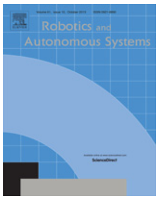
Robotics and Autonomous Systems 62 (2014) 1153–1174

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

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



Learning object deformation models for robot motion planning

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HIGHLIGHTS

- We present a planning system for robots in environments with deformable objects.
- A manipulation robot determines the deformation parameters of real objects.
- We consider the costs of object deformations by finite element simulations.
- The deformation costs are modeled using Gaussian processes for efficient planning.
- Application to wheeled and manipulation robots operating in real environments.

ARTICLE INFO

Article history:
Received 9 September 2013
Received in revised form
31 March 2014
Accepted 11 April 2014
Available online 19 April 2014

Keywords:
Mobile robots
Deformation models
Parameter estimation
Motion planning
Robot navigation

ABSTRACT

In this paper, we address the problem of robot navigation in environments with deformable objects. The aim is to include the costs of object deformations when planning the robot's motions and trade them off against the travel costs. We present our recently developed robotic system that is able to acquire deformation models of real objects. The robot determines the elasticity parameters by physical interaction with the object and by establishing a relation between the applied forces and the resulting surface deformations. The learned deformation models can then be used to perform physically realistic finite element simulations. This allows the planner to evaluate robot trajectories and to predict the costs of object deformations. Since finite element simulations are time-consuming, we furthermore present an approach to approximate object-specific deformation cost functions by means of Gaussian process regression. We present two real-world applications of our motion planner for a wheeled robot and a manipulation robot. As we demonstrate in real-world experiments, our system is able to estimate appropriate deformation parameters of real objects that can be used to predict future deformations. We show that our deformation cost approximation improves the efficiency of the planner by several orders of magnitude.

1. Introduction

Perceiving the surroundings and modeling the environment is an important competence of intelligent mobile robots since such models are required for efficiently solving other high-level tasks. For instance, generating a collision-free path through the environment in an efficient way requires path planning, which in turn builds on top of a model of the environment. There exists a variety of approaches for robots to autonomously generate an appropriate model of the environment by addressing the simultaneous localization and mapping problem [1–4], by autonomous exploration [5–7], or by addressing both problems jointly [8,9].

In order to plan motions in learned environment models, the majority of path planning approaches assumes that the environment contains only rigid obstacles [10–12], although there are a few notable exceptions such as the works of [13–17]. In reality, not all obstacles are rigid. In domestic environments – a key target domain for service robots – a robot must deal with many deformable objects such as plants, curtains, or cloth. Considering that an object such as a curtain is deformable can enable a robot to accomplish navigation tasks that otherwise cannot be carried out.

To consider deformable objects in the path planning process, such objects need to be handled in a simulation system underlying the planner. The realistic simulation of object deformations is still an active area of research with a variety of relevant applications in computer graphics, virtual reality, games, movies, but also in robotics [18,19], and medical simulations [20–22]. In most applications, the underlying parameters for an appropriate deformation

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http://dx.doi.org/10.1016/j.robot.2014.04.005
0921-8890/

simulation are adjusted manually until the results appear visually plausible. This might be applicable for computer games or movies, but does not necessarily lead to a physically realistic computation of the involved forces. These forces, however, need to be known accurately for navigation in the presence of deformable objects. For example, whenever a robot interacts with real-world objects, only limited forces should be applied to them. This is of utmost importance in medical applications or in domestic settings, for instance, whenever robots have to manipulate plants or clothes. Particularly in these domains, robots need exact knowledge about the parameters of the deformation process.

In this paper, we present a complete robotic system that is able to perceive the environment and model the deformable objects in the scene. The system estimates the deformation properties of objects, and finally is able to plan a trajectory through the environment, taking potential object deformations into account.

Estimating the elasticity parameters of objects not only involves observing and reconstructing the three-dimensional surface of an object. Physical interaction with the object under consideration is required to learn about its behavior when exposed to external forces. Therefore, we equipped our robot with a force sensor at the end of the manipulator and with a depth camera. Based on the observed surface deformations and corresponding forces, our approach seeks to determine the elasticity parameters of the object. This is done by simulating the object deformation under the applied forces using a linear finite element model. An error minimization approach is applied to iteratively adapt the deformation parameters such that the difference between the real object under deformation and the simulation is minimized. As we will demonstrate in the experimental section of this paper, our approach is able to find elasticity parameters that enable our robot to accurately predict the deformations of real-world objects.

