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Vibration-free position control for a two degrees of freedom flexible-beam sensor

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ABSTRACT

This work presents a position control for a two degree of freedom flexible-beam made of a composite material, whose aim is to control the tip of the flexible-beam by decreasing the vibration when the beam moves. A mechatronic unit that uses a multi-axis force/torque sensor has been specially designed and we propose to control the system by using a reduced dynamic model. The control method makes use of an inner-loop to control the position of two servo-motors, by means of PID regulators, and an outer-loop that cancels the tip vibration. Moreover, the closed-loop motor dynamics has been reduced by using a series connection of filters that invert its dynamics. The motor controllers have proved to be fast and precise, and cancel the non-modelled components of the motor friction without the need for a previous estimation. The flexible-beam vibration has been controlled by implementing an input-state feedback linearisation which includes compensation terms for the nonlinear beam dynamics, a linear feedback control law and a full state estimator. The experimental validation of the complete control method showed a significant trajectory tracking of the tip, while vibrations were prevented.

1. Introduction

In this work, a two Degrees of Freedom (2DOF) flexible-beam is used as an extension of a multi-axis force/torque sensor (F–T sensor). A simple mechanism was designed to join the flexure and the F–T sensor in order to accomplish the desired motion and force transmission. It is a robotic prototype that will be used for control purposes, and may be similar in function to some sensory systems present in nature (e.g. antennae and whiskers). However, in this work no effort is made to attempt to mimic the physical appearance, shape or any other physical characteristic of natural sensory systems.

As reported in [1,2], artificial antennae and whiskers are independent of lighting conditions and the properties of the sensed objects. The sensing task could be performed in dusty or foggy conditions regardless of visibility. By using tactile capabilities, a robotic device can distinguish among textures, and perform short-range navigation and object exploration. In certain applications, the use of artificial vision produces remarkable results, but the complex electronics and dense information needed for sensing and control may be impractical for some particular tasks. Active sensing usually entails sensor movement, but more fundamentally, involves the control of the sensor apparatus, in whatever manner best suits the task used to maximise information gain, as reported in [2].

Some artificial flexible-beam sensors have been built previously, such as those shown in [3–7]. In these studies, the dynamics were modelled in order to obtain the contacted point when the beam touched an object. In [3,4,7], the contact information was acquired by processing the vibration signals while driving the beam that was searching for an object. In contrast, in [5,6] the works made use of an elastic equation of the static beam deflection. The contact information was then obtained by means of kinematic considerations, using motor angles and force/torque measurements.

Some prior works made use of different controllers to move the flexible-beams according to the task assigned, and most of them moved the beam by using open-loop methods. For instance, a Proportional Integral Derivative (PID) feedback law controlled a whisker providing sinusoidal movements, regardless of the disturbance torque from the object contacted, see [5]. In [7], a Repetitive Learning (RL) regulator moves a whisker which regulates the vertical contact force using torque and encoder measurements as feedback sensors. In [8,9], bio-mimetic tactile sensors and their control methods are presented, whose controllers were based on free simple movements of the beam.

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This work argues that active sensing should consider the controlled movement of the vibrissal shaft as a characteristic feature of the system. It also shows the time interval reduction between the motion control stimulation at the shaft and the response of the beam, and whose control has to be robust to the contact disturbance when performing the searching trajectory. Most of the research carried out on both artificial active sensing and flexible-beam sensors have, to date, focused on processing the information when the beam makes contact, as seen in the reviewed literature [9]. However, the beam trajectory, precision and the vibration damping have not been considered. In this study, the sensor free-air movement of the beam, the mechanism control, and the vibration damping for each manoeuvre are important, since the beam tip will be used to search for specific points, will follow pre-specified trajectories, and will be pointed in a precise manner while recording the information before and after the contact has been made.

In previous works [10,11], an experimental beam was built which consisted of a rigid unit connected to a flexible-beam. The assumed rigid unit was not considered in the dynamic model and only the flexible-beam was modelled by assuming lumped masses. A reduced dynamic model was then used to design an open-loop controller to decrease the tip vibration by dynamics inversion, see [11]. As a result, the open-loop controller continued to exhibit a vibration at the tip. The mechanical design was therefore modified, and the new platform made use of a closed-loop control method to reduce the persistent flexible-beam vibration.

However, many issues must be taken into account when addressing the system design, such as the facts that the flexible-beam must be light-weight, made of composite material, and hence very flexible. The system used is a non-minimum phase whose model must be represented using high order dynamics. Moreover, the system is driven by two small Direct Current (DC) servo-motors for high precision, in which the limited torques, intermittent operation and the strong non-linearity owing to the static friction limits the motor control design. The stability of the closed-loop control is additionally sensitive to non-modelled dynamics and parameter uncertainties.

