Mechatronics 53 (2018) 56–71

Contents lists available at ScienceDirect

Mechatronics

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

Equilibrium area analysis for nonprehensile manipulation of a three-link object by two cooperative arms in a plane☆

Omar Mehrez[a,b,c], Zakarya Zyada[a,d,*], Tatsuya Suzuki[c,e], Yoshikazu Hayakawa[c,e], Ahmed Abo-Ismail[b], Shigeyuki Hosoe[c,e]

[a] Mechanical Power Engineering Department, Faculty of Engineering, Tanta University, Siberpay, Tanta 31511, Egypt
[b] Mechatronics and Robotics Engineering Department, Egypt-Japan University of Science and Technology (E-JUST), P.O. Box 179, New Borg El Arab City, Alexandria 21934, Egypt
[c] RIKEN-TRI Collaboration Center for Human-Interactive Robot Research, Moriyama-ku, Nagoya 463-0003, Japan
[d] College of Engineering, Taibah University, Taibah, 42353 Medina, Kingdom Saudia Arabia
[e] Mechanical Science and Engineering Department, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan

ARTICLE INFO

Keywords:
Equilibrium analysis
Frictional contact
Nonprehensile manipulation
Cooperative arms

ABSTRACT

Equilibrium points exploration is crucial for successful nonprehensile manipulation of multi-link objects by cooperative arms which is promising for a class of future robotics applications. This paper presents the equilibrium area numerical analysis, with experimental verification, for nonprehensile manipulation of a three-rigid link object by two cooperative arms in a plane. Inspired by an assistive nursing robot project for manipulating a patient, the interaction between the object and the arms is performed in a way that one of the arms contacts two links of the object while the other arm contacts the object third link. It would be a useful step for the most complicated process of a patient manipulation. The purpose of the equilibrium area analysis is to obtain the equilibrium contact area, associated with different interaction forces, for statically holding the object at all its possible configurations. The dynamic model of the system is presented from which the static equations are deduced. Static equations are analyzed in the presence of friction forces and motion constraints leading to equilibrium contact lengths for a range of angles leading to equilibrium area for every object's configuration. Numerical simulation results for the equilibrium area analysis are presented. Experimental results, for validating the presented numerical results, are also introduced.

1. Introduction

Nonprehensile whole-arm manipulation is the manipulation without form- or force-closure [1]. It utilizes manipulators with simple design to deliver more DOFs to the manipulated object. It is an alternative technique for manipulating heavy and/or large objects, where all available contact surfaces of the manipulator are utilized. The manipulation problem becomes more complicated concerning articulated objects. In this case, cooperative manipulation using multi-manipulators is proposed to perform the object manipulation [2]. This work presents the equilibrium analysis for nonprehensile manipulation of a three-rigid link object by two cooperative arms in a plane which is a remarkable key for multi-link object manipulation planning and/or control.

There is much research work in the literature dealing with the nonprehensile manipulation of one-link object using either one manipulator [3–6], or more than one manipulator [7,8]. The problem of nonprehensile manipulation of a multi-link object using multi-manipulators is still a promising challenge for research. An elementary study for the basic task requirements and its difficulties is given in [2]. More mature studies for the modeling and the design of model-based and fuzzy controllers of a two-rigid link object manipulated by two arms is presented in [9–12].

1.1. About the paper

In this work, nonprehensile planar manipulation of a three-rigid link object using two cooperative arms is proposed. This underactuated system is not studied before. The main goal is to perform an equilibrium analysis; obtaining the equilibrium contact points, associated with appropriate interaction forces, required for statically holding the object for all its possible configurations in the presence of the friction. This

☆ This paper was recommended for publication by Associate Editor Dr Wei-Hsin Liao.

* Corresponding author at: Mechanical Power Engineering Department, Faculty of Engineering, Tanta University, Siberpay, Tanta 31511, Egypt
E-mail address: zzyada@f-eng.tanta.edu.eg (Z. Zyada).

https://doi.org/10.1016/j.mechatronics.2018.05.002
Received 23 May 2017; Received in revised form 12 January 2018; Accepted 12 May 2018

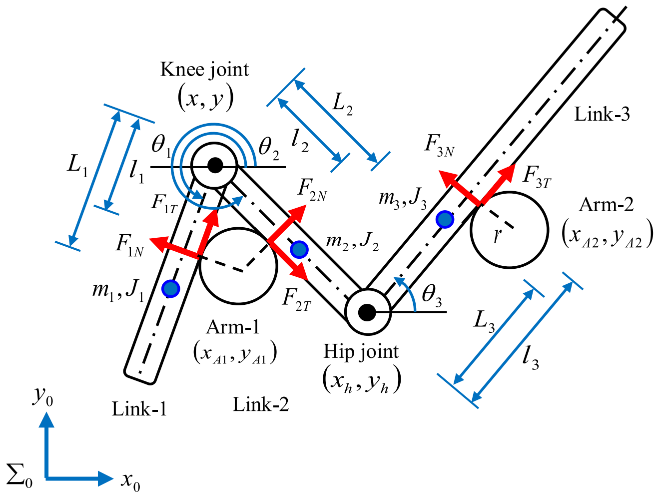

Fig. 1. System schematic diagram.

permits placement of the arms in contact with the object at any point in a region of equilibrium and at the same time providing the required interaction forces for statically holding the object. The interaction between the object and arms is performed in a way that one of the arms contacts two links of the object while the other arm contacts the object third link. This configuration is inspired by a patient lift using a two-arms humanoid robot [13], see Fig. 1. It would be a useful step for the most complicated process of safe patient manipulation. A previous work of the authors has been done to obtain the equilibrium points in the frictionless case as well as designing a model-based controller for tracking the object state variables according to specified trajectories, [27,28]. In addition, a preliminary work related to explore the frictional effect on the equilibrium contact lengths has been discussed in [29]. Here, the frictional effect on the equilibrium contact angles is firstly introduced in addition to the work presented in [29], from which the concept of the equilibrium contact area is produced and experimentally verified.