Furthermore, we address the problem of planning motions for robots navigating in environments with deformable obstacles and to adequately consider the costs of object deformations. In this context, we present an efficient approximation of the deformation cost function of objects. Throughout this paper, we assume that the robot can deform the objects but does not move them in the environment. This allows us to generate a set of trajectory samples in a pre-processing step and to predict the costs of new trajectories by applying efficient Gaussian process regression. Using this regression approach, the robot is able to efficiently plan trajectories in the presence of deformable objects without the need for time-consuming simulations during runtime. In different experiments, we demonstrate that our approach yields accurate estimates and, at the same time, allows for efficient planning of trajectories along which the robot interacts with deformable objects.

This paper is organized as follows: after discussing related work in the next section, we will give an overview of our planning approach that considers deformable objects and describe the basic principles of the deformation model and the physical simulation underlying our planner in Section 3. In Section 4, we describe how to learn models of deformable objects with our manipulation robot. Next, we present our approach to approximate the deformation cost functions of objects using Gaussian process regression in Section 5. Subsequently, we present two applications of our path planning system applied to a manipulation robot and a wheeled robot. Finally, in Section 7, we evaluate our system in different experiments.

2. Related work

2.1. Deformable modeling and parameter estimation

Deformable modeling and parameter estimation are active areas of research. To represent non-rigid objects and to simulate deformations, mass–spring systems have been frequently used. They are easy to implement and can be simulated efficiently [23,24]. Their major drawback is the tedious modeling as there is no intuitive relation between spring constants and physical material properties in general [25]. Finite element methods (FEMs) reflect physical properties of objects in a more natural way [26]. They are based on elasticity theory and describe object deformations with a small number of physical parameters. Their disadvantage lies in the computational resources required to calculate deformations.

The co-rotational finite element approach [27,28], which we also use in our current system, avoids nonlinear computations and is computationally more efficient. Our system, however, does not depend on the underlying deformation model and therefore, arbitrary approaches can be used in our algorithms. For example, Mousavi et al. [29] employ a principal component analysis as a precomputation step in order to gain efficiency for a minimal loss of accuracy. Similarly, reduced deformable models [30–32] employ the modal analysis for a more efficient simulation. Other approaches use third order polynomials for this purpose [33].

There are different approaches to determine the physical parameters of models. Bianchi et al. [34] learn the stiffness constants of mass–spring models using a genetic algorithm and comparing it to an FEM reference model. The identification of mass–spring parameters is also discussed in the work of Lloyd et al. [35]. They derive an analytical formulation for the spring parameters from a linear finite element model. Data-driven representations for deformable objects were employed, among others, by Fong [36] and Bickel [37]. Fong [36] extracts force-fields for different contact points and displacements on the objects. For haptic rendering of unseen contact points, the forces are interpolated using radial basis functions. In a similar way, Bickel et al. [37] represent heterogeneous and nonlinear material. The homogeneous parts of objects, however, are modeled using the linear FEM, similar to our approach.

Different approaches deduce the elasticity parameters of objects by optimizing an objective function that relates the observations to a finite element simulation, which in turn depends on the parameters to be determined. For instance, Kajberg and Lindkvist [38] determine the material parameters of thin metal sheets including plasticity effects. Choi and Zheng [39] identify Young's modulus and Poisson's ratio of soft tissues from indentation tests. Schnur and Zabaras [40] estimate different parameters including Young's modulus of a two-dimensional nonlinear finite element model. The approach of Becker and Teschner [41], in contrast, works for three-dimensional objects, allows for the simultaneous estimation of Young's modulus and Poisson's ratio, and furthermore can be reduced to a linear least squares problem. Both approaches, however, have been validated using simulated data only.

Estimation of material parameters from real data has been investigated in the context of soft-tissue modeling for surgical simulation applications, such as simulation and training, or computer-aided surgery. Kauer et al. [42] present an inverse finite element algorithm that estimates the material parameters of soft biological tissues. They consider complex material constitutive laws, such as nonlinearity and anisotropy, furthermore they account for viscoelastic behavior. Deformation forces are measured with an aspiration instrument operated by a human. Their estimation procedure is designed to operate on two-dimensional image data. Fugl et al. [43] present an approach to determine Young's modulus and different parameters to model heterogeneous material from observations of deformations due to gravity with an RGB-D camera. Lang et al. [44] collect data of object deformations with a robotic measurement facility, including force sensors and stereo cameras. They model deformable objects as a discrete boundary value problem and estimate Greens' functions from measured forces and displacements. An interesting approach was recently presented by Boonvisut et al. [45]. In this work, a robotic manipulator performs