An Autonomous Robotized Cell for Polymer Foaming

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Abstract

We illustrate challenges and preliminary results of the FoAIming project (artificial intelligence and robotics in polymer foaming) that aims at exploiting robotics and artificial intelligence (AI) methods in the fields of materials science/engineering and chemical engineering to improve foaming processes and to achieve new foams with better properties. In this project, we propose the design and development of a robotic system for the management of foaming experiments that allows: i) the autonomous/interactive conduct of the experiments, ii) the measurement of the properties of the foams, and iii) the analysis, modeling, and tuning of the foaming process. In the proposed system, a robot manipulator is used to handle polymeric samples and products. The robotic platform is managed by an autonomous/interactive control system responsible for experiment planning, execution, supervision, and evaluation. The introduction of AI techniques is expected to contribute to the understanding of the complex phenomena associated with the foaming of polymers. In this perspective, machine learning methods are expected to support effective experiment setting and data interpretation. From an infrastructural point of view, the development of a robotic platform that permits remote and autonomous experiment execution can lead to interesting implications in terms of safety, innovative teaching, and sharing of information, materials, and equipment with research centers and companies.

Keywords

AI and Robotics for Self-Driving Laboratories, Autonomous Robotic Cell, Polymer Foaming

1. Introduction

Polymeric foams are of great interest for countless applications in both the technological-scientific and the industrial field (e.g., sport equipment, helmets, packaging, etc.). The diffusion of these materials is due to their versatility. Indeed, by varying the density and morphology of the bubbles, as well as the chemical nature of the polymeric matrix, it is possible to modulate their properties, such as their rigidity, resistance, light and thermal insulation, acoustical absorption, or impact protection. Every day, new foam-based products are put on the market, providing

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innovation in terms of the polymeric matrix and/or the properties of the foam. Recently, the importance of the environmental impact of foams has emerged, thus future efforts must focus on the development of new sustainable materials and the definition of the related process parameters. The process that gives a polymer a foamy structure is called 'foaming'. Among the foaming processes, the most widely used and industrially important is that of gas foaming, through which a gaseous blowing agent (e.g., carbon dioxide) is first solubilized into the polymer at a high pressure and, subsequently, due to a sudden release of pressure, it is induced to form bubbles in the polymeric matrix.

Over the past three decades, many authors have thoroughly investigated the foaming of a large number of polymers (e.g., polypropylene, polystyrene, and polycarbonate) with benign environmental gases, such as carbon dioxide or nitrogen. Some studies have been carried out on the production of foams from biodegradable polymeric matrices, such as polycaprolactone and polylactic acid, which are of great economic interest. In particular, detailed analyses of the foaming processes have been performed in terms of the effects of the process parameters on the final foam structure [1].

In this perspective, the FoAIming project (artificial intelligence and robotics in polymer foaming) aims at introducing robotic systems and artificial intelligence (AI) methods in materials science/engineering and chemical engineering to design and develop a robotic platform and a control/supervision system for the production, analysis, modeling, and optimization of polymeric foams. For this purpose, a robotic cell is proposed in which a small collaborative robotic manipulator is able to take samples, place them into a foaming vessel, extract the foams and analyze them by means of specific measurement tools.

The deployment of robotics and AI methods to flexibly and autonomously manage self-driving experiments in material research laboratories is considered very promising and appealing. For example, a very recent and influential work [2] describes the use of a mobile robot equipped with a manipulator for the management of the conduction of a chemical reaction, with AI intervention for the identification of the optimal operating conditions, which is justified by the number of available catalysts and of experiments to be carried out (about 1000 in 10 days). Other interesting approaches can be found in [3, 4]. Remotely-guided experiments have also been proposed by Cloud Chemistry projects [5], yet, in this case, the experimental activities were carried out by operators in the laboratory, while autonomous robotic platforms were outlined as possible future scenarios. Inspired by this work, a simple robotic platform to remotely perform a plastic foaming experiment was proposed by [6]. In this regard, the FoAIming project aims at extending this approach to develop an autonomous/interactive robotic platform for flexible and robust experiment management.

