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Survey on model-based manipulation planning of deformable objects

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A B S T R A C T

A systematic overview on the subject of model-based manipulation planning of deformable objects is presented. Existing modeling techniques of volumetric, planar and linear deformable objects are described, emphasizing the different types of deformation. Planning strategies are categorized according to the type of manipulation goal: path planning, folding/unfolding, topology modifications and assembly. Most current contributions fit naturally into these categories, and thus the presented algorithms constitute an adequate basis for future developments.

1. Introduction

Manipulation planning differs from standard motion planning in that the focus is not on the robot and its displacements but rather on the object(s) to be manipulated. Manipulation of *rigid* objects consists basically in changing their *pose* (position and orientation), while avoiding collisions, in the context of pick-and-place or assembly tasks. Realistic instances of the problem take also constraints on the stability of the grasp and of the placement of the object into account (see [1] for a small survey on the subject). When *deformable* objects are involved, manipulation will in most cases also affect their *shape*, with geometrical or topological changes. This behavior has to be considered in the whole planning process.

Most existing robotic systems that handle deformable objects rely heavily on a sensor-based control scheme. Many of them are ad-hoc algorithms, which lack generality [2]. Moreover, flexibility of such systems is also poor, as they implement fixed strategies. Sensorial feedback may be necessary in real implementations to overcome uncertainties in the model, which will probably arise except in very controlled environments. Furthermore, sensorial information is also needed in the automatic acquisition of behavior models of deformable objects under manipulation (i.e., machine learning of manipulation), a little explored issue. A collection of control-related articles can be found in [3].

Planning chooses and/or instantiates a sequence of actions from a given repertoire. This choice is not only conditioned by the intended sequence of states (in this case, configurations of the manipulated object) but also by the constraints that each state poses on the possible actions. Here, internal and external constraints have to be considered, as well as feasibility (hard) and optimization (soft) constraints. Constraints allow to narrow the search space of actions to consider, and to introduce criteria for evaluating different choices.

The present work concentrates on model-based off-line manipulation planning, which is based on geometrical (and to some extent also physical) descriptions of the object to be manipulated and its environment. We also assume that the wealth of possible sequences of elementary motions or actions makes it necessary to devise the manipulation plans automatically. Furthermore, some kind of prehensile grasping is involved in manipulation (see [4] for nonprehensile manipulation). In the works referenced in our survey, simplified models of grasping are adopted, in the form of *manipulation constraints* that define the location of grasps on the object and tangents of its surface at these points, and assuming that the forces exerted by the fingers ensure the intended deformations without damaging the object.

Deformations depend on the material properties of the objects, on their initial shape and dimensions, and also on the localization, direction, intensity, duration and frequency of the applied forces. As for manipulation planning, there are two features that characterize object deformations: reversibility and direction/extension of the shape change. The first criterion refers to whether the object recovers completely its original (rest) shape once the external forces have ceased (*elastic* deformation), or if permanent, stable deformations appear on the body of the object (*plastic* deformation). A third category of deformations may be considered, as for reversibility, which is applicable to material like cloth or rope.

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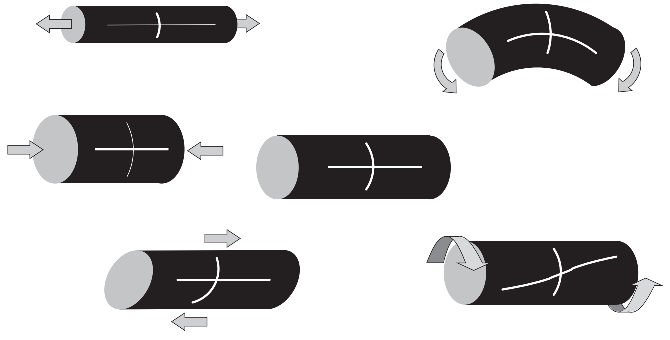

Fig. 1. The undeformed cylinder appears in the center of the figure. Arrows stand for the forces and moments exerted on the cylinder, while the cross drawn on it helps to visualize the resulting deformation. At the left, tension, compression and shear, and on the right bending and torsion are exemplified.

We call them *flexible* deformations, as they are neither elastic (due to friction and gravity, the object does not recover anything like a "rest shape" once manipulation ends) nor strictly plastic, as they can be altered with very slight effort. Such definition is not a standard one in materials science or deformation theory, but it is intuitive and useful for robotic planning purposes.

Deformations are also characterized by the direction in which they take place, as a result of the direction of the applied forces and moments. Fig. 1 displays a schematic view of some basic deformation types for a cylinder.

