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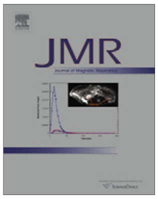

Determining object boundaries from MR images with sub-pixel resolution: Towards in-line inspection with a mobile tomograph

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ABSTRACT

This work evaluates the performance of edge-detection algorithms to determine the sample geometry with high spatial accuracy from low-resolution MR images. In particular, we show that by applying such numerical methods it is possible to reconstruct the internal and external contours of the object with a spatial precision that surpasses the nominal spatial resolution of the image by more than one order of magnitude. Special attention is paid to find the spatial resolution and signal-to-noise ratio required by the described numerical methodology to achieve a desired spatial accuracy. Finally, we discuss the potential application of this image processing approach for in-line quality control of extruded rubber materials, where micrometer spatial precision has to be achieved from images measured in short experimental times. The results presented here prove that the sensitivity of mobile MRI sensors is enough to achieve the spatial accuracy required to proof check the production of extruded rubber fittings in acceptable experimental times.

1. Introduction

Magnetic resonance imaging (MRI) is a powerful non-invasive technique routinely used for medical diagnostics. Compared to X-ray or ultrasound tomography, MRI offers an outstanding diversity of contrast in soft matter that can be applied to resolve tissues of similar density but different molecular structure, morphology, and even molecular mobility. The possibility to spatially resolve physical and chemical properties across the sample under study has spread the application of MRI into several areas of material science [1,2]. Although several industrial processes would considerably benefit from the implementation of MRI at the production site, the required equipment typically cannot be installed in a production area for technical and security reasons. Conventional MRI magnets use expensive and sophisticated superconducting coils to generate strong and homogeneous magnetic fields. In general they are bulky units that require large footprint to assure sufficient distance to personnel and the magnetic material in the surrounding. Moreover, the fragility of the superconducting wires cooled to liquid helium temperature limits the mobility of the tomograph and its use at different stages of a production line. Finally, the operation of the magnet requires permanent maintenance with cryogenic coolants which further complicates the use of such magnets on the factory floor.

Most of these limitations can be overcome by discarding superconducting magnets in favor of portable magnet arrays built from permanent magnetic materials instead of superconducting coils. These magnets have been largely avoided in the past due to their poor performance in terms of field strength and homogeneity, but thanks to a novel shimming strategy, the large magnetic field inhomogeneities inherent to permanent magnetic materials can be efficiently corrected [3]. This shimming concept uses a set of movable magnets included in the magnet array by which spherical harmonic correction terms to the magnetic field can be generated. After mapping the magnetic field in the volume of interest, the inhomogeneities are decomposed in the basis set of the movable magnets and the required displacement of the shim blocks are calculated. An iterative application of this procedure leads to homogeneity improvements up to values very close to the optimal performance predicted by numerical simulations with ideal magnet blocks. By applying this approach we have recently demonstrated that mobile magnets can be used to measure magnetic resonance images free of distortions caused by background gradients [4,5].

Although achieving these experimental conditions with portable magnets opens the door to implementing MRI at the production site, at the time of considering these setups for in-line control, the fact that the total time available for the measurement

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is limited, considerably affects the quality of the images [6,7]. This problem is particularly severe for samples with short relaxation times T_2, where slow imaging methods sampling the k-space line-by-line must be used. Under these conditions it becomes very challenging to achieve a nominal spatial resolution comparable to object size deviations tolerated by quality standards. At this point, the use of edge-detection algorithms developed in the imaging processing area appears to be the solution to reconstruct the geometry of the sample with an accuracy better than the nominal resolution [8–10]. In this work we investigate the performance of such algorithms to determine the geometrical structure of the samples with high spatial accuracy from images measured with modest spatial resolution in a mobile MRI system. In particular, we show that from images with a nominal spatial resolution of 1 mm^2 this methodology can extract the cross section of the sample with an accuracy of some tens of a micrometer. Since the achievable sub-pixel resolution is determined by the signal-to-noise ratio in the image, for these we used studies a tomograph based on a recently optimized compact magnet geometry [5]. It generates about the highest field strength achievable with a magnet of such dimensions, maximizing the sensitivity of the sensor.

