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Review

A review on two-link flexible manipulators

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ABSTRACT

This paper presents a survey in the field of two-link flexible manipulators (TLFMs). Two-link flexible manipulators are more used in comparison with other types of flexible manipulators. Therefore, this paper discusses various aspects of the reported works of TLFMs available in the literature. The papers based on TLFMs are classified into modeling methods, dynamical analyses, complexities involved and control schemes used. The modeling methods discuss the various types of modeling used for a TLFM. A brief note on the complexities involved in the flexible manipulators are presented. The main categories of the control problems addressed by the available papers are also discussed. The classification of the control techniques is made according to the nature of controllers. It is also mentioned in the paper as to whether the reported work deals with only simulation based results or are validated with the experimental work.

1. Introduction

Robot manipulators are an important research area. Advancement in the research of the manipulators is divided into two parts: rigid manipulator and flexible manipulator (FM). The current research is more inclined towards FMs because of their several advantages over rigid manipulators. Some important advantages of the FMs are: light weight, low energy consumption, smaller size, more workspace, portability, economical, etc. Some of the limitations of flexible manipulator include:

1. Control complexity
   - Non minimum phase system (Chen & Paden, 1996).
   - Under actuation problem (Xin, 2011).
   - Non collocation (Spector & Flashner, 1990).
2. Uncertainties
   - Truncation of flexible modes (Zhang, Feng, & Yu, 2004).
   - Control spillover (Khorrami & Jain, 1992).
   - Observation spillover (Khorrami & Jain, 1992).
   - Eigenvalue problem (Book, Maizza-Neto, & Whitney, 1975).
3. MIMO and nonlinear system (Wang & Gao, 2003).

The main reasons for the above complexities are the choice of dynamical model (Buffinton & Kane, 1985), required structure and operation of FMs (Buffinton, 1992). The dynamical model of a flexible manipulator depends on the type of modeling methods used. In the last three decades, many methods have been developed for modeling FMs. Generally, mathematical model of a manipulator is derived. Three methods are mainly used. These are finite element method (FEM) (Jonker, 1989), assumed modes method (AMM) (Morris & Madani, 1988) and lumped parameter method (Kim & Uchiyama, 2000). The most widely used method for modeling of FMs is AMM. It has several advantages like computational efficiency, flexibility in the choice of proper boundary conditions, etc.

The structure of an FM is also an important factor that needs to be focused while discussing the complexities associated with the dynamic model. Generally, the structure of an FM depends on its required operations. The operation of FMs is basically its control. The major categories of the control problems for flexible manipulators can be classified as: tip position control (Matsuno & Yamamoto, 2007), joint position control (Chen, Yu, Zhao, & Sun, 2011), tip trajectory tracking control (Pradhan & Subudhi, 2014), joint trajectory tracking control (Parida & Ranasingh, 2011), vibration control (Khorrami & Sandeep, 1994), motion control (Hu & Ulsoy, 1994), force control (Bazaei & Moallem, 2011), hybrid control problem, etc.

Different control techniques are developed depending upon the type of the control problems like PID control (Parida & Ranasingh, 2011), feedback control (Alazki, Ordaz, & Poznyak, 2013), LQR control (Cetinkunt & Book, 1986), observer based control (Mosayebi & Ghayour, 2010), SMC/VSC (Sanz & Etxebarria, 2006), adaptive control (Slotine & Weiping, 1998), H_∞ control (Sayahkarajy, Mohamed, Faudzi, & Supriyanto, 2016), backstepping control, optimal control (Cetinkunt & Book, 1986), LQR control,

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fuzzy logic control (FLC) (Wang, Feng, & Yu, 2008), artificial neural network (ANN) based control (Sasaki, Asai, & Shimizu, 2009), GA based control technique (Zhang, Feng et al., 2004), QFT control (Karande, Nataraj, & Ghandhi, 2009), hybrid control techniques, etc.

