. A set of convergent images was acquired with calibrated camera for each trial (figure 6). The fixed plate allows to define the same reference frame for all photogrammetric acquisitions, whereas the calibrated bar located on the higher plate states the accurate scale. Procrustes transformation method has been used to evaluate the attitude difference between the first and the subsequent trials. for the targets placed on upper plate. The transform residuals are considered as figure of merit for the attitude accuracy.

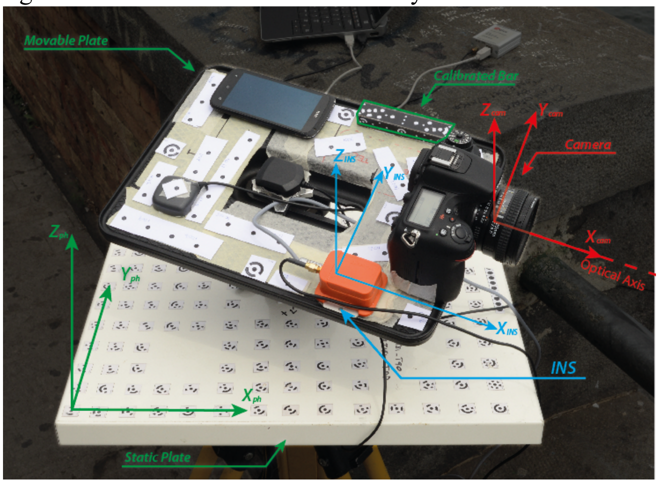

Fig. 5. System setup for the different sensors and definition of coordinate system. The movable plate simulates the movement of a ship, and therefore are located all employed instruments.

Low-cost IMU devices could be considered as a competitor system. In order to compare the proposed approach with such low-cost systems it was adopted inertial sensors based on MEMS (Micro-Electro-Mechanical Systems) technology. Such devices are characterized by lightness, small size and low cost but with poor performance, hence the error would rapidly increase without applying a suitable technique to limit its growth. A static data collection has been performed and so it has been possible to apply the ZUPT technique for the whole data set, avoiding the typical performance degradation of INS solution [20].

A Nikon D7100 reflex camera was used as video recording device; the video file is sent as input data to a C++ software developed ad-hoc. Such software uses the OpenCV library as well to extract automatically the horizon line. Once that the detection is concluded the results are transferred in Matlab Environment to evaluate roll and pitch angle for each frame. A simple integrity value, based either on the gradient magnitude and its orientation along the horizon line, allows to assume if a line is to be considered as horizon or not. Afterward the roll and pitch angles are estimated using the over-mentioned method. When a generic horizon is corrupted (the integrity value is zero) the attitude computation is skipped.

B. Results analysis

The video tape of test was acquired during a winter day, in order to have a clear scenario with only few trouble elements; furthermore, the sunset moment was chosen to test the algorithm for high presence of light reflection on the sea waves.

A calibrated Nikon D800 camera with a 35 mm lens was used for the photogrammetric survey. All the acquisitions are composed by a dataset of at least 12 convergent images for each trial. The mean precision of the overall root mean square points for all acquisitions is 0.071 mm, that implies an accuracy on the angle computation less than 0.05 degrees. The results provided by this method is taken as reference, due to the high accuracy achieved.

The INS sensors are MEMS-based, therefore their performance degrade continuously and their errors can become very large (several degrees) in few seconds. The ZUPT approach helps to limit the aforesaid drift, bringing the angle precisions to less than 0.5 degrees.

In the Horizon approach every frame recorded (25 per second) was processed with the algorithm above described. The accuracy obtained is less than 0.5 degrees and the results (figures 6 and 7) are quite stable.

In terms of accuracy the INS and Visual solutions are comparable, while the precision the inertial one is slightly better and is more stable from trial to trial.