1.2. Literature review

Equilibrium analysis is important for successful nonprehensile manipulation planning and control. The presented review is related to previous work of the equilibrium analysis for different object/manipulator arrangements either with or without considering the frictional effect. For the problem of the two-link object in [10], the equilibrium analysis of the object is analytically introduced for getting the equilibrium contact points at all possible object configurations. A unique set of equilibrium points, normal forces at contact locations, is clarified. However, the effect of tangential forces in the presence of friction on the equilibrium points has not been studied.

The effect of the friction at the contact on the equilibrium has been discussed, either for one-link or articulated object and undergone either nonprehensile or grasping manipulation. Regarding nonprehensile manipulation, the frictional effect is considered for the equilibrium analysis of one-link object manipulated by a flexible sheet in [14], where the tension generated in the sheet is utilized to control the object pose. The object position and orientation are controlled by manipulating the sheet under no-slip condition; that is the tension in the sheet is less than the static friction force for all contact points. Another work is the planar manipulation of one-link object using multi-fingered robot hand introduced in [15,16]. The manipulation is altered between sliding and tumbling operations, which is undergone the non-sliding condition. The tangential component of the interaction force compared to the friction force is the key difference to alter between the two processes. A hierarchical approach for planning sequences of nonprehensile and prehensile actions to a rigid-object is given in [17]. The last step of the proposed hierarchical approach is to determine the set of feasible contacts between the object and the manipulators according to its pose at which the contact forces can stabilize the object against gravity. This range of feasible contacts depends on the object orientation and the coefficient of friction.

Regarding grasping manipulation, the frictional effect is also remarkable whether the object is one-link or articulated one. For a rigid-link object; three and four contacts are sufficient to immobilize 2D and 3D objects, respectively, because of the frictional effect [18]. Extended studies for different object shapes have been done to meet these criteria and provide precise grasps; such as ones done for 2D objects in [19,20], and for 3D objects in [21,22]. However, precise placement of the contacts exhibits some errors which led to the concept of independent contact regions (ICRs) introduced in [23], where contacts could be applied within certain regions while providing force-closure grasp regardless of the exact contacts. Relevant work to this concept could be found for example in [24].

Considering grasping manipulation of articulated objects, a relevant work [25] presented a systematic procedure to find a set of frictionless contact points that immobilizes a 2D serial chain with n polygons. Another work, [26], proposed a procedure to compute ICRs on 2D articulated objects considering frictional contacts. The obtained ICRs guarantee the immobilization of all the object internal degrees of freedom, and the spatial immobilization of the object.

In this paper, exploration of friction effect on the equilibrium points of contact is numerically analyzed and experimentally verified, for nonprehensile manipulation of a three-rigid link object by two cooperative arms in a plane, see Fig. 1. This permits placement of the arms in contact with the object at any point in a region of equilibrium and at the same time providing the required interaction forces for statically holding the object. The paper presents the concept of the equilibrium contact area. It is a range of equilibrium contact lengths for a range of angles leading to an equilibrium area for every object's configuration. It is obtained under the assumption of non-sliding condition; that once the tangential force exceeds the frictional force at one contact, sliding of the object over the arms occurs. The dynamic model of the system is presented from which the static equations are deduced. A numerical procedure for obtaining the equilibrium contact angle range, and the equilibrium contact lengths range from which the equilibrium contact area is presented for all possible configurations. Experimental verification of the numerically obtained equilibrium contact area is then introduced.

The paper is organized as follows: Section 2 presents the system model. A numerical procedure for obtaining the equilibrium angle range, the equilibrium length range, and the equilibrium area for all possible object configurations is presented in Section 3. Section 4 introduces and discusses the simulation results. A description of the experimental system, experimental procedure for verifying the numerically obtained equilibrium contact area, and experimental results are introduced in Section 5. Conclusions and recommendation for future work are presented in Section 6.

2. System model

2.1. Dynamic model

Fig. 1 illustrates the schematic diagram of the system. The object consists of three-rigid links (link-1, link-2 and link-3) connected by two passive joints: the knee and the hip joints. The angular positions of the links are given by θ_1, θ_2, and θ_3, respectively. The position of the knee joint (x, y) is referred to the world coordinate frame Σ_0.

The masses and moments of inertia of the links are denoted by m_1 and J_1, m_2 and J_2, and m_3 and J_3 for links-1, 2, and 3, respectively. The distance from the knee joint to the center of gravities of links-1, and 2 are denoted by L_1, and L_2, respectively, and from the hip joint to the