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Fibre Bragg grating (FBG) sensor system for highly flexible single-link robots

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ABSTRACT

This paper presents a sensor system based on optical fibre sensors (FBG) with which to measure the deflexion of a highly flexible lightweight beam. Epoxy glue is used to attach these optical sensors to specific locations on the surface of the beam in order to measure local strain measurements. These strain measurements, provided by FBG sensors, are used in a method proposed in this paper to estimate the deflection of the beam (the tip position and the tip rotation angle) in both static and dynamic cases. The correct number and the optimum distribution of the sensors on the beam are chosen by using the Chebyshev criterion which minimizes the error in estimating the position and the rotation angle of the tip link. Static and dynamic experiments are presented to verify the effectiveness of the estimation method and the sensor system proposed.

1. Introduction

The last few decades have seen the emergence of new applications in the field of robotics [1](e.g., aerospace applications which require lightweight materials which can be moved easily; minimally invasive surgery which needs to control thin flexible instruments which can be inserted with precision into vital organs of the human body; robotic manipulators used to help handicapped people without causing them personal injury; large telescopic arms for boom cranes or fire rescue turnable-ladders which are considered to be flexible arms). These applications have necessitated the development of innovative actuators and sensor systems, along with complex control algorithms, in order to command this new generation of manipulators which have certain special characteristics that make them different from the old and well known rigid industrial robots. The main distinguishing feature of this new generation of robots is the flexibility presented by various parts of its structure, owing to the lightness of the material or a higher length to thickness ratio of its links. This lightness permits a more rapid motion and lower energy consumption than in rigid robots. Moreover, in the case of a collision with an object or a human, certain damage can be minimized as a result of the flexibility of the links and these manipulators can therefore be designed with important safety measures in order to allow them to work among human beings. In order to grasp fragile object it is also important to provide robotic fingers with a certain amount of flexibility if we are to avoid damaging the object in question. Despite these advantages, structural flexibility, a common feature in these manipulators, involves mechanical vibrations and a great control effort is necessary to cancel these vibrations if we are to achieve a good position or force control. Within this generation of flexible robots we can distinguish two kinds of manipulators: (a) metal robots (e.g. steel or duraluminium) with links whose cross sections are more reduced than in rigid robots and in which the deflections undergone present linear behavior since they are not too great; and (b) composite robots (glass or carbon fibre) or highly elastic metal robots (steel spring) which present smaller cross sections than previous metal robots and are consequently lighter and more flexible, thus undergoing large deflections with non-linear behavior. In these cases, it is also necessary to use new lightweight sensors (without influencing the system dynamics) with which to measure tip deflections. In contrast to rigid robots, which only need encoders placed at each joint of the robot to obtain the end position of each link in a precise manner, flexible manipulators, in addition to encoders, need other kinds of sensors with which to measure the deflections undergone by the links and an appropriate estimator algorithm with which to obtain the end position of flexible links from the measurements given by sensors. Therefore, the choice of an appropriate sensor system and a reliable estimation algorithm with which to obtain the tip position of a flexible manipulator is highly important and this choice will depend on the kind of manipulator, i.e. whether it undergoes linear or non-linear defections. Many different sensors have been used to measure deflections and vibrations of flexible manipulators. Cannon and Schmitz [2] and Feliu et al. [3] used a sensor system based on an optical camera which tracks a led placed at the tip to give its position, but this method is useless if there is

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an object between the camera and the led. Other authors have used torque sensors (commonly known as strain gauges) placed at the base of the flexible arm [4] or at several locations along the length of the arm [5]. These sensors have the advantage of being small and lightweight but necessitate a complex cable network when a large number of sensors are required. Collins et al. [6] also use strain sensors (piezoelectric film) to estimate the flexible states of a multiple-flexible-body. Other kinds of sensors used for measuring deflections in flexible robots are accelerometers placed at the tip of the manipulator (e.g. [7,8]) but this configuration has the disadvantage that accelerometers can be damaged if an impact occurs between the manipulator tip and an object. All of the above sensors have been used for flexible robots which undergo linear deflections and they are heavy enough for their dynamics not to be influenced by sensor weight, but when robots are very lightweight and flexible and undergo non-linear deflections, it is necessary to use lighter sensors which do not affect the dynamics of the robots. As has been previously mentioned, another important point which must be considered is the choice of an appropriate estimation algorithm with which to obtain the tip position from the measurements given by sensors. In scientific literature, certain estimation algorithms have been proposed which are either based on a dynamic model of the flexible link or based on a geometric model of the flexible link. The former need few measurement points along the flexible links to estimate the tip deflection and the latter use more measurement points to attain the same objective. Some estimators based on dynamic models of the link are those of: Canon and Schmitz [2] who estimated the system's states based on dynamic calculation using signals from the tip position sensor and the hub rate sensor; Moallem at al. [5] who designed a nonlinear observer to estimate the rates of change of flexible modes; and Parsa et al. [9] who estimated the flexural states of a macro–micro manipulator using point-acceleration data. Other authors have developed estimation algorithms based on geometric models to obtain the deflection of a flexible link. These authors include Scholz and Rahn [10] and Clements and Rahn [11] who designed an actuated whisker to determine contacted object profiles using the joint angle information and a hub load cell for a 2D motion [10] and a 3D motion [11]. The joint angle and the load cell signal were, in both cases, numerically processed to determinate the whisker shapes which involved large deflections. Other works related to estimation algorithms based on geometric models were carried out by Gu and Piedboeuf [12], who placed several strain gauges on the structure, and the curvature along the link was reconstructed by using second order polynomials. They were thus able to estimate the tip position and the force applied at the tip.