2. Modeling deformable objects

Models aim at capturing the behavior of the represented objects when they are manipulated. The scope and granularity of such models is obviously application-dependent, and a compromise between accuracy and computational efficiency is always sought. Unlike for rigid objects, in most cases the manipulation of deformable objects is quite tolerant to collisions (the shape adapts to the colliding object). This allows to do also simplifying assumptions about their shape.

2.1. General deformable volumetric models

The most distinguishing feature of deformable objects refers to the changes in shape that they experience under the influence of external and internal forces. From the point of view of planning, these shape modifications can be the goal of planning itself (e.g., if they allow to avoid obstacles along a path) or a side-effect of a given planned action. In any case, there is an underlying physical behavior that governs these shape alterations in real three-dimensional objects. This physical behavior can be implicitly considered while restricting to use pure geometric models (like *splines and patches* manipulated by their control points) or it can be explicitly reflected in the model. In the latter case, *physical analogues* like mass-spring models, particle systems or linked volumes, or more accurate *continuum models* may be used. Accurate models, like those associated with the Finite Element Method (FEM), are in fact more appropriate for off-line simulations. More recent approximate models meet both the requirements of realistic behavior and real time execution. Also *hybrid models* exist that combine some of the features of these different types. Excellent surveys exist on this subject in the field of Computer Graphics [5] as well as in Surgery Simulation [6], where not only elastic deformations but also incisions and suturing have to be considered. Considering the suitability for robotic purposes, the choice among the different types of models is a matter of available programming time and computational resources, as well as of the required accuracy. Physical analogues like mass-spring models are popular as they are relatively easy to implement and to tune, and provide a good compromise between accuracy (which can also be tuned, by varying the number of nodes and springs) and speed. However, tight tolerances may require the use of FEM, in an off-line pre-programming stage.

2.2. Deformable planar models

Planar objects have two privileged dimensions, whereas thickness, the third one, is negligible for manipulation planning purposes, besides grasping or collision detection. A paradigmatic example is sheet metal bending: thickness—together with material properties—plays an important role when determining the required punch displacement for a given bend angle in a bending machine, but it can be neglected when computing the necessary manipulation of the part during the bending process [7]. Roughly, one may distinguish between models that aim at reproducing continuous deformations, and models that operate on a more abstract level accounting for plastic deformations at prespecified discrete points. Among the first ones, a further distinction can be made depending on whether the material has a regular isotropic behavior or not.

Continuous deformations of uniform and isotropic material: Thin metal and plastic plates subject to elastic deformations can be easily modeled as a low-degree Bézier surface [8]. Its configuration is determined by the initial (load-free) shape, the deformation, and the rigid transformation. An energy model of the surface penalizes deformations that lead towards high curvatures, extension or shear of the surface, based exclusively on geometric parameters. In [9,10] a more realistic elastic deformation model, which takes the material properties directly into account (Young modulus and Poisson ratio), is used. Together with the *grasping conditions* (a.k.a. *manipulation constraints*, see Section 5) that determine the location of specific control points and the corresponding tangents to the surface, elastic energy minimization determines the position of the other control points, and consequently the deformation of the plate. Similar models are used in [11]. The issue of extending such models to deal with permanent deformations is difficult and remains open.

Deformations of anisotropic material: Materials like cloth or fabric exhibit a complex behavior and are thus hard to model. Difficulties include the highly deformable nature of cloth, where subtle mechanical variations are amplified into large draping or motion variations, and its highly intricate anisotropic and nonlinear mechanical behavior [12]. Standard protocols, as the Kawabata Evaluation System (KES) [13], based on experimental measurement of strain–stress curves (elongation, bending and shearing), as well as surface properties, provide a basis for an adequate parameterization of the mechanical properties of different kinds of cloth (the fabric drape coefficient is related to the mechanical properties from KES tests in [14]). The Computer Graphics community has devoted large efforts to cloth modeling and simulation, since a couple of decades ago. Fabric has been modeled mainly with continuum models, implemented with finite difference [15] and finite elements methods [16–19], and with discrete models like particle systems [20,21] and mass-spring models [22–24,12]. In the latter, immediate neighbors are connected with "structural springs", diagonal neighbors with "shear springs" and also cross-springs connecting non-immediate neighbors are necessary for modeling the flexural resistance of cloth. Continuum models face serious drawbacks when applied to cloth, due to their high computational requirements (very fine meshing to produce large deformations) and difficult integration of highly variable constraints [12], mainly the high