		Trial 01	
	[deg]	Roll	Pitch
Photogrammetry		-13.79	-5.04
INS	Mean	-13.74	-4.81
	SD	0.31	0.38
	Accuracy	**0.05**	**0.23**
Visual Horizon	Mean	-13.90	-5.35
	SD	0.48	0.81
	Accuracy	**0.11**	**0.31**
	% outlier	1.19	

Table 1- Statistical Parameters of trial 1

		Trial 02	
	[deg]	Roll	Pitch
Photogrammetry		20.47	5.61
INS	Mean	19.35	5.53
	SD	0.29	0.21
	Accuracy	**-1.12**	**0.08**
Visual Horizon	Mean	20.24	6.07
	SD	1.21	1.21
	Accuracy	**0.23**	**0.46**
	% outlier	4.49	

Table 2- Statistical Parameters of trial 2

		Trial 03	
	[deg]	Roll	Pitch
Photogrammetry		-21.05	-750
INS	Mean	-19.35	-6.93
	SD	0.30	0.35
	Accuracy	**1.70**	**0.57**
Visual Horizon	Mean	-20.99	-7.25
	SD	0.54	2.12
	Accuracy	**0.06**	**0.25**
	% outlier	3.23	

Table 3- Statistical Parameters of trial 1

The photogrammetric survey results, together with those ones coming from the other methodologies are reported, for three trials, in table 1-3.

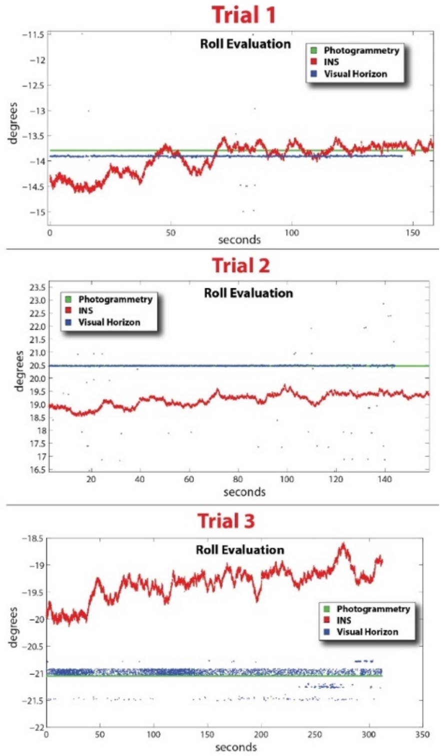

Fig. 6. Comparison of Roll angles evaluated with Photogrammetry, INS and Visual Horizon

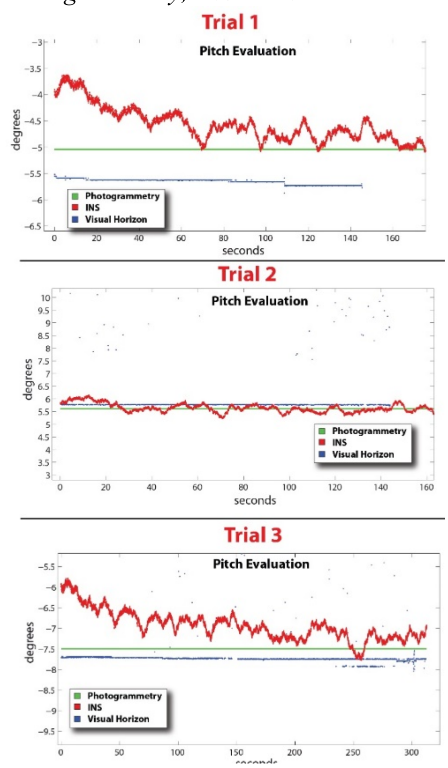

Fig. 7. Comparison of Pitch angles evaluated with Photogrammetry, INS and Visual Horizon

The high dispersion of roll results in the visual horizon of the third trial is due to the above-mentioned condition of light reflections of the sun close to its sunset. It is also evident that the difference in the mean results between photogrammetry and INS increase with the growing of the roll angle.

V. CONCLUSION AND FUTURE DEVELOPMENT

This work presents a new methodology to compute in quasi-real-time the attitude of the camera. Specifically, the roll and pitch angles are computed starting from the relative position between two detected horizons (one of them considered as reference). The proposed procedure is basically composed by two fundamental steps: automatic detection of the horizon line and computation of roll and pitch angles. The performed investigation provided competitive results compared to others methods, even with consistent light reflections of the sun on the sea surface. A custom filter developed ad-hoc on the edge map has improved the horizon detection in critical scenarios. Furthermore, the image processing was developed in low-level programming languages, allowing to achieve the quasi real-time computation.

The robustness showed by the proposed methodology during the inspections suggests an integration with INS measurements through a Kalman filter. Future development will concern: dynamic inspection in order to confirm the results of the static test fields analysis carried out; the use of infrared-camera in order to obtain measurements during the night and in low visibility condition.

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