Experimental validation of a digital twin approach to image registration

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1. Introduction

The non-destructive nature of X-ray tomography renders the technique well-suited to study dynamic processes. Image registration plays a central role in the analysis of these 4D datasets. Conventional global registration algorithms enable correcting for potential sample drift over time, as well as for homogeneous geometrical changes of the sample such as volumetric expansion or shear [1]. More advanced algorithms exist as well to match more complex deformation patterns [2]. While these algorithms have been successfully applied in a wide range of applications, they are unaware of physical limitations, such as material properties or conservation laws. In a previous study [3], we introduced a novel physics-based registration method that enables accounting for these constraints through the use of a digital twin. The current study aims at experimentally validating this approach.

2. Materials and Methods

We focus on a bimetallic strip, composed of two metals (Fe and Cu) having different thermal expansion coefficients. The bimetallic strip is immersed in a PMMA vessel filled with distilled water (Figure 1). The water temperature is controlled by a submerged silicone tube connected to a thermostatic bath. The imposed temperature profile consists of plateaus at 25°C, 60°C and 25°C, with linear ramps between them. A thermocouple tracks the true water temperature that differs from the imposed setpoint. The bimetallic strip curves in response to variations of the water temperature. This phenomenon is captured by time-lapse x-ray radiography, performed in a Tescan UniTOM XL. The first radiography serves for the construction of the digital twin. Image segmentation enables separating the water from the bimetallic compound, and the latter is split in two along its length. A finite element mesh is constructed, theoretical material properties are assigned to each phase and appropriate boundary conditions are imposed. The space occupied by the silicon tube is replaced by an unknown heat source. Thermoelastic finite element calculations are performed and the error between the digital twin and the measured radiographies is iteratively minimized by adjusting the unknown heat source. Upon convergence, the calculated temperatures and heat source over time are compared to the measured data.

3. Results and discussion

While comparing the measured temperature evolution at the location of the thermocouple with the calculated temperature at that point is straightforward, the experiment does not directly provide a value to compare the heat source with. We constructed an analytical model of the entire test setup. Using theoretical material properties and the basic equations of energy conservation, the model quantitatively reproduces the measured temperatures in the vessel. The model enables extracting the heat exchange between the silicon tube and the fluid in the vessel and comparing it with the calculated heat source from the digital twin. A good match was obtained in both temperature and heat source, confirming the validity of the proposed physics-based registration approach.

4. Conclusion

We introduced a novel physics-constrained registration method that respects conservation laws and material properties, as well as initial and boundary conditions, through the use of a digital twin. The experimental validation for the bimetallic strip example demonstrated the predictive capabilities of the registration approach, showing good consistency between simulation and experimental results, and paving the way for future applications in areas where complex and evolving deformation fields are encountered.

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6. References

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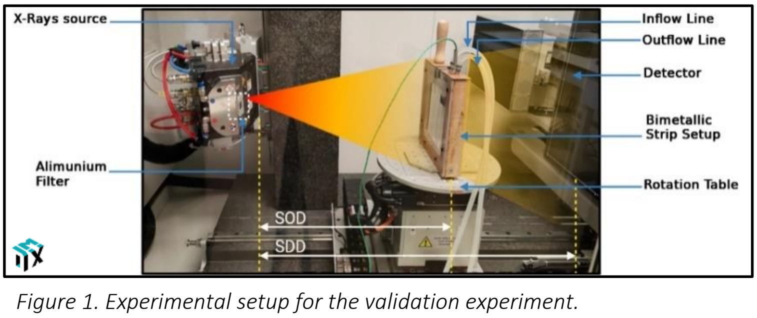

Figure 1. Experimental setup for the validation experiment.