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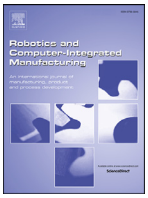

Object carrying of hexapod robots with integrated mechanism of leg and arm

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ABSTRACT

Hexapod robots are easy to realize walking in complicated environments and have the characteristic of high redundancy. It is well worth taking advantage of hexapod robots' versatility, such as using legs to do manipulation or carry objects. In this paper, several methods are proposed to deal with issues of carrying objects by transforming one or two legs as arms while walking on other legs for hexapod robots. Firstly, practical gaits for one-legged carrying and two-legged carrying are presented respectively. Secondly, problems existing in gait planning, for instance how to estimate the mass of object and how to calculate joint motions according to desired center of gravity (COG) trajectory, are solved by dynamic analysis and a kinematic method based on COG Jacobian. Finally, the effectiveness of our methods to implement carrying objects is demonstrated by two successful experiments of carrying a bottle of water and a box.

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1. Introduction

Legged robots have been a research hotspot in recent decades because of some urgent requirements for some special scenarios such as rescue response at nuclear power stations. The DARPA Robotics Challenge, which was partially stimulated by Fukushima nuclear disaster, putted legged robots into spotlight [1-4]. Many kinds of legged robots, such as humanoids, quadrupeds [5], hexapods [6] and wheel-leg integrated robots [7,8], tried to accomplish several tasks like going through rough terrain or picking up tools to drill holes, etc. In terms of humanoid robots, the biggest challenge is to keep balance when they are walking either with objects in hands or without objects, which is due to their narrow supporting polygons. There is only one robot that belongs to WPI-CMU team finished all of the missions during DRC Finals without falling and being "rescued" [9]. For quadruped robots, since they cannot use three or two legs to walk, they have to mount an extra arm to pick up objects and carry them to other places [10,11]. Compared with humanoids and quadrupeds, hexapod robots are more practical and flexible to be used in complicated environments when considering balance capability and versatility because hexapod robots have large supporting polygons and more redundant degrees of freedom. This paper will propose several methods to deal with the issues of carrying objects by transforming legs as arms for hexapod robots. There are several choices for hexapod robots to transform legs as arms to do manipulation as shown in Fig. 1.

Some researchers have studied the subject of using hexapod robots to move objects. Kalouche et al. [12] still applied an extra arm on a hexapod robot to grip things. In [13], a hexapod robot developed for humanitarian demining activities is endowed with a 5-d.o.f. manipulator in front, which handles a sensor head to scan the terrain. Halvorsen [14] designed an ant inspired hexapod robot with a gripper mounted on the head like an ant with big mandibles. Lewinger et al. also created a small ant inspired hexapod robot and simply introduced the performance of their BILL-Ant-p robot in [15]. In 1995, Koyachi et al. [16,17] proposed the concept of Integrated Limb Mechanism (ILM) which tries to integrate the functions of leg and arm into one limb in order to omit additional manipulator. Later, they developed two prototypes of "MELMANTIS-1" and "MELMANTIS-2" [18,19]. However, they just showed that the robots could pick up a ball or a can and put them into a basket next to the robot without any walking steps. As shown in Fig. 1(c), it's obviously that a special strategy should be employed to keep COG projection within the supporting triangle in order to realize walking on other four legs. But they haven't done research on that. Chen et al. [20,21] tried to apply ILM to a modular and reconfigurable robot "MiniQuad" which didn't realize the purpose of carrying objects using two fore legs due to COG problem as well. Ding and Yang [22] studied how to use two adjacent legs to pick up an object and throw it out. But

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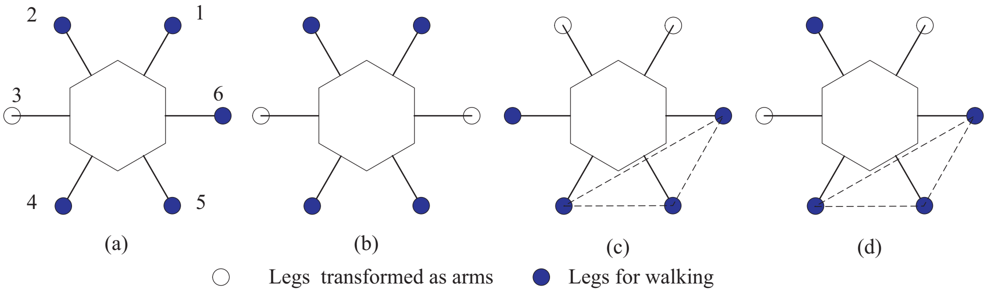

Fig. 1. Three possible choices (a-c) and one impossible choice (d) for hexapod robots to carry objects without extra manipulators.

they didn't enable the robot to walk while carrying an object. Bartsch et al. [23] developed a very interesting robot MANTIS that is expected to carry and manipulate external objects like a mantis. But they have only done the design of the novel robot. Further issues such as gait planning and balance control have not been implemented on MANTIS. Booysen et al. [24] suggested sliding the body of the robot in order to move COG into the supporting triangle before lift a rear leg. It should be acknowledged that Booysen's suggestion is a good idea. But they didn't analyze how to move COG to desired point through the motions of active joints. However, only when the COG is in the supporting triangle, the robot can walk using static gait successfully. Therefore, an analytic relationship between the motion of COG and the motions of joints should be given in order to guarantee the desired motion of COG while moving joints.

