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Geometric and elastic error calibration of a high accuracy patient positioning system

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Abstract

Important robotic tasks could be effectively performed by powerful and accurate manipulators. However, high accuracy is generally difficult to obtain in large manipulators capable of producing high forces due to system elastic and geometric distortions. In this work, a high-accuracy patient positioning system is calibrated, consisting of a six degree of freedom manipulator used to position cancer patients during proton therapy sessions. It is found that the original manipulator does not meet the required absolute accuracy due to both geometric and elastic deformation positioning errors. The experimentally identified errors are used to predict, and compensate for, end-point errors as a function of configuration and measured forces, improving the system absolute accuracy. Experimental results show that the adopted methodology is able to effectively correct for the system errors.

Keywords: Manipulator parameter identification; Elastic deflections; Medical applications

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1. Introduction

Large robot manipulators are needed in field, service and medical applications to perform high accuracy tasks. Examples are manipulators that perform decontamination tasks in nuclear sites, space manipulators such as the special purpose dexterous manipulator and manipulators for medical treatment [1–3]. In these applications, a large robotic system is often needed to have very fine precision. Its accuracy specifications may be very small fractions of its size. Achieving such high accuracy is difficult because of the manipulator's size and its need to carry heavy payloads. Further, many tasks, such as space applications, require systems to be lightweight, and thus structural deformation errors can be large.

In such systems, two principal error sources create significant end-effector errors. The first is kinematic errors due to the non-ideal geometry of the links and joints of manipulators, such as errors due to machining tolerances. These errors are often called geometric errors. Task constraints often make it impossible to use direct end-point sensing in a closed-loop control scheme to compensate for these errors. Therefore, there is a need for model-based error identification and compensation techniques, often called robot calibration.

The second error source that can limit the absolute accuracy of a large manipulator is the elastic errors due to the distortion of a manipulator's mechanical components under large task loads or even its own weight. Classical error compensation methods do not correct the errors in large systems with significant elastic deformations, because they do not explicitly consider the effects of task forces and structural compliance. Methods have been developed to deal with this problem [4,5], based on analytical models of the manipulator structural properties.

Considerable research has been performed in robot calibration [6–9]. In these methods, robot position accuracy is improved using compensation methods that essentially identify a more accurate functional relationship between the joint transducer readings and the workspace position of the end-effector based on experimental calibration measurements. A major component of this process is the development of manipulator error models, some of which consider the effects of manipulator joint errors, while others focus on the effects of link dimensional errors [10–13]. Error models have been developed specifically for use in the calibration of manipulators [14,15]. Some researchers have studied methods to find the optimal configurations during the calibration measurements to reduce the manipulator errors by calibration [9,16]. Solution methods for the identification of the manipulator's unknown parameters have been studied for these model-based calibration processes [17,18]. Most calibration methods have been applied to industrial or laboratory robots, achieving good accuracy when geometric errors are dominant.

Classical calibration methods do not explicitly compensate for elastic errors due to the wrench at the end-effector. While conceptually very similar to the classical geometric problem, the combined problem is far more complex. Compensating for geometric errors requires building a model that is a function of the n (usually six) joint variables. To compensate for a general six variable end-point task wrench (three end-point forces and three end-point moments) requires a model that is a function of both the joint variables and the end-point wrench variables, or a function of at least 12 variables. The time and cost of the physical calibration measurements often dominates the calibration problem. Simple calculations suggest that a brute force identification would require several million calibration measurements.