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Reconstructing individual shape histories of fish otoliths: A new image-based tool for otolith growth analysis and modeling

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ABSTRACT

In this paper is presented a novel image processing tool for the extraction of geometric information in otolith images. It relies on the reconstruction of individual otolith shape histories from otolith images. Based on the proposed non-parametric level-set representation of otolith shape history, applications to the extraction of growth axes and ring structures in otolith images are first considered. A second category of applications concern the analysis of 2D otolith growth. The potential of the proposed framework is illustrated on real otolith images for various species (e.g., cod, pollock) and discussed with a particular emphasis on the genericity of the approach and on applications such as otolith shape analysis, multi-proxy otolith analysis, otolith modeling.

1. Introduction and problem statement

As they grow according to an accretionary process, fish otoliths can be viewed as a succession of three-dimensional concentric layers. The composition of these layers, in terms of physico-chemical characteristics, varies according to endogenous and exogenous factors (Panfili et al., 2002). The accretionary process generally involves a periodic rhythmicity, typically daily and/or seasonal, deposit, such that these biological structures depict concentric ring patterns, also called growth marks, in an observation plane going through the initial core . These characteristics provide the basis for exploiting these structures as biological archives to define environmental proxies (e.g., for instance to reconstruct temperature series) (Hoie et al., 2004), or to reconstruct individual life traits (e.g., individual age and growth information or migration paths) (Fablet et al., 2007). To further stress the key importance of these biological structures in marine ecology, it can be pointed out that well over one million fish (Campana and Thorrold, 2001) are analyzed each year to estimate age structures for fish stock assessment.

Following ongoing developments (Alvarez et al., 2008; Fablet, 2006; Fablet et al., 2007) aimed at information extraction and interpretation in fish otolith images, this paper addresses the extraction of geometric otolith characteristics and their application to otolith growth modelling and analysis. Though extensively studied and exploited (Campana and Casselman, 1993; de Pontual and Prouzet, 1988), the analysis of the shape of fish otoliths and other calcified structures has usually been restricted to the analysis of the outline of the otolith in a given observation plane, especially for stock and species discrimination. However, the presence of internal ring structures potentially provides the mean for back-tracking the evolution of the shape of the otolith from the core to the edge. Such information is of great interest for analyzing, modelling and extracting the main features of otolith growth. Recently, we developed a new computational tool aimed at reconstructing the sequence of the successive shapes associated with an accretionary growth process in a given observation plane containing the otolith core (Fablet et al., 2008b). We benefit from this representation of the otolith growth to develop new solutions for information extraction in otolith images. Experiments on real otolith images for various species for various species are reported, and, we investigate a quantitative analysis of the 2D otolith growth. The genericity of the approach is further discussed as well as its broad interest for applications to otolith shape analysis, multi-proxy otolith analysis and numerical otolith modelling.

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2. Materials and methods

2.1. Otolith material

In this study, the considered biological material is a set of images of whole otoliths or otolith sections associated with an interpretation of the internal growth structures in terms of age and growth pattern. Otolith sections have been prepared in the transverse plane. We focus on seasonal growth and thick sections are considered. The proposed methodological developments are evaluated for several species (namely, examples of cod (*Gadus morhua*), hake (*Merluccius merluccius*), plaice (*Pleuronectes platessa*), pollock (*Pollachius virens*), and whiting (*M* erlangus merlangus) are considered). These species are chosen for the panel of complexity levels they convey in terms of image contrast and ring structures. This choice is also aimed at demonstrating the improvements compared to previous work (Fablet, 2006; Guillaud et al., 2002; Palmer et al., 2005; Traodec et al., 2000) which was mainly limited to the analysis of whole plaice otoliths.

Otolith images have been acquired under a binocular using transmitted or reflected light depending on the species with a 1000×1000 digital camera.

2.2. Reconstruction of individual histories of 2D otolith shapes from images

The core of the proposed computational framework is the reconstruction of the evolution of the 2D otolith shape in a given observation plane from an image. With a view to modelling and representing the 2D otolith growth, we adopt a level-set setting of the accretionary growth process. It relies on the definition of a potential function U such that the 2D shape $\Gamma_t(U)$ of the otolith at time t is given by a level line of U, that is to say the set of points p for which the associated potential value $U(p)$ equals t:

$$\Gamma_t(U) = \{p \in \mathcal{R}^2 \ \text{ such that } \ U(p) = t\} \quad (1)$$

This level-set representation of the accretionary growth of fish otoliths is illustrated (Fig. 1). The potential function U is displayed as a 3D surface, and the successive level-lines of U, for potential values uniformly sampled, are visualized in the horizontal plane. By definition, potential function U is convex: as it can be considered that fish otoliths never resorb (Panfili et al., 2002), the shape at time t is included in the shape at any time t' posterior to t. This level-set setting is of great interest for several reasons:

- It intrinsically conforms to the requirements that the accretionary growth is normal to the shape and that the successive shapes are concentric.[1]
- It is a compact representation of a series of successive shapes, the whole series of shapes being represented by a single mathematical function U.
- It is generic as it accounts for elliptic-like shapes, such as whole plaice otoliths, as well as more complex non-convex examples such as hake or cod otolith sections.
- It is non-parametric. Contrary to the parametric approach proposed in (Alvarez et al., 2008), no assumption is made on the evolution of the shape, so that subsequent analysis is not biased by some parametric *a priori* which may not be fulfilled in practice.

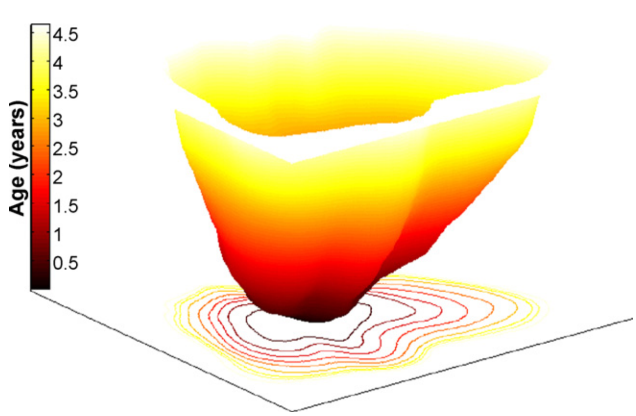

Fig. 1. Level-set representation of the accretionary growth of fish otoliths: each level-line of the increasing potential function represents the shape of the otolith at a given age.

Our goal is to fit the level-set model U to an otolith image in a given observation plane, such that the successive level-lines of U match the internal rings of the otolith. We further assume that we are provided with additional constraints, referred to as boundary conditions, at least the position of the nucleus of the otolith and the edge of the otolith which can be extracted automatically (Cao and Fablet, 2006). Additional internal rings may also be provided. Fitting model U is then viewed as its interpolation to the whole image domain given known boundary constraints. This interpolation is stated as the minimization of an energy criterion involving two different terms. The first term is a regularisation energy setting that the successive shapes $\Gamma_t(U)$ should be smooth. This term is computed as the sum of the perimeters of all the shapes $\{\Gamma_t(U)\}$. The second term relies on image-based features. Exploiting previous work on the estimation of local image orientations (Chessel et al., 2006), this term states that the normal to shape $\{\Gamma_t(U)\}$ at point p should be orthogonal to the local tangent to ring structures, referred to as the local orientation and denoted by $w(p)$. An example of an estimated map of local image orientations is reported for a pollock otolith section (Fig. 3). Formally, the considered energy criterion is given by:

$$E(U) = (1-\gamma)\int_{t\in[0,T]}\int_{p\in\Gamma_t(U)} 1 + \gamma\int_{t\in[0,T]}\int_{p\in\Gamma_t(U)} \cdot \left| \left\langle \frac{\nabla U(p)}{|\nabla U(p)|}, \omega(p) \right\rangle \right| \quad (2)$$

where γ is a weight setting the relative influence of the two terms, $\nabla U(p)/|\nabla U(p)|$ the orientation of shape $\Gamma_t(U)$ at point p and $\langle \nabla U(p)/|\nabla U(p)|, \omega(p)\rangle$ the scalar product evaluating whether the two orientations are orthogonal. We let the reader refer to (Fablet et al., 2008a, b) for details on the numerical implementation of the gradient-based minimization of criterion E. Cross-validation experiments carried out on synthetic examples have shown that values of γ in the range [0.4, 0.8] are optimal in terms of mean-square error (Fablet et al., 2008a). Though no theoretical evidence can validate this experimental statement, our experiments on a variety of otolith images show that setting γ to 0.6 is appropriate in practice and that results are stable if γ is set in the range [0.4,0.8]. This is corroborated by the numerous applications of variational techniques in computer vision (Sethian, 1999). Concerning the computational cost, the proposed scheme is implemented as a C code[2] under Linux and runs in about 1 min for a 1000×1000 image.

If the otolith growth pattern along a given growth axis is known, the estimated potential function U provides at any pixel p an age

[1] The term "concentric" should not be understood in a strict sense. We mean here that the shape at time t is included in all the shapes posterior to time t.

[2] All source codes, Matlab and C codes currently running under Linux, used in this study are available on request to ronan.fablet@telecom-bretagne.eu.