

Abstract

Highly flexible manipulators offer unique advantages in various applications due to their dexterity, lightweight design, and ability to navigate complex environments. However, their inherent flexibility presents significant challenges in terms of modeling, control, and accurate positioning. This thesis investigates the mechanics of highly flexible manipulators to address these challenges and enable their effective utilization in diverse fields. Understanding the mechanical behavior of highly flexible manipulators is crucial for their successful design, control, and operation. Due to their significant deflection and complex dynamic characteristics, traditional rigid-body manipulator models fail to capture their behavior accurately. This thesis explores the mechanics of highly flexible manipulators, developing models and analysis techniques to predict their motion and design them for optimal performance.

First portion of the thesis describes the modelling approaches in highly deformable structures. Generally, conventional approaches such as Euler-Bernoulli beam models are insufficient to model highly deformable structures due to their inherent assumptions of small rotation. Hence more sophisticated methods are required which relaxes the assumptions. Geometrically-exact beam theories are of such category. Mainly, continuous, and discrete methods are employed to model highly deformable bodies. Continuous methods treat deformable bodies as continuum and derive the governing partial differential equations that represent the dynamic behaviours. One of such methods is Cosserat rod modelling, which is very popular in modelling continuum manipulators. On the other hand, discrete methods such as the Finite Element Method (FEM) discretize the continuum structures into a finite number of elements to obtain a numerical solution for the manipulator's mechanical response. Cosserat rod model offers a robust framework to model flexible manipulator mechanics considering the external interactions and are widely used in various applications involving slender deformable bodies called *rods*. The flexible manipulator is modelled under the formalism of Cosserat Rod theory where the link is assumed to be inextensible and unshearable but can bend and twist. It can simulate complex deformations such as combined twisting and stretching. The static equilibrium equations of Cosserat rod are nonlinear coupled ordinary differential equations (ODEs), where numerical solution is only viable.

The second part of the thesis presents a medical application of cable driven continuum surgical manipulator specially designed for minimally invasive neurosurgical procedures. The study focusses on the designing of such manipulators based on the specific requirement of a surgical task such as manoeuvrability and stiffness. The designing process and modelling was carried out by employing Cosserat rod theory. The primary characteristics of the design are simplicity, compactness, and inherent ease of sterilization. The prototype demonstrated adequate dexterity during a basic functionality test.

The third portion of the present thesis is an exploration of the behavior of highly flexible initially curved manipulators, and beam like structures. Curved beams have inherent nonlinearity due to their initial curvature, which makes their analysis difficult. A new discretization approach is presented using piecewise clothoid elements. The clothoid curves interpolates the initial shape of the centreline of the beams in terms of piecewise linear curvatures. The use of clothoid curves for discretization is found to yield accurate results with lower computational effort. In addition, the model is simple, intuitive, and easy to implement. Incorporating the clothoid curves in the Cosserat

rod model resulted in an isogeometric method, where a unified set of parameters govern the geometric design as well as static simulation.

The final portion of the thesis presents a preliminary attempt to model the dynamic behaviour of planar curved beams by incorporating piecewise clothoid interpolation into the dynamic Cosserat rod model. Cosserat rod dynamic equations are a system of coupled partial differential equations (PDEs) and are very difficult to solve. An implicit numerical solution algorithm discretizes the time variable, and a shooting method solves the resultant boundary value problem (BVP) in space variable. The effect of number of control points and the numerical damping on the dynamic response of cantilever beam systems was discussed. A preliminary experiment was also conducted to study the dynamic response of a cantilever beam oscillating on its own weight. The experimental response was compared with the simulated response obtained using dynamic Cosserat rod simulations. Kelvin-Voigt viscous damping was utilized to simulate the real physical damping. A close match between the responses were observed.