TLFMs are more suitable in industry, aerospace, nuclear plant, military, defense, agriculture, home care, etc., in comparison with single link and multi-link FMs. Thus, it is interesting and important to present the extensive and exclusive review on different aspects of dynamical complexities, modeling, control problems and control techniques reported on TLFMs. Only six papers are available on the review of FMs. These are reported by Benosman and Le (2004), Dwivedy and Eberhard (2006), Kiang, Spowage, and Yoong (2014), Hussein (2015), Sayahkarajy, Mohamed, and Faudzi (2016) and Rahimi and Nazemizadeh (2013). Benosman and Le (2004) reviewed the work from 1983 to 2004 and focused on the different aspects of the control techniques for multi-link flexible manipulators. A total of 119 papers published between 1983 and 2003 is considered by Benosman and Le (2004) for review of one-link, two-link and multi-link FMs. The review work of Dwivedy and Eberhard (2006) is focused mainly on the dynamical analyses of one, two and multi-link flexible link and flexible joint manipulators. Dwivedy and Eberhard (2006) also highlighted some experimentally validated works and control techniques published in between 1974 and 2005. A total of 433 papers is considered by Dwivedy and Eberhard (2006). Recently in 2014, a review is reported by Kiang et al. (2014). The work of Kiang et al. (2014) is based on different aspects of the control techniques and sensors reported on FMs. Kiang et al. (2014) reviewed the work on the types of control techniques till 2014 including intelligent control techniques and hybrid control which were not covered by Benosman and Le (2004). A total of 167 papers is considered by Kiang et al. (2014) and classified them in three main categories: modeling methods, control techniques and sensors used for FMs (flexible link, flexible joints including one-link, two-link and multi-links). Rahimi and Nazemizadeh (2013) presented review on the dynamical analysis and intelligent control of flexible manipulators. Rahimi and Nazemizadeh (2013) focused on the brief description on the three commonly used modeling methods, i.e., assumed modes method, finite element modeling method and lumped parameter method. The review work of Rahimi and Nazemizadeh (2013) considered different types of intelligent control (fuzzy logic, neural network, genetic algorithm) only for controlling the flexible manipulators. A total of 115 papers is considered by Rahimi and Nazemizadeh (2013). A review on control of flexible arm using visual servoing is presented by Hussein (2015). The review work of Hussein (2015) first presented the visual servoing architectures for the rigid robot, then use of visual servoing control for flexible manipulator is presented. Some problems like estimation of state variables, combination of different sensor properties and some applications are addressed by Hussein (2015). A total of 70 papers is considered by Hussein (2015) consists of rigid, flexible with single, two and multi-link manipulators. Sayahkarajy et al. (2016) presented a review on the modeling and control of multi-link flexible manipulator. A little more emphasis is given on the application and model based control of TLFMs. In Sayahkarajy et al. (2016), a manipulator is considered as TLFM which has either both flexible link, one flexible and other rigid. A total of 146 papers is considered by Sayahkarajy et al. (2016) for review but, only 50 papers are considered particularly on TLFM. It revealed from the available six review papers that (i) all types of FMs, i.e., single link, two-link, multi flexible links with flexible joints are considered, (ii) present two review papers considered the applications of intelligent control techniques, vision based control and some insight on modeling and control of multi-link, single link, two-link flexible manipulator (iii) the work of Sayahkarajy et al. (2016) considered only 50 papers on TLFMs. Thus, a rigorous review on all aspects of TLFMs is not available, to reflect the current state of art.

In this paper, a review on two-link flexible manipulators is presented. The following points highlight the contribution of the paper:

1. A total of 204 papers on TLFMs is considered from 1974 to 2016.
2. A brief note on the advancement and analyses of the modeling for TLFMs using different methods is presented.
3. The paper describes the complexities involved with TLFMs.
4. A note on the common type of the control problems associated with TLFMs is presented.
5. The paper describes the advancement in control techniques used to solve the control problems.
6. The control techniques used for TLFMs are categorized into different sections according to the nature of the controllers.
7. The paper also mentions whether the reported works are experimentally validated or not.
8. State of art is also presented at the ending of the paper.

The rest part of the paper is organized as follows. Section 2 describes the modeling methods used for FMs. Section 3 presents the review of some papers on dynamical analyses of TLFMs. The complexities involved in the FMs are highlighted in the Section 4. The main categories of the control problems for TLFM are presented in Section 5. Section 6 describes the control schemes used for TLFMs. Section 7 gives the review summary. The state of art and the conclusions of the this review work are presented in Section 8 and Section 9, respectively.

2. Modeling of two-link flexible manipulators

For improving the performance of a manipulator, the first step is to obtain a reasonably accurate dynamic model which involves the recognition of the flexible nature of the links. The mathematical structure of the flexible manipulator is derived from the energy principles. The characteristics of modeling of a flexible link are:

1. The flexible link has a rigid as well as a flexible body which is a distributed parameter system (Kanoh, Tzafestas, Lee, & Kalat, 1986).
2. Robot manipulator can have one or many links. During operation, the configuration changes and the analysis becomes very complicated with each link flexibility.

Physical limitations of flexible robot include:

1. Application of contact forces and torque only at the joint.
2. Finite number of sensors with finite bandwidth are to be used.

In mathematical modeling, if the flexibility effect is not taken into account, there occurs two kinds of error, the error in the torque requirements of the motors and the end-effector positioning inaccuracies. In order to have a precise end-effector positioning, there should be ideally little or no vibration at all. Hence, in order to achieve precise accuracy, the mathematical modeling of the system should be very accurate.

Generally, in robotic manipulator, the mathematical modeling is derived from energy principles. In a rigid manipulator, the kinetic energy and potential energy are stored by the virtue of inertia and its gravitational field position, respectively. But, in a flexible manipulator, the potential energy is stored by the virtue of its flexible links, drives and joints. Joints when modeled as spring can store only potential energy because of their concentrated compliance.

Shafts or belts are the drive components and due to their low inertia, they have less kinetic energy. Links are affected by torsion, compression and bending. Torsion stores less kinetic energy and greater potential energy. In the case of compression, it stores little