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Gait and trajectory rolling planning and control of hexapod robots for disaster rescue applications

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HIGHLIGHTS

- A complete control architecture based on gait and trajectory rolling planning method is proposed for hexapod robots.
- A method based on COG Jacobian is proposed to calculate joint motion depending on desired the robot's COG trajectory and end-point trajectories of each leg.
- Typical gaits are obtained according to environmental adaptability and ZMP stability margin.

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ABSTRACT

Hexapod robots have stronger adaptability to dynamic unknown environments than wheeled or trucked ones due to their flexibility. In this paper, a novel control strategy based on rolling gait and trajectory planning, which enables hexapod robots to walk through dynamic environments, is proposed. The core point of this control strategy is to constantly change gait and trajectory according to different environments and tasks as well as stability state of robot. We established a gait library where different kinds of gaits are included. Zero moment point, which indicates the stability of robot, is estimated by a Kalman filter. According to this control strategy, a hierarchical control architecture consisting of a man–machine interface, a vision system, a gait and trajectory planner, a joint motion calculator, a joint servo controller, a compliance controller and a stability observer is presented. The control architecture is applied on a hexapod robot engaging in disaster rescue. Simulation and experimental results show the effectiveness of our control strategy.

1. Introduction

Legged robots have attracted the attention of researchers because of their superior adaptability to complex environments than their wheeled counterparts. Legged robots can be divided into two-legged humanoid robots, quadruped robots, hexapod robots and others with more legs. Among these items, hexapod robots can easily implement statically stable walking, and therefore have been investigated widely all over the world. The leg mechanisms of most existing hexapod robot prototypes are 3 Degrees-of-Freedom (DOFs) serial mechanisms including 3 links and 3 revolute joints, which is based on bionics principle. However, in our previous works [1–3], we proposed a novel hexapod robot called as PH-Robot with parallel leg mechanism so as to bring the advantage of parallel mechanisms to legged robots.

Compared with multi-legged robots, biped robots can achieve fast locomotion like what human beings do, but it is hard to keep balance. Even some very advanced biped robots, such as Atlas [4,5] and Asimo [6], still cannot run over rough terrain. Quadruped robots [7–9] might be a good choose for utility application of robotics because it cannot only move very fast but also have larger stability margin than humanoids. By contrast, hexapod robots have higher stability, but also have more complicated gait planning problem due to the increased number of legs. It can be demonstrated by creatures of nature. Children need time to learn upright walking because it is more difficult to keep balance by just two legs than when climbing using two legs and two arms. Most of mammals use four limbs to walk and run, whereas only human can walk upright. Insects always have six or more legs. So insects can traverse very rough terrain even can climb walls. But they need to

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be lightweight in order to achieve fast locomotion. From this point, that is one reason for why only small features have six or more legs. As for humanoid robots, most of them depend on the control of zero moment point (ZMP) [10–12] to walk with balance. More research on this issue is implemented on quadruped robots [13–15]. Meanwhile a common dynamic model of inverted pendulum is applied for simplification due to the heavy body relative to their legs. By contrast, hexapod robot' legs make more contribution to the entire mass of robot than the body. Therefore, their method is not suitable for hexapod robots. Actually, hexapod robots have enough static stability margin to withstand most of external disturbance from the environment. Thus, we focus on gait planning and detection of ZMP rather than the planning and control of ZMP. Only in rare cases, we need to plan ZMP or center of mass (COG) trajectories and then track them using feedback control. We will show an example of carrying object using two adjacent legs to explain this special case in this paper.

In order to implement rolling planning of gait according to different missions and environmental conditions, different types of gait should be generated. Many studies have focused on the gait generation. As far as we know, it is hard for hexapod robots to execute dynamic gaits, such as trot or gallop which belongs to mammal gaits. The static gaits including tripod, quadruped, one-by-one types of gait as in [16] and other free gait in [17,18] are widely used in hexapod robots. Wang et al. [19] discussed three different gaits, i.e., insect-wave gait, mammal-kick gait and mixed gait. They still belong to static gaits. Asif et al. [20] proposed a method that is to increase the number of supporting legs according to the roughness of terrain in order to increase stability. Other researchers [21–24] focused on the analysis of fault tolerant gait as one or more legs are prevented from supporting and swing. Grzelczyk et al. [25–27] discussed the application of central pattern generators (CPGs) on hexapod robots to get stable and low energy consumption gaits. In this paper, we will give some typical gaits according to different tasks and environments, which establishes the gait library for rolling gait planning.

