Robotics and Autonomous Systems 83 (2016) 169–176

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

journal homepage: www.elsevier.com/locate/robot

Coordination control of robot manipulators using flat outputs

Elisha D. Markus [a,*], Hamam Yskander [b], John T. Agee [b], Adisa A. Jimoh [b]

[a] Department of Electrical, Electronic and Computer Systems, Central University of Technology Free State, South Africa

[b] Department of Electrical Engineering, Tshwane University of Technology Pretoria, South Africa

HIGHLIGHTS

- Flatness based coordination of multiple interconnected flexible robots presented.
- Constraints of coupling dynamics are taken into account in the synchronization design.
- Flexibility in the choice of synchronization parameters.
- Synchronization of multiple robots is enhanced via trajectory design based on flatness.

ARTICLE INFO

Article history:
Received 19 March 2015
Received in revised form
24 April 2016
Accepted 13 May 2016
Available online 21 May 2016

Keywords:
Differential flatness
Synchronizing control
Flat output
Flexible robot
Robot formation

ABSTRACT

This paper focuses on the synchronizing control of multiple interconnected flexible robotic manipulators using differential flatness theory. The flatness theory has the advantage of simplifying trajectory tracking tasks of complex mechanical systems. Using this theory, we propose a new synchronization scheme whereby a formation of flatness based systems can be stabilized using their respective flat outputs. Using the flat outputs, we eliminate the need for cross coupling laws and communication protocols associated with such formations. The problem of robot coordination is reduced to synchronizing the flat outputs between the respective robot manipulators. Furthermore, the selection of the flat output used for the synchronizing control is not restricted as any system variable can be used. The problem of unmeasured states used in the control is also solved by reconstructing the missing states using flatness based interpolation. The proposed control law is less computationally intensive when compared to earlier reported work as integration of the differential equations is not required. Simulations using a formation of single link flexible joint robots are used to validate the proposed synchronizing control.

1. Introduction

The problem of robot coordination and cooperation has been studied by researchers over the years [1–9]. The coordination control problem involves synchronization of a formation of robot manipulators in a specific task. It may be required for a swarm of robotic manipulators to cooperate towards accomplishing a given mission in form of a common predefined trajectory. There are many areas where single robots are limited in terms of manipulability, flexibility, reachability and maneuverability [10]. In such instances, cooperative robots are deployed to execute the job. Such cooperative multi-robot behavior results in increased efficiency and reduced turn around times in industrial processes. Reliability is also improved when multi-robot systems are put in parallel redundant formations. Robot cooperation has been a major area of application in space applications [11–13], confined spaces like in the mines [14–16], assessing hazardous areas [17,18], power systems like the overhead Transmission Line Inspection Equipment [19,20] and in production lines [21].

This work is motivated by recent results in the area of robot coordination. For instance in [21,22] a synchronized tracking control was developed for the multi-robotic manipulator systems (MRMS) in the presence of uncertain dynamics. The authors also applied neural network to enhance synchronization of the MRMS. Kris in [11] presented a nonlinear control solution for spacecraft formations indicating the stability of their controllers. Chiddarwar [23] used multi-agent theory to motion planning of coordinated multiple robots. Every participating robot in the coordinated task is considered as an agent. The method allows for the design of optimal trajectories in the presence of dynamic and kinematic constraints. In [24], a new concurrent synchronization scheme for Lagrangian dynamics was proposed. It

* Corresponding author. Tel.: +27 515073514.
E-mail address: emarkus@cut.ac.za (E.D. Markus).

http://dx.doi.org/10.1016/j.robot.2016.05.006
0921-8890/

is a decentralized control strategy where adaptive synchronization and partial state coupling is used. Other works by Lee [25], showed that feedback linearization may be employed to achieve consensus in nonlinear systems. Further work done by Bidram [26], presented a heterogeneous multi agent cooperative formation synchronized using feedback linearization. This approach led to a higher order synchronization problem which is effectively controlled using a microgrid as a test bed. While most of these studies are recent, they often require cross coupling within the network topology and resolution of communication protocols to achieve coherent coordination. The structure of these systems can be relatively complex and computationally expensive.

In this paper, the control problem is formulated as follows: it is desired to design a feed-forward and feedback control that synchronizes two or more robots working together. It is assumed that only one measured parameter is available to the lead robot. The remaining control parameters such as velocities and acceleration need to be reconstructed. The other robots in the network will have to synchronize their control variables when interconnected to the leading robot. The network of robots may be of similar or different dynamics. It is assumed that all the robots in the formation are differentially flat hence each of the robots can be characterized in terms of their respective flat outputs. The flat output is a fictitious parameter that always has a physical meaning. The flatness-based cooperative control depends on the flat outputs and their derivatives up to a certain order and not on the system state variables.

The benefits of using the flat outputs as synchronization parameters are numerous; the nonlinear system is well characterized by its flat output and defines the system behavior globally as opposed to using just any state parameter. The flat output can be freely chosen thereby providing a flexibility in design of the controller and liberty to synchronize heterogeneous robot formations. Unmeasured parameters can be easily estimated in the control problem. Lastly, motion planning which is a major benefit of using differential flatness is effortlessly solved in the coordination schemes.

