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Modeling and Force Control for the Collaborative Manipulation of Deformable Strip-Like Materials

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Abstract: This work analyzes and evaluates state-of-the-art force control strategies for the collaborative multi-arm handling of deformable materials. We exploit and validate the well-known catenary equation to predict the materials sag and interaction stiffness. The material properties are considered in the manipulator design and coupled system stability is investigated including the dynamics of a first-order force low-pass filter. The analysis provides practical relevant conditions for the selection of the force controller parameters. Different force control strategies are implemented on a multi-arm manipulator, comprising two biaxial gantries, and are evaluated in the light of praxis-oriented case studies.

Keywords: Force Control, Impedance Control, Deformable Materials, Collaborative Handling

1. INTRODUCTION

Deformable materials like textiles, leather, porous tissues, and adhesive foils are used in many industries. Typical manipulation tasks in the cloth, shoe, and garment industry involve transportation, handling, and folding. Similar tasks are encountered in composite manufacturing for the lay-up of preimpregnated or dry fabric sheets on a mold. Although economically important, the manipulation of this material class is hardly automated and hence still labor intensive, time consuming, and lacks of reproducibility, see, e. g., Saadat and Nan (2002) and Lankalapalli and Eischen (2003).

Automatic manipulation of deformable materials is challenging because of their low bending stiffness and geometric diversity. Typical solutions from the field of machine tool engineering focus on the design of highly-sophisticated, special-purpose end-effectors mounted on a single manipulator, e. g., area- or multi-gripper, see Fig. 1. The approach, however, is rather inflexible and becomes inefficient for large-scale objects or more complex tasks, e. g., folding or lay-up on non-flat surfaces. Recently, several authors proposed a more human-like approach, namely, the cooperation of multiple manipulators. For example, the multi-functional cell of Krebs et al. (2013) consists of two industrial robots mounted on gantries. The handling and the lay-up of a preimpregnated composite sheet is based on pure position control. Koustoumpardis and Aspragathos (2008) present a robot manipulator collaborating with a human to handle a fabric based on a neural network force controller. Besides force feedback, the follow-up work of Koustoumpardis et al. (2016) additionally exploits visual feedback to percept the humans intention. Their robot manipulator is capable of folding a rectangular piece of fabric by human guidance. An approach to collaboratively manipulate a deformable sheet between a person and a dual-armed robot is presented by Kruse et al. (2015). To follow the human motion, the robot utilizes a hybrid controller which combines force and vision information. A comprehensive review on the challenges and solutions on the robotic manipulation of deformable objects is provided by Khalil and Payeur (2010). During the handling of deformable materials it is crucial to maintain the appropriate amount of internal tension force, i. e., a tension force which is high enough to avoid sagging or wrinkles and low enough to avoid tearing or loss of gripping. To solve the force controlled manipulation problem, different control strategies are presented in literature, see, e. g., Zeng and Hemami (1997); De Schutter et al. (1998); Vukobratovic et al. (2009). These strategies, however, have hardly been applied to the coordinated manipulation of deformable materials. One reason is the complex interaction behavior between the manipulator and the handling object during physical contact.

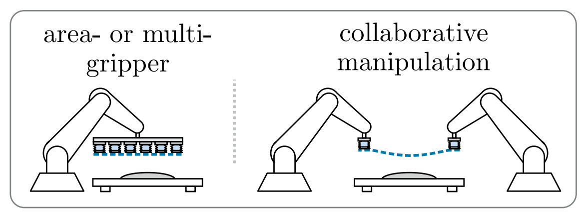

Fig. 1. Different approaches for the manipulation of deformable materials.

Although a number of mathematical models for the shape prediction of this material class are available, see, e. g., Henrich and Wörn (2000); Syerko et al. (2012), they are hardly used for control, mainly due to their complexity. A rather simple, but interesting modeling approach proposed by Grießer and Taylor (1996) is based on potential and bending energy stored in a two-edges lifted fabric. A closer examination of their work reveals that the derived ana-

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lytical function is equivalent to the well-known catenary equation, see, e. g., Routh (1891).

In order to enable and support the coordination of multiple manipulators for the handling of deformable materials, this work exploits and validates the catenary equation as a suitable interaction model for strip-like objects. Utilizing parallel position and force control, which generalizes pure force and impedance control, and a low-pass force filter in the loop, an extension of the coupled system stability criterion proposed by Šurdilović (2007) will be presented. The stability analysis provides practically relevant conditions for the selection of the controller parameters and motivates an intrinsic compliance in the mechatronic manipulator design to further enhance the force control performance. Moreover, different force control implementations on a multi-arm manipulation system are experimentally evaluated and compared in view of a collaborative handling approach.

The paper is organized as follows: Section 2 utilizes the catenary model to determine the materials shape and interaction parameters. Moreover, an appropriate model of the considered multi-arm manipulation system consisting of two biaxial gantry robots is introduced. Section 3 briefly classifies state-of-the-art force control strategies and provides a stability analysis for the general parallel position and force control approach with additional force low-pass filtering in the loop. Finally, Section 4 presents experimental results and compares different force controller implementations for the collaborative handling of a deformable strip-like material. In a future work, the results of this publication will be utilized for a collaborative layup of deformable materials on a complex mold.

