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Identification of a scaled-model riser dynamics through a combined computer vision and adaptive Kalman filter approach

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ABSTRACT

Aiming at overcoming the difficulties derived from the traditional camera calibration methods to record the underwater environment of a towing tank where experiments of scaled-model risers are carried on, a computer vision method, combining traditional image processing algorithms and a self-calibration technique was implemented. This method was used to identify the coordinates of control-points viewed on a scaled-model riser submitted to a periodic force applied to its fairlead attachment point. To study the observed motion, the riser was represented as a pseudo-rigid body model (PRBM) and the hypotheses of compliant mechanisms theory were assumed in order to cope with its elastic behavior. The derived Lagrangian equations of motion were linearized and expressed as a state-space model in which the state variables include the generalized coordinates and the unknown generalized forces. The state-vector thus assembled is estimated through a Kalman Filter. The estimation procedure allows the determination of both the generalized forces and the tension along the cable, with statistically proven convergence.

1. Introduction

The non-intrusive characteristics of the image-based instrumentation necessary to implement motion analysis is an important advantage of this approach compared to the classical measurement methods based on the use of accelerometers and load cells. Successive advances in the area of computer vision, concerning video segmentation, object tracking and camera calibration, have also contributed to the application of image-based methods to the analysis of kinematics phenomena that are difficult to measure, like the human motion [1], or that occur in regions of difficult access, as the underwater environments [2].

Recently, this technique has been included in the palette of experimental methods of the oceanic and naval engineering center of São **P**aulo **I**nstitute of **T**echnology (IPT, Brazil), in order to improve the quality of the measurements required by the hydrodynamics tests in a towing tank with scaled-models of ships and oceanic structures like platforms and risers (long flexible ducts used by the petroleum industry to pump oil and natural gas to the platforms). Although these measurements have been successfully accomplished with the aid of a motion analysis tool, the camera calibration

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Nomenclature

PRBM	pseudo-rigid body model
θ_i	PRBM's angular displacements
$\dot{\theta}_i$	PRBM's angular velocities
$\ddot{\theta}_i$	PRBM's angular accelerations
m	PRBM's bar mass
K_i	PRBM's spring coefficients
K_θ	PRBM's standard spring coefficients
L	PRBM's bar lengths
γ	PRBM's largest bar length to actual bar length ratio
p	weight per length ratio
p_s	underwater weight per length ratio
E	modulus of elasticity
I	PRBM's bar section area inertia moment
T	kinetic energy
V	potential energy
L	Lagrangian
$F_{\theta i}$	generalized force at node i
F	traction force

algorithms [3] adopted by this software assume the use of calibration objects to previously measure the three-dimensional space according to a metrological procedure difficult to be done in an underwater environment.

To cope with the various constraints imposed by the measurement environment, several camera self-calibration methods have been proposed in the literature [4–7]. Since these methods are based on invariant geometrical properties of the projective space [8,9], they do not depend on the use of calibration artifacts and, consequently, give rise to a calibrated space that is not limited by the volume of those objects. Such characteristics are especially helpful in the approach of underwater experiments with scaled-model risers.

Although the dynamics of cables has been approached in the early literature of theoretical mechanics [10,11], the recent technological advances observed in the petroleum industry concerning subsea fields extraction has fostered the research of this subject. A thorough investigation about the static and dynamic behaviors of risers under two-dimensional configurations was performed by [12]. Using the theory of thin rods, it was shown that the effect of flexural rigidity is restricted to the regions close to the extremities of the riser; the dynamic model, on the other hand, was formulated as the solution of a perturbation problem around the equilibrium configuration. Both models – the static and the dynamic – were validated against experimental results. Using a finite element program, Campos [13] developed a computational non-linear model for a catenary riser, whose responses, concerning the dynamic bending moments near the touchdown point, are close to the ones derived from the application of previously proposed analytical models. Likewise, in [14], dynamical models through the finite element method representing the catenary riser by beam elements were generated. Firstly, a complete non-linear dynamical model was analyzed using a time-domain technique. Then, the non-linearities of the original model were removed and a frequency-domain technique was applied, giving rise to results that compared well with the previous ones.

Computer vision methods are not yet extensively adopted by the naval laboratories as a measurement tool; therefore, not so many papers have been reported concerning application of those techniques to identify riser kinematics. Bando [15] utilized a single video camera to register the motions of the bottom end of a flexible cable forced to move on a still water test channel through the action of an oscillation mechanism; application of image processing techniques to the successive frames permit to reconstruct the model kinematics and their principal frequencies are finally identified through the use of classical Fourier analysis. Aided by an image processing and computer graphics tool, researchers in [16] constructed a computer vision procedure whose temporal estimates of the scaled model riser configuration were very close to the ones generated by a set of accelerometers fixed to the model. Using classical image segmentation algorithms, in a work by [17], a computer vision procedure was implemented to identify the temporal geometrical variations of a catenary riser near the touchdown point; in his work, the direct linear transformation (DLT) was applied to map the Euclidean three-dimensional space to the projective two-dimensional spaces of the cameras. The DLT was also adopted by [18] to properly calibrate a video camera used to register the motion of small markers distributed on free-vibrating slender columns; moreover, the natural frequencies obtained through modal identification analysis showed excellent agreement with the results anticipated by the theoretical models of slender columns.

Inspection of underground water pipes has also benefited from the use of computer vision techniques for the sake of predictive maintenance, as reported in [19]. In this work, the authors employed a robotic platform on which a laser beam sensor, acting as a range measurement device, performed a two-fold task: first of all, upon scanning the inner surface of pipe, the location of the platform could be determined for positioning control purposes; on the other hand, the scanned profile of the inner pipe, once compared to the a priori known profile, was able to pinpoint anomalies on that surface. An important contribution of this work is the use of a linear Kalman filter to account for uncertainties both on process and on measurement models, which reduced the location error when compared to results obtained directly from the computer vision techniques. Nevertheless, the authors do not state clearly how the covariance matrices, specially the process noise matrix, were tuned. In a laboratory scenario, it does not represent a drawback, since it is always possible to previously scan the basis profile in order to compare with the results coming from processed images; however, in a field environment, one should assure the estimates match the actual profile with statistically proven confidence, which could have been done in this work.

In the present article we use the Lagrangian formalism to construct a simplified lumped dynamic model for a scaled-riser in catenary configuration. Then, the derived motion equations are validated against experimental data using a computer