2. Architectural Overview

In this work, our goal is to design a robotized cell that can perform and evaluate foaming tasks autonomously. To this end, we conceived a ROS-based architecture (see Figure 1) in which the low-level controllers of the hardware components, i.e., the sensors, the robot, and the foaming device, as well as the AI-based predictor, are connected to a central executive system. A new foaming task can be started in two ways: on the one hand, remote users can propose specific

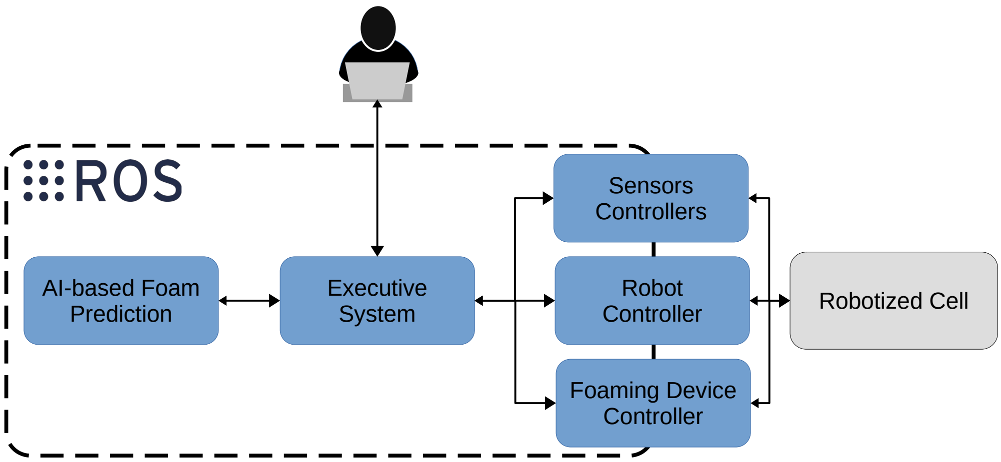

Figure 1: Overall schematic representation of the system. The architecture includes 5 main software components (blue blocks) controlling the execution of the robotized cell (gray block). Remote users can interact with the executive system.

experiments to be scheduled and executed by the system; on the other hand, the AI-based prediction module autonomously suggests a new experiment to be performed in order to update the estimated model of the foaming process. The role of the executive system is to maintain a structured and parametric representation of the foaming tasks, to schedule the activities that are commanded by users or spawned by the prediction module, and to supervise the controllers during the execution.

2.1. Robotized Foaming Cell

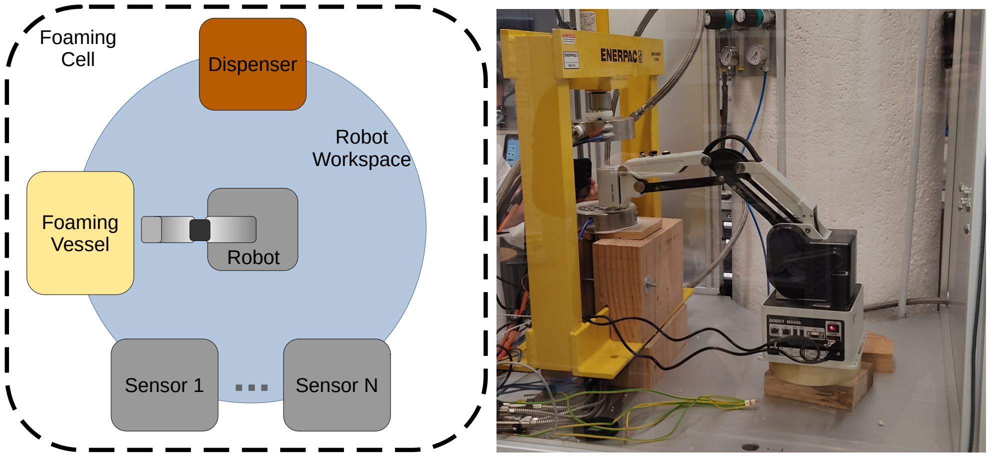

Figure 2: Schematic top view of the disposition of the devices into the foaming cell (left) and side view of the manipulator entering the foaming vessel (right).