Besides setting the limits and conditions required for the implementation of sub-pixel algorithms, the experimental results presented in this work demonstrate that mobile MRI is at the stage to be used for quality control in-line at real time. The described methodology is applied to MR images of extruded polymer materials. Rubber fittings, for example, are produced by continuous extrusion of uncured rubber through a die that defines its shape. In general, multiple rubber mixtures are co-extruded and vulcanized to meet specific properties and mechanical stability, making such fittings suitable for their use in the building and automotive industry. Knowledge about the material properties, surface quality, and profile dimensions, is essential for quality control [11–14]. Depending on the type of contrast, MRI images could provide information about filler distribution, specific gravity, shore hardness, and cross-link density, which nowadays are typically tested off-line by random sampling and manual inspection [12,14]. We demonstrate that for this type of industrial process, edge-detection algorithms can be applied to obtain the inner and outer contours of such profiles with the required spatial accuracy from images measured with a mobile MRI system. It is important to notice that even though optical methods have become commercially available for in-line quality control, they are limited to monitor only the external dimensions of the profile (optical methods are used to inspect the inner shape off-line after profiles are cut [15]).

2. Rubber extrusion

Fig. 1a shows a scheme of a rubber extrusion line used to continuously produce rubber fittings. In the extrusion process, uncured rubber is continuously transported by a screw rotation in a cylinder from a feed port to the die of the extruder. At the extrusion die, the profile is formed out to its final shape. Usually, it is also possible to find a co-extrusion process where multiple layers or parts of different material are simultaneously extruded. By applying this technique, or by integrating inlays made of other materials, e.g. thermoplastic polymers, textiles or metals, the physical properties of the rubber profile can be tailored to meet the technical demands. After its shaping, the profiles are vulcanized in the curing unit of the extrusion line. Here, the material develops elastic properties and becomes geometrically stable. Further processing steps, e.g. flocking, can be applied and the profiles are packaged. The length of typical extrusion lines exceeds 100 m.

Since rubber is a viscoelastic material, when it leaves the extrusion die effects like swelling, draw down, cooling and relaxation start affecting the actual size and shape of the extrudate. These effects are not stationary and non-linear. Especially for rubber mixtures, with up to more than 30 ingredients, they are still not yet fully understood [11,12,16]. Thus, the geometry of an extruded profile is not only depending on the shape of the extrusion die. It is influenced by several interdependent process parameters, such as the temperature distribution in the extruder, its screw speed, the take-off speed of the extrusion line, the viscosity of the samples, etc. Therefore, starting-up an extrusion process for a new product requires adjustments of the mentioned variables. This is a time consuming procedure that requires feedback quantifying the product geometry and leads to many meters of start-up scrap inhibiting a wrong geometry, which are produced while the user adapts the process parameters [11]. Moreover, once the parameters are adjusted, in a running extrusion process disturbances due to several reasons are likely to occur [12] leading to a lower

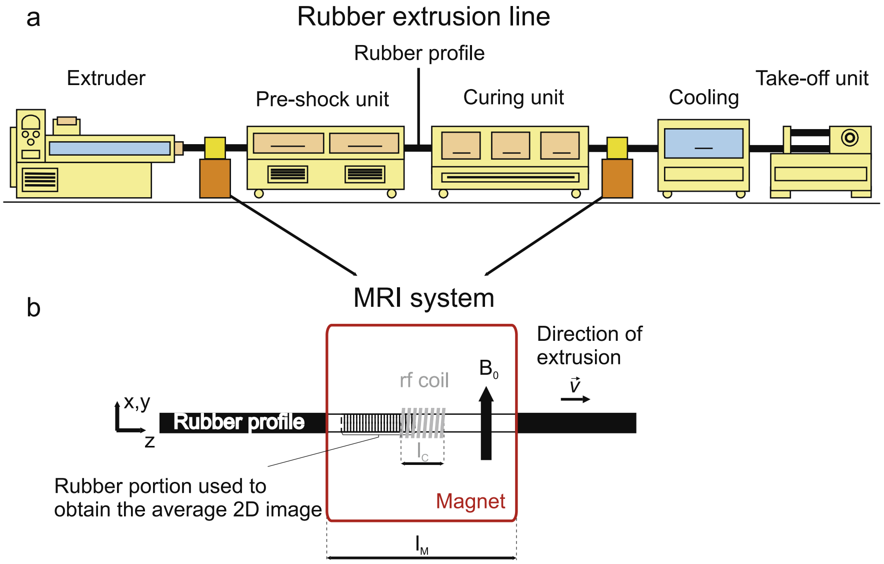

Fig. 1. (a) General scheme of an extrusion line showing the potential places where the MRI monitoring system could be mounted. (b) Scheme of the MRI system where the extrusion direction z and the transverse xy-plane are shown. By using a Halbach magnet, the direction of the magnetic field, transverse to the magnet axis, allows the use of a solenoid rf coil which is also schematized.