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Two-time scale control and observer design for trajectory tracking of two cooperating robot manipulators moving a flexible beam

Ali Tavasoli, Mohammad Eghtesad *, Hamed Jafarian

Department of Mech. Eng., Shiraz University, Mollasadra Ave., Shiraz, Fars, Zip Code: 71348-51154, Iran

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ABSTRACT

In this paper, we present two-time scale control design for trajectory tracking of two cooperating planar rigid robots moving a flexible beam, which does not require vibration measurement for the beam. First, the kinematics and dynamics of the robots and the object are derived. Then, using the relations between different forces acting on the object by the manipulators' end-effectors, dynamics equations of the robots and the object are combined. The resulting equations show that the coupled dynamics including beam vibration and the rigid motion take place in two different time domains. By applying two-time scale control theory on the combined dynamics, a composite control scheme is elaborated which makes the beam orientation and its center of mass position track a desired trajectory while suppressing the beam vibration. For the controller algorithm, first a slow controller is utilized for the slow (rigid) subsystem and then a fast stabilizing controller is considered for the fast (flexible) subsystem. To avoid requiring measurement of beam vibration for the fast control law, a linear observer is also designed. The simulation results show the efficiency of the proposed control scheme.

1. Introduction

Many manufacturing processes exploit deformable objects such as rubber tubes, beams, sheet metals, cords, leather products, and paper sheets which are now being automatically handled by special equipment with high costs and low efficiency or still done by human workers.

In space, large, lightweight structures, satellite solar arrays, and structural members all exhibit noticeable flexibility. In the aerospace industry, non-rigid composite materials are used to replace metals in many products. Underwater, large bundles of cabling, for power or for signals (e.g., sonar) are necessarily flexible. Many vehicles, including automobiles and airplanes, are manufactured by joining flexible plates of metal or composite materials together. In shipbuilding industries, flexible frames and plates are used in the assembly of various kinds of ships. In industry, spring-loaded parts are becoming more common, particularly as design for assembly becomes more prevalent.

In many of these applications, vibration-free movement of flexible objects is required. To handle flexible objects by automatic machines, other than using some special tools and devices, robot manipulators can also accomplish the task. Robotic manipulation of flexible objects is a complex and challenging problem and has recently attracted a lot of attention due to its current and potential applications in industry and space.

There are two problems that need to be addressed in flexible object manipulation; the object dynamics modeling and the control design. Mathematical modeling of handling flexible objects has been extensively studied, [1–4]. Kita et al., [5], used stereo cameras and 3D shape estimation for observation, modeling and handling of clothes. Wakamatsu et al. used differential geometry for static modeling, [6], and dynamic modeling, [7], of linear object deformation. The motion of a flexible object, for example a beam, consists of its rigid body motion and its vibration. The rigid body motion is regarded as the position and orientation of the beam as if the beam were a rigid body. The vibration of the beam is then taken into account with respect to the rigid body motion. This vibration can be modeled by assuming the flexible object as a distributed parameter system or assuming that it consists of lumped masses and springs (infinite or finite dimensional modeling). Usually mode summation procedure, finding the mode shapes and natural frequencies of the beam, is used. Tanner and Kyriakopoulos viewed a manipulated deformable object as an underactuated mechanical system [3]. They discussed controllability issues and the results on the nature of the constraints and the controllability properties of an important class of deformable objects being modeled by finite element method were stated.

Zheng and Chen [8] and Arai et al., [9] examined position control of flexible objects by one robot manipulator. Their purpose was to insert flexible object's one end into a hole in concrete while moving the other end by a robot manipulator. Nakagaki et al., studied

* Corresponding author. Tel.: +98 711 2303051; fax: +98 711 6287508.
E-mail addresses: p.tavasoli@gmail.com (A. Tavasoli), eghtesad@shirazu.ac.ir (M. Eghtesad), hamed.jafarian@gmail.com (H. Jafarian).

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the same problem using static shape functions of the object, [10]. Yukawa and Uchiyama, unlike the above studies, dealt with the problem of handling one end of the flexible object by a robot while the other end was fixed in the wall, [11].

The importance of multi-arm robotic systems has been realized by the robotics community. Having a wider set of functional capabilities, robots with several manipulators can be successfully used not only in industry but in unstructured environments as well. The advantages of multi-arm robot utilization have been especially realized in the space applications where, as it is expected, remote manipulation systems with cooperating arms may be required to perform future in-orbit construction, servicing and repair tasks with the minimum involvement of astronauts. In these applications the object to be manipulated may be too heavy, too large or too flexible. If the load is heavier than the carrying capacity of a single robot, multiple robots can distribute the load among them and better move the object. Also, if the object shows some flexibility, multiple robots can move the object much better and more accurately than one robot, just the same as a human with two arms can move a flexible object better than moving it by only one arm.