Our interest lies in analyzing the case of large deflections caused by the motion of highly flexible arms. This flexibility appears in beams with a very small cross section, as a consequence of the desire to design an arm which is as lightweight as possible (e.g. aerospace applications). In this paper we therefore propose a method with which to estimate the position and the rotation angle of the tip of a highly flexible single link beam, made of a composite (glass fibre) which experiences large deflections. This estimation is carried out by using strain states of the link given by FBG sensors placed at certain positions along the link according to the Chebyshev criterion. By using this position criterion for sensors, we minimize the error committed in estimating the position and the rotation angle of the tip. We demonstrate, both theoretically and experimentally, how fibre Bragg gratings (FBG) can be valuable tools for obtaining strain states at several locations along a flexible beam in order to calculate its deflexion. From these local strains, the proposed method reconstructs the curvature along the link by using an n-order polynomial approximation by minimum square ($n+1$ being the number of sensors used). The position and the rotation angle of the tip are then obtained by integrating the

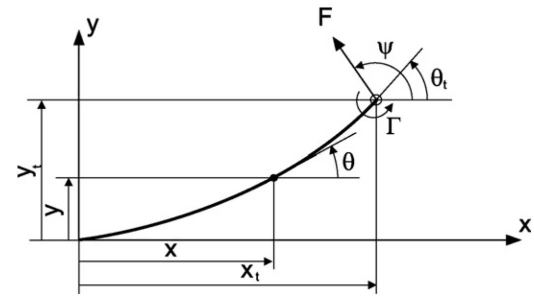

Fig. 1. Scheme of a deflected beam.

curvature function. We prove that FBG can be usefully employed as both static and dynamic sensors. Strain has been conventionally measured with resistive strain gauges, but the most recent developments in optical fibre sensors have given rise to the opportunity of using this technology to measure dynamic strains [13–16]. Although fibre optic technology has a prominent place in the communications industry, research into optical fibre sensors has also become important in the last three decades. Important reviews of optical fibre sensors are those of [17,18] which show some of the advantages presented by these sensors, such as low-loss transmission; high information carrying capacity; small size and weight; immunity to electromagnetic interference; the possibility of their use in an explosive atmosphere (gas or oil); the fact that all the sensors are written on a single optical fibre thus eliminating the complex wiring of conventional systems; resistance to corrosion and fatigue. These sensors have already been widely used in real-time structural health monitoring systems, such those of [19,20]. In this paper, we prove the effectiveness of these sensors for the development of a reliable sensor system for robotic applications. These sensors do not affect the manipulator dynamics owing to their small size and weight (similar to a human hair) and their use as strain sensors is therefore appropriate for robotic applications in which manipulators are very lightweight. Moreover, with these sensors, we avoid certain problems that appear with some traditional sensors, such as: complex cable networks used with common strain gauges; noise signals which may appear in some electrical sensors, such as strain gauges, piezoelectric and accelerometers as a result of electromagnetic interferences; or damage to the sensor system if an impact occurs between the arm and the environment which surrounds it. In addition to all of the above advantages of this sensor system (FBG array), the proposed estimation method can be applied in real-time control systems for flexible manipulators which undergo large deflections, such as that which appear in [21].

This paper is organized as follows: In Section 2 the deflection model of a beam is described for both static and dynamic cases. Section 3 shows the working principle of an optical fibre Bragg grating sensor. In Section 4 a method with which to estimate the deflection of a flexible beam is presented. In Section 5 some simulations are carried out to discover an appropriate number and the best distribution of the sensors along the beam. Section 6 shows a comparison of our estimation method with the well known linear method and Gu and Piedboeuf's method (which also uses distributed sensors to estimate tip deflection). In Section 7 static and dynamic experiments demonstrate the effectiveness of the proposed estimation method. Finally, our conclusions are set out in Section 8.

2. Model of a deflected beam

2.1. Static geometric model

Fig. 1 shows a scheme of a deflected beam which is fixed at one end, and whose other end is free. Certain external forces (a force F