The main aim of this paper is to study the synchronization of cooperating robots where the flatness of the robots has been established to show that any system parameter such as system states or inputs can be freely selected as the synchronizing parameter. This is made possible by the flat output which is a fictitious parameter that can be freely chosen. This contributes to the problem of cooperation of robot manipulators.

The coordination control problem is posed using two or more flexible robot manipulators. Flexible robots are employed in situations where speed, dexterity and compliance are required. Cooperation of flexible manipulators with effective vibration control systems will be more beneficial when compared to single robots in terms of their low mass of moving parts, extended reach and increased accuracy, reduced cost and power consumption.

It is assumed that at least one robot parameter can be measured. The other unmeasured parameters can be estimated using flatness based reconstructors (see [27–29]). In this work, the concept of flat coupling in the interconnections is proposed whereby only the flat outputs are used to connect the systems together. The proposed synchronization controller based on differential flatness is quite attractive since velocity and acceleration sensors will not be required thereby reducing the cost of the controller. A similar work in literature is that of Levine [30] where synchronization was carried out for a pair of independent windshield wipers. In this paper, clock control was used to achieve synchronization for torque limited motors in a leader–follower formation.

The rest of the paper is hereby presented: the model of the cooperative robot formation is presented in Section 2. Differential flatness is revised in Section 3. The proposed controller is presented in Section 4. Simulations and results obtained are illustrated in Section 5. The concluding remarks are recorded in Section 6.

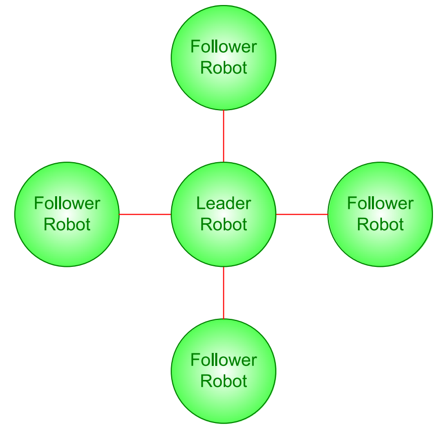

Fig. 1. Model of robot formation.

2. Modeling the cooperative system

The robot cooperative system can be modeled as a set of homogeneous or heterogeneous formation. Once the flatness property of each robot is established, synchronization can take place for the task at hand. The formation has a leader robot with dynamics $f(q_L, \dot{q}_L, \ddot{q}_L)$ where q_L is the generalized coordinate of the leader robot. For this study we consider a single link robot with joint flexibility to illustrate our proposed control. The flexible manipulator arm has been described in our earlier studies [31]. We also assume that the cooperative robots formation is similar in dynamics. However to differentiate between them, different physical parameters such as inertia and mass values for the links can be used. Joint flexibility magnifies the control problem since we have to account for link deflections which are unactuated and difficult to track. This is more so as the model of the flexible robot arm is oriented vertically which introduces gravity in the spring. This means that any torque on the motor will result in displacements both at the motor and in the link deflection.

Fig. 1 shows a schematic of the robot formation. The formation represents a leader robot and follower robots. The leading robot provides the reference trajectory to be synchronized by the other follower robots. If we are able to plan the motion for the lead robot and the respective follower robots are able to track this lead motion, then the coordination problem is said to be resolved. The synchronization of all the motions of the multi robotic system can be seen as a form of cooperation or coordination of the system. Hence synchronization, coordination, and cooperation will be used interchangeably to describe similar behavior of the robot formation. In this study, we will consider two similar cooperating robots. One is the robot leader denoted in the dynamic equations as L and the other a follower F. The dynamics of the leader and follower robots are given by [31]:

$$\begin{aligned}
&J_{Li}(\ddot{\theta}_i + \ddot{\alpha}_i) + K_{si}\alpha_i - m_i g h_i sin(\theta_i + \alpha_i) = 0 \\
&(J_{Li} + J_{hi})\ddot{\theta}_i + J_{Li}\ddot{\alpha}_i - m_i g h_i sin(\theta_i + \alpha_i) = \tau_i - B_i\dot{\theta}_i \\
&y = \theta_i + \alpha_i \quad i = L, F
\end{aligned} \tag{1}$$

L and F signify the leader and follower robots. θ and α are the motor angle and link deflections respectively. J_L, K_S, m, g, h, J_h and B_i are constant physical parameters that are known. The Torque of the motor is driven by the voltage applied to the armature V. The relationship between Torque and the applied voltage is:

$$\tau = \frac{K_m K_g}{R_m} V - \frac{K_m^2 K_g^2}{R_m} \dot{\theta} \tag{2}$$

where $\dot{\theta} = w$, $i = \frac{\tau}{K_g K_m}$ and $V = iR_m + K_m K_g w$.

Henceforth, the voltage V applied to the armature will be used as our control variable for the flexible robot.