After gait planning, we need a trajectory generator to plan the motion of body and swing legs. On this issue, we must address the coupled kinematics of legs and body. In fact, we have derived the inverse and forward kinematics in our previous work [1]. We will present a new expression of kinematics that will lead to a solution of redundancy problem. On the other hand, the curve of trajectory function should be determined according to some rules like avoiding impact between feet and the ground. To avoid impact, the initial and final velocities and accelerations of the trajectory are chosen to be zero. Wang et al. [28] used the combination function of sine and cosine functions to satisfy the abovementioned condition. We have successfully applied a similar function called as cycloid curve to accomplish tripod gait in [1,3]. Rebula et al. [29] proposed a combined curve consisting of two linear segments and a parabolic segment. Kalakrishnan et al. [13] applied a series of quantic spline segments (fifth order polynomials) as the trajectories of COG and the endpoints of swing legs. Kolter et al. [14] used a very simple trajectory like a box as the foot trajectory. We will also employ fifth order polynomials which can provide convenience for rolling trajectory planning.

Another crucial aspect for legged robots is compliance control because we cannot get accurate information of ground via vision system. Asif et al. [30] proposed a control framework constituting a modified hybrid force–position controller to deal with the environmental disturbances. Mistry et al. [31] used model-based control to decrease the feedback gain of PD controller, and then decrease the stiffness of the whole controller in order to get compliant ability toward non-perceived obstacles and terrains. But it depends on precise dynamic model of robots, whereas dynamic modeling for legged robots is a difficult thing especially for our robot with parallel leg mechanisms. Another choice for getting compliant ability is to use elastic mechanical device to realize passive compliance. However, the price to pay is a typical degradation of robot performance. In fact, the elastic mechanical device applied in the passive compliance induces position errors, which reduces robot accuracy in tracking tasks, because of lightly damped vibrations and static deformation under gravity. That is why compliant robots like Baxter cannot achieve very accurate position control performance [32,33]. The solution to cope with the control issue of rigid manipulators interacting with the working environment is the active compliance strategy, which ranges from the concept of impedance control to the concept of hybrid position/force control. Especially, compared with hybrid position/force control, the impedance control has unique advantages in trajectory tracking studies because it is essentially a position control [3]. Furthermore, the principle of impedance control is to change the desired trajectory in Cartesian space after contacting ground.

In this study, a complete control architecture for hexapod robots applied to disaster rescue is presented based on seven subsystems. The main contributions of this paper can be stated as follows.

(1) A variety of gaits are proposed from different views from walking speed and stability margin to different tasks, and since gaits have large stability margin usually with slow walking speed, robots will choose different gaits according to the roughness of ground and assignment.
(2) A method based on COG Jacobian is proposed to calculate joint motion depending on the desired robot's COG trajectory and end-point trajectories of each leg.
(3) To address the problems associated with smooth contact with environment resulting from inaccuracy of LIDAR's detection, the present work adopts an impedance controller as compliance controller.
(4) In order to get more time for adjusting gait and trajectory, a stability observer based on ZMP is employed to predict stability margin of robots, which stems from the predictive ability of Kalman filter.

The rest of this paper is laid out as follows. In Section 2, we give a brief overview of the PH-Robot's hardware. Then, in Section 3, kinematics of PH-Robot is formulated. The proposed control architecture and detailed analysis of some parts of the control architecture are presented in Section 4. In Section 5, we present some experimental results. Finally, conclusions are presented in Section 6.

2. PH-Robot description

PH-Robot is very different with most popular hexapods due to its parallel leg mechanism as shown in Fig. 1. The purpose of using parallel mechanism is to improve payload capability, which has been analyzed in [2]. The robot stands approximately 820 cm in initial state (The height of robot depends on the length of linear actuators.) with a total mass of about 130 kg. There are 18 actuated degree of freedom excluding the one freedom of LIDAR. Each active joint is a prismatic joint corresponding to a linear actuator driven by servo motor with absolute encoder. An inertial measurement unit (IMU) mounted on the body can provide accurate 3-axis angle, angular rate and 3-axis acceleration data. Motion state will be estimated by the combination of IMU and encoders. There is a 6-axis force/torque sensor mounted on each foot to measure the contact force with ground. Data offered by all the above sensors is processed by an embedded controller CX2030 produced by Beckhoff. CX2030 can accomplish all the computation within 2 ms that is the servo cycle.