Model-based and learning approaches to cloth manipulation by robots

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Abstract. Manipulating textile objects in a versatile way remains a challenging problem in robotics, triggered by applications in assistive and industrial domains. The vast number of degrees of freedom involved in deformations undermines the effectiveness of the modelling, planning and control methods available for rigid objects. Within the CLOTHILDE project (https://clothilde.iri.upc.edu/), we have combined geometrical and physical modelling to represent cloth states with reinforcement learning and model-predictive control to endow robots with dynamic manipulation skills. Regarding the former, we defined a taxonomy of grasps and characterized macro-states of textiles by encoding task-relevant cloth-configuration changes, so as to enable planning in the resulting state-graph to accomplish a task. Dynamic cloth manipulation has been attained through learning by demonstration and reinforcement learning, and then applying model-based control by modelling cloth dynamics as that of an inextensible surface. Some robot prototypes equipped with these skills will be shown in the talk, highlighting the design of grippers with specific cloth-handling functions, and the use of virtual reality for collecting data in learning approaches. The work of a highly interdisciplinary team is acknowledged, including mathematicians, computer scientists, mechanical, industrial, telecommunication, and software engineers, as well as a philosopher dealing with the ethical deployment of assistive robots.

Keywords: Robotic manipulation, Deformable objects, Robot learning.

1 Introduction

Textile items pervade human environments, and automating their manipulation would have an important impact on society, in sectors ranging from healthcare to the clothing industry. However, while the robotic handling of rigid objects in industrial settings can be considered reasonably solved, the manipulation of deformable materials in a versatile way remains an open research problem. The difficulty lies in the huge jump from the 6D pose of rigid objects to the potentially infinite-dimensional deformation spaces, which prevents the extension of the techniques developed for rigid objects and calls for innovative approaches to perception, planning, learning and manipulation. In what follows, some results of the project *CLOTHILDE – CLOTH manIpulation Learning from Demonstrations* (ERC Advanced Grant 741930) as regards to cloth state representation, data-driven learning, and model-predictive control for robotic manipulation will be presented, together with some robot prototypes implementing them for cloth manipulation.

It is worth distinguishing between quasi-static and dynamic manipulation of textiles, as each has particular demands that require to be addressed with quite different methods. For example, to fold clothes lying on a table using a bimanual robot can be tackled as a pick-and-place task, which can be planned as a sequence of subgoal states to be reached on the way. Under some constraints, the trajectories followed and the cloth deformation along them do not matter and only the subgoal states are relevant. Contrarily, when folding clothes in the air or unimanually, not just the path followed, but also the velocities and accelerations become crucial. These two types of manipulation will be addressed in the following two sections.

2 Representing cloth states and grasps for quasi-static manipulation planning

2.1 Topological characterization of cloth macro-states

We like to characterize sets of cloth states, called macro-states, that permit the same type of manipulations, i.e., have similar affordances. Two approaches have been developed: one relies on the cell complex decomposition of the C–space of some distinctive points on the textile [1] and the other on the matrix of the Gaussian Linking Integral derivative (dGLI) of pairs of segments in the cloth border [2] (see Fig. 1). The dGLI representation has been used to semantically label sequences of human manipulations using virtual reality together with a cloth simulator [3].

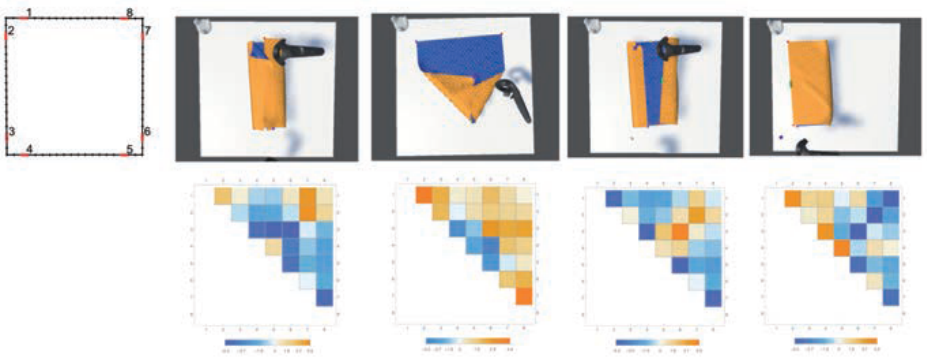

Fig. 1. Characterization of the states of a cloth using the dGLI matrix [2].

2.2 A taxonomy of grasps and manipulation primitives

To plan a cloth manipulation task like folding, we need to represent both cloth states and transitions between such states, namely grasps and motions. For the latter, we devised a taxonomy of grasps and manipulation primitives [4], which, together with the mentioned labelling of cloth states permit generating graphs of possible manipulation sequences on which planning can rely. Moreover, the taxonomy has proven very handy to define benchmarks and to design versatile grippers specific for cloth manipulation.

3 Modelling and learning for dynamic cloth manipulation

When the task requires handling dynamics to be successfully accomplished, we advocate for applying learning algorithms, not in an end-to-end fashion, but rather in combination with as much physical modelling as possible.

3.1 Modelling textiles as inextensible surfaces

A physically-accurate, analytical model of textiles, as inextensible but highly deformable surfaces, has been developed [5], especially oriented to cloth manipulation by robots. Friction and collision reaction are integrated in the same way as inextensibility, as constraints in a system of equations of motion [6]. Discretizing these equations naturally leads to a sequence of quadratic problems with equality and inequality constraints. The accuracy and low computational cost are crucial for sim-to-real transfer and for viable control of cloth dynamic manipulation.

3.2 Reinforcement learning and model-predictive control for cloth handling

An approach to teach dynamic manipulation skills to a robot, which consists of initialized through learning from demonstration, followed by refinement using reinforcement learning has been fully developed [7] (see Fig. 2), some refinements include symmetry exploitation, incorporating Gaussian process dynamical models [8], and coupling with variable impedance control to learn force profiles. Moreover, the model of textiles in Section 3.1 is being used within a model-predictive control approach to perform a target cloth dynamic manipulation [9], and holds great promise to bootstrap learning approaches through simulation and surmount the sim-to-real gap.

Fig. 2. Experimental scenario for teaching a bimanual robot to fold clothing, through an initial demonstration (left image) followed by autonomous reinforcement learning (right image) [7].

4 Concluding remarks and further research

Several authorized voices within the robotics community are currently advocating for the need to combine physical modelling with data-driven approaches to come up with efficient, reliable and explainable robotized solutions to accomplish a wide range of

tasks in human-centred environments and beyond. In this way, knowledge of the physical system allows for a compact and low-consumption model, complemented with an easy-to-apply procedure to reduce the sim-to-real gap due to the remaining uncertainty. In robotized cloth manipulation, we are pursuing this strategy in two follow-up projects of CLOTHILDE: the Momentum project (https://www.iri.upc.edu/project/show/339), aimed at turning the modelling of textiles described in Section 3.1 into an enhanced simulator of garments specifically for robotics, and the EU project SoftEnable (https://www.iri.upc.edu/project/show/295), to help workers in the manipulation of soft laminar materials in healthcare and food handling applications. In many of these developments, and the last project in particular, the ethics questions raised by human-robot interaction in the workplace, assistive and social environments, need to be taken into account, thus our interdisciplinary group addresses these issues, both as a research endeavour [10] and in teaching university courses in technical degrees [11].

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