Before discussing the issue of how to calculate joint motions according to COG movement, there is a convenient choice that is just using one leg to do manipulation as shown in Fig. 1(a). Heppner et al. [25,26] has created a hexapod robot called as LAURON which can grip objects to a storage on the back of the robot through a gripper mounted on a leg and can realize the purpose of walking using six legs while carrying objects. In order to grip objects into the storage on the back, the leg with the gripper is designed exclusively to have a large reachable workspace. Actually, we can use the other five legs to implement walking while one leg remains leaving ground with gripped objects. That has been demonstrated by researchers who did research on fault tolerant gaits [27-29]. We also designed a gait to implement this method to carry objects. But it should be noted that the gripper could not pick up large objects limited by the size of gripper. Therefore, it is worth solving the problem existing in four-legged walking with two-legged grasping as mentioned previously.

For the issue of obtaining joint motions according to desired COG trajectory, we can resort to some methods proposed for humanoid robots. Humanoid robots have narrow supporting polygons. As a consequence, researchers need to plan the motions of humanoid robots very carefully. Unfortunately, most of the existing literature about locomotion of humanoid robots employs a method to treat the body motion as COG's motion approximately [30-32]. The reason for this approximation is that the body of a humanoid robot is much heavier than its legs. Therefore, this simplification method is feasible for the majority of humanoid robots. Although some robots can walk based on this imprecise method, most of walking robots do not have light legs, especially for our PH-Robot that was designed with heave parallel mechanism legs [33]. An accurate calculation method to solve this problem is to use optimization method as proposed by Kuindersma et al. [34,35]. They firstly treated zero moment point (ZMP) dynamics as a Linear-quadratic regulator (LQR) problem, and then employed quadratic program (QP) to obtain desired joint motions constrained by whole body dynamics, actuation limits, and contact constraints. However, inspired by the concept of COG Jacobian [36,37], we can get the analytic solution of this problem rather than optimization method. In this paper, we will describe a method based on COG Jacobian that can derive the joint motions according to desired COG motion while enforcing the desired end-point motions of each leg.

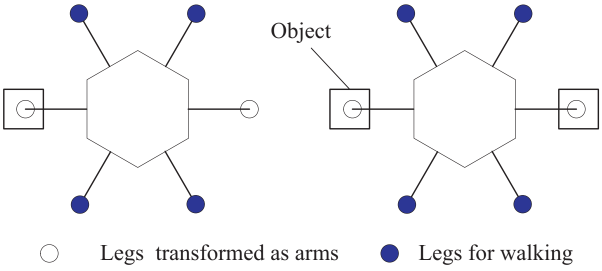

Fig. 2. Lifting two legs to become a mammal type of the other four legs.

On the other hand, it is worth pointing that joint motion range will limit the static stability margin for any multi-legged robots. In other words, the size of supporting polygon will affect robot's ability of carrying objects, i.e., how heavy the robot can lift and carry. The main contributions of this paper can be summarized as:

1) Complete and practical gaits of one-legged carrying and two-legged carrying for hexapod robots are proposed.
2) A novel method based on COG Jacobian is created to deal with the problem of establishing analytical solution for the relationship between joint motions and COG motion.

The remainder of this paper is organized as follows: Gait for one-legged carrying is analyzed in Section 2.1. Gait for two-legged grasping with four-legged walking is analyzed in Section 2.2. Problems of mass estimation and inverse computation of joint motions are solved theoretically in Section 3. Experiments are presented and analyzed in Section 4. Section 5 concludes the paper.

2. Gait planning of carrying objects for hexapod robots

2.1. Carry objects using one leg

One of the critical issues for robot walking is how to keep balance. There are two types of gaits can be chosen for multi-legged robots, i.e., static gait or dynamic gait (trot gait). Trot gait only can be adopted by robots that have mammal shape like BigDog. However, for hexapod robots, it is difficult for them to run just as insects in nature usually climb rather than run. Static gait means robots need to keep COG in supporting polygon consistently. For one-legged grasping, we have two choices as shown in Fig. 1(a) and (b) respectively. What is interesting is that the choice of Fig. 1(b) can be understood either as one-legged grasping or two-legged grasping as shown in Fig. 2. The supporting polygon constructed by the rest four legs is a rectangle that is the type of quadruped robots. In other words, it is easy to walk as most of quadruped robots do [38,39]. Moreover, if the swing speed of leg is fast enough, the robot can run using trot gait as well.

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