Multi-Arm Cooperating Robots

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Multi-Arm Cooperating Robots

Dynamics and Control

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PREFACE

Under the notion ‘cooperative work’, is understood, in a widest sense the realization of a coordinated action of several participants (cooperators) engaged in a given task. Cooperative work is performed by a cooperative system consisting of cooperators and work object.

Cooperative work incorporates the joint work of the cooperators, their coordinated action in task execution, contact with the environment, and mutual contact of the cooperators, either directly or indirectly via the work object.

In joint work, the action of individual participants in the cooperation cannot be independent in time and space from the work (action) of the other participants. It is assumed that the actions of the cooperation participants take place simultaneously and not consecutively. Thereby cooperation means that each participant in the joint work carries out its own work taking care of the state of the other cooperation participants. Namely, to every different state of an individual cooperator corresponds an equal number of different states of the other cooperation participants. It is assumed that each cooperator obtains, in some way or other, information about the state of the other participants. The object on which cooperative work is performed, along with all cooperation participants, represent to an individual participant a dynamic environment with which it interacts.

There are a lot of tasks that can be performed in cooperation. Most often they are related to manipulating bulky objects whose weights exceeds the working capacities of the individual participants in the cooperation. For example, assembly of mechanical blocks carried out by several participants is a common case in technological practice. A frequent task is passing an object from one participant or group of participants in the cooperation to another participant or group of participants. In cooperative work, the participants perform mutually coordinated actions, while ensuring different types of contacts or avoiding them.

If, however, the extremities of an animal are considered as participants in cooperative work (manipulation or locomotion), then such synchronized motion is a specific cooperative task. The same also holds for the work (cooperation) of the fingers of a hand holding an object.

Analogous to the cooperative work of an animal's extremities is the robotic manipulation performed by several robots or by the fingers of an artificial hand. While object grasping and transferring, as well as the work on it, are the tasks of manipulation cooperation, synchronized work of the lower extremities represents locomotion cooperation that enables motion of the locomotion platform (vehicle) in the form of a bipedal or, more frequently, multipedal gait. Therefore, cooperative work of artificial systems has its biological counterpart in locomotion-manipulation activities of living beings. It can be said that results of studying active locomotion-manipulation mechanisms and their cooperation counterparts with living beings can be generally used in the corresponding procedures of the synthesis of artificial gait and control systems in manipulation and locomotion robotics.

When cooperative manipulation is concerned, a fundamental research task is to find out the appropriate way to control the system of robots and object in the work space at any stage of cooperative work. This requires an exact understanding of the physical nature of the cooperative system and deriving the mathematical basis for its description. In the realization of this goal, two crucial problems are encountered. The first of them is the occurrence of kinematic uncertainty and the second one is the force uncertainty in the mathematical description of the physical nature of the cooperative system. These problems have been considered by a number of authors [1–5, 12–20, 42–46, 50–55], and they can be interpreted simply as the impossibility to uniquely determine contact forces, driving torques of the manipulation mechanism, as well as kinematic quantities of cooperating robots, starting from the required motion of the object of cooperative manipulation.

On the basis of their research in the domain of cooperative manipulation, the authors of this monograph have recently come up with several consistent solutions concerning cooperative system control. This was achieved by solving three separate tasks that are essential for solving the problem of cooperative manipulation as a whole. The first task is related to understanding the physical nature of cooperative manipulation and finding a way for a sufficiently exact characterization of the cooperative system statics, kinematics, and dynamics. After successfully completing this task, in the frame of a second task, the problem of coordinated motion of the cooperative system is solved. Finally, as a solution to the third task, the control laws of cooperative manipulation are synthesized.

The starting point in dealing with the above three tasks of cooperative manipulation was the assumption that the problem of force uncertainty in cooperative manipulation can be solved by introducing elastic properties into the cooperative system. This monograph is concerned with the case when elastic properties are introduced only in that part of the cooperative system in which force uncertainty arises. Coordinated motion and control in cooperative manipulation are solved as the problem of coordinated motion and control of a mobile elastic structure, taking into account the specific features of cooperative manipulation.

The contents of this monograph are organized into seven chapters.

Chapter 1 defines the notions and basic problems related to a cooperative system, cooperative manipulation and contact in cooperative manipulation. Also, coordinate systems used to describe the cooperative system characteristics are introduced.

In Chapter 2, some basic problems of cooperative manipulation are analyzed and a mathematical interpretation of the problem of kinematic uncertainty and force uncertainty is given.

Chapter 3 provides a concise systematization of previous solutions of the task of cooperative manipulation. It gives an analysis of the assumptions that are to be introduced in order to correctly solve the problem of cooperative manipulation under static conditions. It is shown that the problem cannot be solved without introducing the elastic properties of the loaded structure. Further, it is demonstrated that the cooperative system must be approximated by a mobile elastic structure. Also, it is shown how the problem of force uncertainty can be resolved by considering the deformation work of the elastic structure as a function of absolute coordinates. In other words, on the basis of such analysis, using a concrete simple example, a way is indicated for establishing a methodology of modeling dynamics of complex cooperative systems.