Chen and Zheng studied the coordinating of two grippers to handle a deformable object, [12]. They investigated passive approaches for vibration-free handling of deformable beams, [13]. Svinin and Uchiyama applied the geometrical analysis to perform the position control and suppression of the flexible object vibration, [14]. Sun, Liu and Mills studied a more general case: handling a flexible object with an arbitrary shape, [15]. They showed that under a simple PD position feedback, the position/orientation of a general flexible object handled by two manipulators are able to approach the desired ones and at the same time the vibration of each contact point can be suppressed. Kosuge et al., used static bending functions of the flexible object for the same purpose, [16]. Doulgeri and Peltekis considered a rectangular object grasped by two robot fingers with spherical end-effectors that were allowed to roll along the object surface, [4]. Yukawa, et al., assumed the handled beam has two free ends while the contact points with the robots' end-effectors were not located at the ends of the beam, [17]. They also assumed that the beam dynamic parameters are not negligible and proposed a controller which was robust while the vibration could occur in transverse and rotational directions, [18]. Sun and Liu proposed a coupled position/force control law and also an impedance control for handling a flexible beam by two robots, [2,19]. Also, Wada et al., [20], used simple PID for indirect positioning of deformable objects. They considered the stretch of a flexible object by using a springs-lumped masses system.

The above works only contribute to the regulation problem of handling a flexible object to a desired position/orientation using robot manipulators. The regulation problem is less complicated when compared to the tracking problem since stability analysis of vibration suppression when the object arrives at the desired position/orientation and ends its rigid body motion is much simpler than when it continues its motion to track a desired trajectory where the object motion may induce additional vibration.

Svinin and Uchiyama dealt with controlling the transfer motion of a flexible object using a combination of feedforward and feedback coordinations, [21]. AlYahmadi and Hsia presented a simple and computationally efficient scheme for handling a flexible object by two coordinated manipulators, [22]. They also used sliding mode control for the same problem, [23,24]. Jiang and Kohno dealt with the issues of vibration measurement and control design in order to establish a flexible objects manipulating system using industrial robot arms, [25]. They presented a method for vibration measurement of the flexible object using a force/torque sensor equipped at the wrist of the robot and proposed a linear feedback control for the flexible object. Sun and Liu discussed the issue of hybrid position and force control of a two-manipulator system moving a flexible beam using saturation control approach, [26].

By a thorough look at the literature, the following points can be observed:

- Often, researchers use non-model-based and vision-based approaches.
- In the model-based works, regularly, very simple models are utilized; they model deformable objects as simple lumped-mass systems or for more complicated cases, they mostly use rods or strings.
- A few researches for beams and plates are noticed; however, commonly the static effects are considered in those works.
- The most recent researches focus generally on regulation and only a few works for tracking of flexible objects and simultaneously their vibration suppression are seen.
- Control of two rigid robots moving a flexible object, in all of the above mentioned works for tracking, has required vibration measurement of the flexible object, which resulted in the use of some devices such as strain gauges and piezoelectric materials at different points of the object or force/torque sensors at its contact points with the robots.

The motion of a flexible beam consists of its rigid body motion and its vibration. These two motions happen in two different time scales where the rigid motion can be regarded as the slow motion while the vibration appears as the fast motion. Therefore, for moving the mass center of the rigid body on a trajectory of desired positions/orientations, while suppressing the vibration of the beam, two-time scale control theory can be applied. The underlying idea of two-time scale control theory is to decouple the system dynamics into the slow and fast subsystems with separate time scales which is already the case for our system. Control design may then proceed for each lower-order subsystem, and the results are combined to yield a composite controller for the original system. The design is sequential in general, since the fast control design depends on the slow control design, [27]. For our system, the slow subsystem represents the rigid system where the object has no flexibility and the fast subsystem is a linear time variant system. To control the slow subsystem we can use any control scheme applied for the two cooperating rigid robots moving a rigid object, [28]. For the fast subsystem we may use the linear control theory where the poles of the fast subsystem can be placed on their desired values. To avoid vibration measurement difficulty, in this paper, for our proposed control scheme, we design a linear time variant observer that estimates the flexible coordinates for the feedback control of the fast subsystem.

In this paper, two planar robots, each with three revolute joints, grasping and moving a flexible beam are considered, see Fig. 1. The kinematics and dynamics of rigid robot manipulators and the flexible beam are derived. Replacing the contact forces/moments, between two rigid robots and flexible beam, from the robots dynamics into the beam dynamics, the combined system dynamics is obtained. To carry out trajectory tracking of the mass center of the beam, while suppressing the vibration of the beam, we use two-time scale control theory where the system is decoupled into slow (rigid) and fast (flexible) subsystems is applied. To control the slow subsystem, two rigid robots moving a rigid object, a PD controller is used. Linear control theory and observer design are considered to place the poles of the linear fast subsystem into their desired values without vibration measurement of the beam. At the end, the simulation results show that the proposed control and observer scheme is a convenient and effective choice.