ARTICLE IN PRESS

JID: MECH [m5G;November 22, 2016;14:21]

Mechatronics 000 (2016) 1–16

Contents lists available at ScienceDirect

Mechatronics

journal homepage: www.elsevier.com/locate/mechatronics

Force-based cooperative handling and lay-up of deformable materials: Mechatronic design, modeling, and control of a demonstrator

Stefan Flixeder[a,*], Tobias Glück[b], Andreas Kugi[a]

[a] Automation and Control Institute, TU Wien, Gußhausstraße 27-29/E376, 1040 Vienna, Austria
[b] Complex Dynamical Systems, Austrian Institute of Technology, Donau-City-Strasse 1, 1220 Vienna, Austria

ARTICLE INFO

Article history:
Received 6 June 2016
Revised 17 August 2016
Accepted 2 October 2016
Available online xxx

Keywords:
Cooperative handling
Manufacturing
Modeling and design
Compliance control

ABSTRACT

This work presents a cooperative, force-based handling approach for the lay-up of highly deformable materials on a mold, a scenario, e. g., encountered during the manufacturing of fiber reinforced plastics. A two-dimensional preforming demonstrator is designed which reflects the basic functionality of the process under consideration. Suitable mathematical models of the demonstrator and the deformable material provide a basis for the controller design and a force-based motion planning framework for the lay-up process. The framework proves to be most flexible as it does not rely on preplanned position trajectories but calculates the movements of all manipulators on-line and can promptly react to external disturbances. Experimental results on the demonstrator underline the feasibility and performance of the presented approach for the lay-up of a deformable fabric on a double-curvature mold.

1. Introduction

Deformable materials like textiles, leather, and adhesive foils are used in many industries [1]. The handling of these materials, however, is still mostly done manually and is therefore labor intensive and time consuming [2]. The same applies to the manufacturing of fiber reinforced plastics (FRP) made out of technical textiles based on carbon or glass. Key markets of FRP components, e. g., aviation and automotive industry, demand high accuracy, reproducibility, and short cycle times and thus work as a driver for the automation of the underlying production processes. The demands on reproducibility makes automation also important for low volume production [3], which requires utmost flexibility due to high parts variance.

1.1. Scenario

In contrast to conventional FRP manufacturing techniques based on preimpregnated composite materials (pre-pregs), the injection method shows potential for a fully automated production line of composite materials [3]. Fig. 1 depicts the main steps of the injection method, i. e., cutting of the dry fiber textiles, manufacturing of the cuttings to preforms, and the subsequent infiltration of the preforms with resin and curing under specific temperature and pressure.

A key-step of the injection method is the manufacturing of the preforms. The task is to pick up dry, deformable fabrics of different sizes and types from a cutting table (or a storage) and subsequently transfer and place them with a specific position and orientation on a mold [4]. Thereby, a multi-layer fabric is built up. The placement of the layers on the mold is often also referred to as lay-up or draping (see Fig. 1c). The preforming process has proven to be one of the most complex production steps to be automated and only a few prototype solutions are available to this day.

1.2. Challenges and state-of-the-art solutions

A major challenge in preforming is the grasping of the dry fabrics [5,6]. The high permeability to air and the unstable textile structure triggered several innovations in gripping technology, see, e. g., [7,8]. Furthermore, the geometric properties of the semi-finished goods, such as large scale and different sizes, in combination with the low-bending stiffness gave rise to the development of tailored handling devices. An example of such a modular device is presented in [9]. The end-effector is particularly designed for the clearing process of the cutter and consists of a perforated plate, where each opening can be actuated separately.

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[*] Corresponding author.

E-mail addresses: flixeder@acin.tuwien.ac.at (S. Flixeder), Tobias.Glueck@ait.ac.at (T. Glück), kugi@acin.tuwien.ac.at (A. Kugi).

http://dx.doi.org/10.1016/j.mechatronics.2016.10.003
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Please cite this article as: S. Flixeder et al., Force-based cooperative handling and lay-up of deformable materials: Mechatronic design, modeling, and control of a demonstrator, Mechatronics (2016), http://dx.doi.org/10.1016/j.mechatronics.2016.10.003

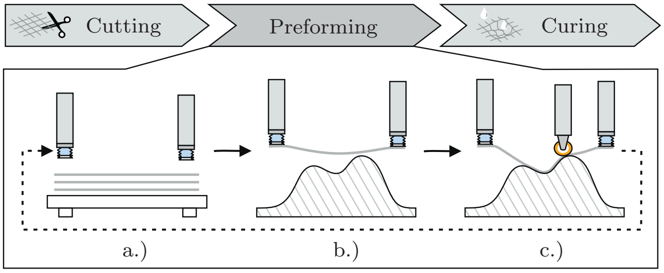

Fig. 1. Schematic of the injection method and the preforming process: a.) Pick-up from cutter/storage, b.) Transfer to mold c.) Lay-up on mold.

In order to automatically lay-up textiles on a mold, various robotic end-effectors have been developed recently. In [10], several grasping elements are mounted on a parallelogram structure which allows for an uniaxial adaptation of the end-effector shape. A deformable tube-shaped end-effector is presented in [11]. Gripping and releasing of the fabrics is realized by a rolling motion. A recent approach presented in [12] is based on the jamming of granular material. Depending on the airflow through the granulate, the developed end-effector may be used as large-area (foam) gripper, drape tool, or form-closure gripper. Apparently, many automation solutions focus on the design and construction of highly-sophisticated, special-purpose end-effectors. This approach exhibits limited flexibility and becomes inefficient for large-scale materials and complex molds.