The design of the proposed foaming cell is depicted in Figure 2. The cell is composed of four main elements: a manipulating robot, a dispenser of polymers, a foaming vessel, and a set of sensors for the measurement of the foamed polymers. The cell configuration is similar to that proposed in [7]: the robotic arm is placed in the middle of the cell to maximize its manipulability, whereas the other instruments (vessel, sensors, polymer dispenser, etc.) are deployed on the sides (see Figure 2, left). The robot is a DOBOT MG400 lightweight 4-axis collaborative manipulator with 750 g of payload, a workspace of 440 mm, and a nominal repeatability of ±0.05 mm. In this scenario, we also provide the robot with a sucking terminal device used to pick, carry, and place polymeric samples during the experiments. The foaming device, a pressurized vessel with pressure and temperature control [8, 9], is designed to be compatible with the capabilities of the robot and autonomous control. It is positioned frontally with respect to the central robot, and the closure mechanism is based on a hydraulic press, leaving enough space for the robot to move between the plates and insert the polymeric samples into specific slots at the lower end of the device (see Figure 2, right). The evaluation of the outcomes of a foaming test is performed by measuring the density and morphology of the produced foams through the 3D scanners and optical systems placed on the left side of the robot.

2.2. Supervision and Control

The activities of the robotic system are managed by an executive system [10, 11, 12] that allows a flexible configuration of the experiments, their execution, the intervention by a remote operator, and the detection of any errors and anomalies during execution. The deployed executive system also enables a local operator to physically interact with the collaborative robot to teach new tasks [13], but this feature is currently not exploited. The monitoring of the correct execution of the experiments is supported by a camera-based vision system to track the stages of robotic operations. In the current version of the platform, the successful execution of pick-and-place operations is monitored by suitably checking the correct placement of the polymers in the slots; if the operation fails, mispositioned polymers should be physically removed from the foaming device. The definition of a web interface is also envisaged to allow the remote user to monitor the evolution of the experiments and possibly intervene by interrupting the operations or repeating them.

2.3. Experiment Execution: Process Regulation and Analysis

Different methodologies are considered for experiment design and interpretation. We are currently defining methods to assess the quality of the foaming process given the operating parameters and to manage the device settings accordingly. In particular, to evaluate the quality of the foaming process, it is necessary to measure the density of the produced foams, as well as their morphology, in terms of number and dimensional distribution of the bubbles, and their primary mechanical characteristics (elastic modulus and strength). As a starting point, we estimate the density of a foam from its volume and weight. The stiffness and strength of the foam can also be measured using a load cell to be mounted on the robotic arm. As for morphology measurements, we plan to deploy optical systems and image recognition routines able to measure the degree of segregation of brightness and/or color and to estimate the morphology of the sample. The selected features will be used to define a suitable fitness function, enabling us to explore the best settings of the foaming process given a polymer type and a target foam. Notice that three main process variables affect the characteristics of the produced foam, namely, its density and cellular morphology: 1) the foaming temperature, 2) the blowing agent concentration, and 3) the pressure release rate.

For the exploration and selection of process parameters, stochastic optimization methods (e.g., adaptive simulated annealing, stochastic gradient descent, etc.) are considered, as well as multiarmed bandit approaches, to online regulate the trials balancing exploration and exploitation. The effectiveness of the proposed techniques will then be validated with the extracted data set and compared with the process models provided in the literature.

3. Conclusions

We presented advancements and challenges of the FoAIming project, which aims at the design and development of a robotic autonomous/interactive platform for the study of polymer foaming. The deployment of AI and robotics methods for the investigation and interpretation of the phenomena involved in the foaming of polymers is a novelty in the field of materials science and engineering. Polymer foaming represents an interesting and original domain for self-driving laboratories integrating experiment planning, autonomous adaptive execution, and machine learning. In particular, since different foam morphologies (e.g., small *vs.* large or monodisperse *vs.* polydisperse bubbles) will be obtained as a result of the variation of the process parameters, e.g., the pressure and the temperature, the images of such foam samples can be labelled by human experts and used to train a neural network with a twofold purpose: on the one hand, the network will be able to automatically classify the morphology of foam samples; on the other hand, a prediction of foam morphology as a function of the process parameter values will be achieved. In this direction, the proposed project aims at developing an initial technological-scientific platform to be extended to flexibly support increasingly diverse and complex experiments.

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