The difference between the way of considering statics and dynamics of the elastic structure of cooperative systems in the present book and in the available literature is in the following. In the literature [1–5], the authors start from the *a priori* implicit assumption that elastic displacements, needed to define the position of the elastic system in space, are not independent variables (state quantities), but they represent the displacements given in advance (like, for example, the known displacement of the support of an elastic structure when defining its statics [6, 7]). A consequence of such an *a priori* assumption is that the position of the unloaded state of elastic structure in the motion is known in advance, and the stiffness matrix of the elastic system is nonsingular. The elastic structure position in space can be defined by choosing any point, including a contact one. As a consequence, the manipulator internal coordinates that contact point belongs to, are given in advance, i.e. they are not state quantities. In deriving mathematical the model used in this work, it is assumed that all displacements of the elastic system (i.e. position of contact points and manipulated object mass center) are independent variables (state quantities), necessary and sufficient for describing elastic-system dynamics [8]. A consequence of such an assumption is that the stiffness matrix of the elastic part of the cooperative system is singular, i.e. it has to also contain the modes of motion of the elastic structure as of a rigid body.

Chapter 4 is concerned with the task of cooperative manipulation of a rigid object by an arbitrary number of rigid manipulators, a task that has been most often considered in the literature. The task was modified by introducing elastic interconnections between the object and manipulators. The problem of modeling cooperative manipulation is analyzed in detail. In order to make the cooperative system properties more comprehensible, assumptions are introduced by which the problem of modeling is significantly simplified. Namely, the cooperative system is divided into its rigid part (manipulators) and elastic part (object and elastic interconnections). Each part is modeled separately using Lagrange equations. The elastic system model is derived on the basis of the description of its deformation work as a function of internal forces defined in dependence of absolute coordinates (extended method of finite elements [9]). The cooperative system dynamics is modeled for the displacement with respect to the elastic system unloaded state. This means that the reference coordinate frame is attached to the unloaded state of the elastic system. The general motion of the cooperative system is described in terms of absolute (external) coordinates, and the mathematical forms of motion equations are generalized. Stationary and equilibrium states of the cooperative system are analyzed in detail. The results obtained by model testing for selected examples show the consistency of our approach to modeling cooperative manipulation.

The problem of the synthesis of cooperative system nominals is essentially made more complex by introducing the elastic properties of the cooperative system [10]. Solving this problem is the subject of Chapter 5, where the nominals are synthesized using the properties of cooperative manipulation, as well as the properties of macro and micro motions. The cooperative system motion, in which the object is firstly gripped and then transferred, whereby the manipulator's motion does not significantly disturb the gripping conditions (i.e. the geometric configuration realized at the end of the gripping phase is not significantly changed) is adopted as the system's coordinated motion. The coordinated motion of the cooperative system is synthesized in a two-stage procedure, in which contact loads of the elastic system are approximately determined. On the basis of the approximate values of contact forces or driving torques, adopted as nominals, procedures are proposed for the synthesis of the other nominal quantities of the overall cooperative system. The synthesis procedures are illustrated by a simple example.

The control of cooperative manipulation is analyzed in Chapter 6 for the model of cooperative manipulation dynamics with the problem of force uncertainty resolved. The analysis encompasses definitions and criteria of controllability and observability of linear systems from the point of view of mapping the domains of inputs, states, and outputs. It is shown that the conclusions about mapping of linear systems can be applied without any change onto the mapping of the domains of inputs, states and outputs of the nonlinear systems. This was the basis for deriving conclusions on the controllability and observability of cooperative systems. Results of this analysis are applied to perform mapping between two of any of the following sets: the set of internal coordinates, the set of external coordinates, the set of driving torques, the set of contact forces, and the set of elasticity forces. A systematization of the controlled outputs along with the typification of control tasks in cooperative manipulation is carried out. Two types of tasks are selected [11]. Control laws are proposed for the asymptotically stable tracking of the object nominal trajectory and nominal trajectories of contact points of the manipulators-followers, along with control laws for the asymptotically stable tracking of the object trajectory and nominal contact forces at the contact points of the followers. The analysis also encompasses the behavior of uncontrolled quantities. The choice of the control laws and behavior of the controlled cooperative system are illustrated with a simple example.

The concluding Chapter 7 provides a brief survey of the research results that have been achieved in studying cooperative manipulation, which is the subject of this monograph. The conclusions are grouped according to particular topics. Also, some possible directions of the future research are indicated.

A complete derivation of the elastic system dynamic model for its immobile and mobile states is given in Appendices A and B, respectively.

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