Generally, the tools used for the manual lay-up are very simple [13]. Since many steps of the lay-up process are not structured and repeatable, it is important to use tools most flexible. With this in mind, the concept of this work is not to develop another special-purpose handling device, but rather focus on the cooperative use of off-the-shelf automation equipment to solve the challenges of the preforming process.

Recently, a number of related approaches have been reported in literature, see, e. g., [14–16]. In [15] a conceptional design of a hyper-flexible handling cell is proposed, however, the work lacks implementation details. The multi-functional cell presented in [16] consists of two industrial robots mounted on gantries. The handling and lay-up of a prepreg sheet is based on preplanned position trajectories. Moreover, both approaches only consider rather simple (flat, low curvature, single curved) molds. An early work by [17] highlights that in order to lay-up a fabric on a double curved mold, an additional consolidation tool is required (see Fig. 1c.). Otherwise the fabric may buckle or curl up due the local minima of the mold shape. The work [18] demonstrates that the application of a single normal force alone is sufficient to drape a composite fabric on a hemispherical mold, however, it is emphasized that an additional tension force on the fabric makes the procedure much more efficient. The handling solution presented in [17] consists of four grasping arms and an extra consolidation arm which allows to apply a constant pressure force on the fabric during the lay-up. The coordination of the manipulators is based on preplanned position trajectories. However, [17] gives an outlook that a very flexible option would be to have the movement of the lay-up arms controlled by the force exerted by the consolidation tool. Firstly, because off-line planning of the position trajectories is time-consuming for frequently changing tasks. Secondly, pure position control of the lay-up arms does not allow to compensate for external disturbances, e. g., a force exerted on the handling material by a consolidation tool. These external disturbances may result in unintended fiber-displacements and/or detaching of the fabric from the gripper. To this end it is clear that cooperative multi-arm manipulation of the deformable materials based on force control strategies is promising.

1.3. Cooperative multi-arm manipulation

Typical applications of cooperative manipulation involve assembly, grasping, material shaping, and load sharing when handling large scale objects. Literature typically discerns two different strategies. (i.) The master-slave, see, e. g., [19–21], and (ii.) the cooperate compliance strategy, see, e. g., [22–25]. With the master-slave approach one manipulator is position controlled and acts as leader, while the slave manipulators maintain a desired interaction force. In contrast, in cooperate compliance control all manipulators are equally responsible for positioning and controlling the internal or/and external force.

Although both strategies are frequently applied to non-rigid materials, e. g., beams [24], boxes [23], chair seat [25], etc., only a few works deal with the cooperative approach for the manipulation of highly deformable materials. In [26], two robots handle a fabric on a table in a similar manner as a human operator during sewing. This includes hands coordination, fabric tension control, and synchronization with the sewing machine speed. The robotic system presented in [27] is capable of folding a rectangular piece of fabric by human guidance. Beside the force feedback, the authors additionally exploit visual feedback to percept the humans intention. An approach to collaboratively manipulate a deformable sheet between a human and a dual-armed robot is presented in [28]. To follow the human motion, the robot utilizes a hybrid controller combining force and vision information. A low-cost camera is used to detect folds and commands the robot to move in an orthogonal direction to smooth them out.

A comprehensive review on the challenges and state-of-the-art solutions on the robotic manipulation of deformable objects using multi-sensory feedback is provided in [29]. According to [22,29], one of the main challenges in cooperative manipulation is related to the physical contact and interaction between the manipulators and the deformable material.

1.4. Modeling of highly deformable materials

In general, dry fabrics are characterized by a very low bending stiffness, ease of relative motions between the yarns, and low permeability to air. For a theoretical prediction of the mechanical characteristics, several modeling approaches at different scale, i. e., whole component scale, yarn scale, and fiber scale have been proposed in literature [30]. While most of these models are essentially developed for material design and the prediction of tensile and bending properties, only a few modeling approaches allow to calculate/predict the shape of the dry fabric in real time.

The work [31] presents an energy-based model in order to predict the state of equilibrium of a sheet draped over a rigid surface. The discrete nodes are endowed with flexional, torsional, stretching, and shear springs. However, the proposed model is computational expensive due to the vast amount (2500) of degrees of freedom (DOF). In [4] a continuous model based on large deflection plate and shell theory is utilized. The proposed energy method allows to predict the shape of limp sheets using simple sin- and cos-functions for three different boundary conditions. The obtained results show good agreement with finite-element simulations for a two- and a four-edges lifted fabric. A modeling approach based on potential and bending energy stored in a two-edges lifted fabric is proposed in [32]. An analytical function for the horizontally one-side clamped bent shape of a fabric under its own weight is obtained from a 4th order differential equation by applying suitable assumptions and boundary conditions. A closer examination of [32] reveals that the derived analytical function is equivalent to the well-known catenary equation [33]. In [34] it is shown that, besides the computationally inexpensive prediction of the bend line, the catenary model allows for the computation of the inter-

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