2. MATHEMATICAL MODELING

The following section introduces suitable mathematical models for the deformable material to be handled and the multi-arm manipulation system. These models serve for simulation purposes and model based controller design.

2.1 Deformable Material

While most modeling approaches are essentially developed for material design and the prediction of tensile and bending properties, only a few models allow for real-time shape prediction. As previously mentioned, the model of Grießer and Taylor (1996) for a strip-like fabric leads to the well-known catenary equation. Subsequently, this static equation is used to predict the shape and the stiffness of a two-edges lifted, strip-like, deformable material.

A catenary is a curve of an idealized hanging string under its own weight, see Fig. 2. With regards to strip-like, deformable materials it is assumed that the material is so thin that any tension force exerted by the string is tangential to the string (zero bending stiffness). Moreover, the mass per unit length is considered uniform and does not change with tension. Let us consider the schematic of a catenary hanging between two supporting points GA_i, with $i \in \{1, 2\}$, as depicted in Fig. 2. Since only gravitational forces act along the negative z-axis, the y-component of the force is uniform at each point of the string and $F_y = F_{\mathrm{GA}_1,y} = F_{\mathrm{GA}_2,y}$ holds. Utilizing calculus

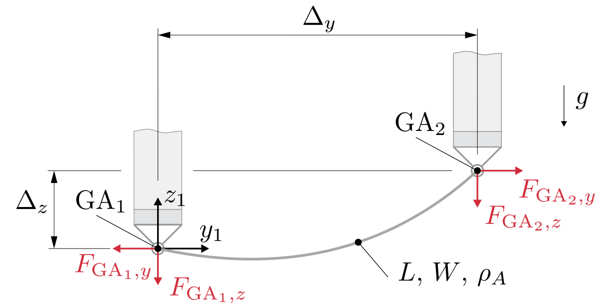

Fig. 2. Catenary with length L, width W, and area density ρ_A under its own weight supported at the grasping points GA_i, $i \in \{1, 2\}$.

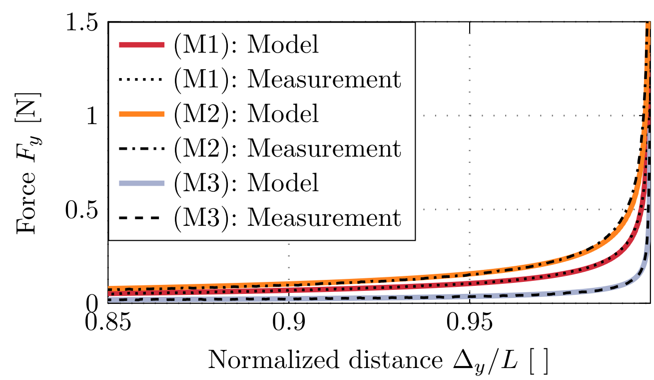

Fig. 3. Horizontal force F_y subject to a normalized distance variation Δ_y/L for various materials, see Table 1.

of variations, the catenary equation reads as, see, e. g., Routh (1891),

$$z = \frac{F_y}{q} \cosh\left(\frac{q}{F_y} y + C_1\right) + C_2 \ , \tag{1}$$

with $q = g\rho_A W$, where g denotes the gravitational acceleration $g = 9.81\,\mathrm{m\,s^{-2}}$, ρ_A is the area density, and W is referred to as the catenary width. The parameters C_1, C_2, and F_y depend on the boundary conditions. Evaluation of (1) with respect to the boundary conditions at the supporting points $z|_{y=0} = 0$ and $z|_{y=\Delta_y} = \Delta_z$ in combination with the catenary length

$$L = \int_0^{\Delta_y} \sqrt{1 + \left(\frac{\mathrm{d}z}{\mathrm{d}y}\right)^2}\,\mathrm{d}y \tag{2}$$

yields the transcendental equation

$$\left(2\frac{F_y}{q} \sinh\left(\frac{q}{2F_y}\Delta_y\right)\right)^2 + \Delta_z^2 - L^2 = 0 \ , \tag{3}$$

with one unknown parameter F_y. Equation (3) can be solved numerically using, e. g., Newton's method, and has at most one solution with $F_y > 0$. The integration constants C_1 and C_2 are derived by means of the remaining independent equations

$$C_1 = \operatorname{atanh}\left(\frac{\Delta_z}{L}\right) - \frac{q\Delta_y}{2F_y} \ , \quad C_2 = -\frac{F_y \cosh C_1}{q} \ . \tag{4}$$

Fig. 3 shows the modeled and measured horizontal force F_y subject to a distance variation Δ_y of the supporting points for a constant distance $\Delta_z = 0$ and different strip-like materials listed in Table 1. Note that although the static model solely relies on the material parameters L, W, and ρ_A, the model (1) fits the measurements very well. The