The objective of our work is, therefore, to design a first control strategy phase that will allow the tip to be placed in a precise manner, and which will be denominated as free-air motion. The movements of the entire mechanism will be controlled, while the vibrations caused by each and every movement will in turn be damped, and it could be used to ensure that each manoeuvre is performed in the least possible amount of time. Then, the system can move the beam by performing long multiple trajectories, keeping the controller robust to disturbances, reducing the time for a complete multiple trajectories, as well as keeping the error minimal. A second control phase should, meanwhile, control the contact conditions. This second phase will, however, be carried out in a future study and will include an algorithm with which to acquire the contact time, point and direction, while keeping the damping control on, or switching it off for a specific time while approaching the object again.

By using our vibration-free control, the system will be prevented from touching undesirable points or points that are out of our particular object. At the same time, the vibration control has to be robust to the contact disturbance when performing the searching trajectory. In this way, the controller remains stable after the disturbance and allows the system to correct its path to go to a different point of search.

A comprehensive study that includes the design of the mechanism, dynamics modelling and a control method has therefore been proposed for the entire strategy. An oscillatory movement of the beam tip with a single vibration frequency must therefore be settled, thus allowing a simple and invertible model to be obtained that will make it easier to design the controller. The beam dynamics should be slower than the motor dynamics which, when considering the motor reaction, represents an advantage. The beam's lower dynamics additionally allows a real-time system with a less demanding sample time to be used, which could be implemented using a basic computer system. This will be in charge of controlling the overall system, tracking the necessary trajectories, and recording the contact/impact events while processing the signals in order to study the vibrations.

The free-air beam motion and the control objectives, such as tip accuracy or residual vibration suppression, have been addressed by applying several control methods to flexible-beams, as is shown in a survey carried out in [13]. This work tests a control scheme that includes two nested loops: an inner-loop as a motor control and an outer-loop or tip position control. In [14,15], various controllers with a similar general scheme were developed for single and 2DOF flexible arms. A previous study was carried out in [16], in which simulations of a nonlinear controller for a 2DOF whisker sensor were presented. In the work presented in [17], which also makes used of the platform presented here, an input shaper technique was used in an attempt to improve the tip positioning. This paper continues as follows, the platform characteristics and setup are introduced in Section 2. The dynamic model is explained in Section 3, including the flexible-beam and motor dynamics. The complete control method is designed in Section 4, while the system validation and control results are shown in Section 5. Section 6 presents the significant conclusions.

2. Experimental platform

In this section, the experimental setup is explained, including certain mechanism characteristics, model assumptions and a previous identification of the system. The basic platform software and hardware requirements, along with the sensory system, are also briefly explained.

2.1. Mechanism characteristics

Fig. 1(a) illustrates the mechanism that is used to hold a multi-axis F–T sensor. Two servo-motor sets are used to drive the sensor, and there is a flexible-beam on the top of the sensor whose initial point at the base of the beam coincides with both motor shafts. Throughout this section, the subscript "*i*" denotes a particular degree of freedom, while the angle subscript is $i = 1$ for the motor that drives the azimuthal angles and $i = 2$ for the motor in charge of the elevation angles. Fig. 1(b) shows the schematic diagram in which the equivalent length of the beam is l, P_t is the tip of the flexible-beam and P_r is the beam tip itself when the beam is considered as a rigid-beam. ΔP is a 3D vector that describes the beam deflection, E is the Young module, I is the inertial moment resulting from the flexible-beam cross section, g is the gravity constant and M is

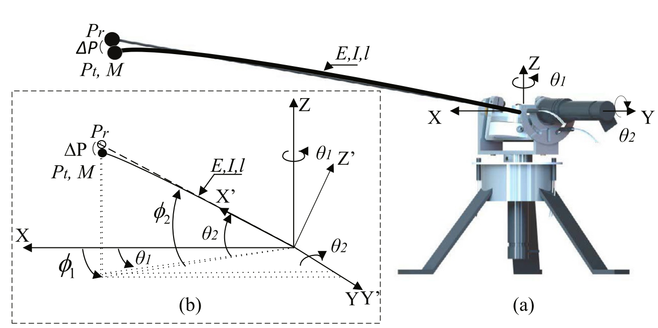

Fig. 1. Flexible-beam sensor: (a) mechanism design and (b) schematic diagram.