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A geometric approach to solving the stable workspace of quadruped bionic robot with hand–foot-integrated function

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ABSTRACT

This paper discusses stable workspace of a hand–foot-integrated quadruped walking robot, which is an important issue for stable operation of the robot. This robot was provided with combined structure of parallel and serial mechanisms, whose stable workspace was the subspace of the workspace in which the system was considered stable. The reachable region was formed under structural conditions, while the stable space was formed by the overall conditions of stability which changed with the robot's pose and the mass of grabbed object. In this paper, based on the robot's main structure, the key issues in solving the robot's workspace are discussed in detail, including searching steady conditions of operation of the robot. To research the robot's workspace, working leg's motion curve needed to be solved by kinematics analysis. Due to the redundant drive, it was problematic to deal analytically with the kinematics of the quadruped walking robot. A geometric method of kinematic analysis was proposed as well. Based on the geometric method, the workspace of the robot under varying postures was analyzed by the method of grid partition and in combination with Matlab, VB and Solidworks software programs. An automated computational system of the stable workspace was developed and an example was given to illustrate the whole process in detail. The theory and analysis procedures were also verified by simulation of the robot and its actual grabbing of an object.

1. Introduction

In general, the robot's workspace refers to an area accessible to a reference point on the end actuators of the robot. The factors such as design of robot mechanism, path planning and execution of work tasks, etc. were involved in the study of workspace [1–4]. The analysis of the workspace was considered as an important issue for the mobile robot. Especially, the stable workspace was defined as the subspace of the workspace in which the system was considered to be stable. While the end actuators of the robot were in operation, the robot could be stable at a desired position that was outside the workspace. Hence, while the robot was stable it was unable to complete the desired task. In some situations, the desired location was reachable but the robot was not stable. This made it important to determine the stable workspace, which was both reachable and stable for operation of the robot [5–7]. Typically, for a scalable hexapod robot (SHeRo), An analysis on the stability and workspace was presented and a dynamic criterion was developed to integrate the concepts of robot stability and constant orientation workspace into a stable workspace. The analytical solution of the lateral stable workspace of SHeRo was derived along with a metric for comparing stable workspace between different robot configurations [8].

For a long time, the research on the multi-legged walking robots attracted wide attention [9,10]. A good example in this regard was development of quadruped bionic robot ZQROT-I by Zhengzhou University of Light Industry and Huazhong University of Science and Technology [11]. One of the legs was designed to operate as a working arm with integrated hand–foot-functions. When the working arm was used to capture objects, the other three legs were employed to support the body. When the robot walked, the working arm executed the function of a normal leg.

For the implementation of the task of grabbing an object, it was necessary to analyze the workspace of the working arm. It was also a prerequisite for the motion planning and control of the robot in starting to grab an object. Moreover, research on the workspace of the robot's swing leg contributed to the toe point of the leg to move within the reachable space, adjust and select rational support point flexibly, which led to improved obstacle-avoidance and obstacle-climbing functions of the robot.

When the quadruped bionic robot with hand–foot-integrated function moved near objects, the position of three legs was fixed and the working arm was used to capture the objects by adjusting the body posture of the robot. The reachable space of working arm was formed by adjusting the body posture and the motion of

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working arm. In many situations, because adjusting the body posture and the motion of working arm changed the center of gravity of the robot, the desired location was although reachable but unstable. In such cases, the positions of the three legs of the robot needed to change. Therefore, it was essential for the robot to determine stable workspace.

A number of researchers reported on the workspace. The earlier research on the workspace focused on the 3 degrees of freedom (DOF) mechanism, while increasing number of recent studies focused on the workspace of 6-DOF mechanism and mobile robot.

In the research studies on the workspace of 3-DOF mechanism, many methods such as Gauss divergence theorem, computer-aided design, analytical method, differential geometry and group theory were employed. Following is the survey of earlier research. Gosselin et al. presented an algorithm for the efficient determination of the workspace of planar three-degree-of-freedom parallel manipulators. Using the direction of motion allowed at each of the limits, and Gauss divergence theorem, the area of the workspace was computed [12]. With the physical model of the solution space, Liu J et al. used the computer-aided design for planar 3-DOF parallel robotic mechanisms, and plotted the performance atlases of the work-space volume [13]. Bonev et al. conducted research on the workspace of the symmetrical and spherical parallel mechanisms and presented procedure for the analytical determination and representation of the workspace boundaries [14]. The differential geometry and group theory were applied by Yang et al. for the workspace analysis of spherical parallel manipulators with 3-DOF [15].

Research results obtained for the workspace of 3-DOF mechanism were extended to 5-DOF mechanism. For example, Lee et al. presented a closed-form solution for the radii of the inscribed and circumscribed circles of the (3-DOF) positional workspace and also the approximate solutions for the (5-DOF) total orientation workspace at a given height in the design of a hexapod mechanism [16].

Additional research on the workspace of 6-DOF mechanism was conducted by Yoon et al. was based on maximizing the mechanism isotropy of parallel manipulators. These authors proposed an optimum design method which satisfied the desired orientation of the sub-workspace at the boundary of the translation workspace [17]. Among the studies conducted on the workspace of 6-DOF mechanism, research on Stewart–Gough parallel manipulators was typical. Using geometrical methods, Tsai et al. presented algorithms based on the boundary curves of two-dimensional cross-sections for determining the compatible orientation of workspace for 6-DOF Stewart–Gough parallel manipulators [18].

The singularity of the workspace attracted wide attention for research. Jiang et al. focused on the determination of the 3D singularity-free orientation workspace of the Gough–Stewart platform [19]. Moreover, a basic theory and new algorithm of the workspace were reported. Bohigas et al. discussed the determination of workspace boundary for general structure manipulators and obtained detailed map of the workspace [20]. This method used branch-and-prune technique to isolate a set of output singularities and then classify the points in such set according to whether or not they corresponded to motion impediments in the workspace. Due to the mechanical interferences, kinematic constraints and singularities, the attainable orientation workspace of a spherical manipulator was invariably a subset of the special orthogonal group with a complicated workspace boundary. Yang et al. adopted a different parameterization method to analyze the numerical orientation workspace [21]. Chao et al. studied the robotic orientation workspace based on the quaternions and differential geometry and gave serial spherical wrist an example [22].

The methods presented above were valid under certain conditions applicable to different mechanisms and situations. However, it should be noted that the research studies on workspace for mobile robots are scant. One important aspect of mobile robots is the reachable workspace. Typical research carried out on reachable workspace of is as follows. Agheli et al. introduced an equivalent of 2-RPR planar parallel mechanism for the lateral reachable workspace of an axially symmetric hexapod robot [23] and presented its analytical solution [24]. The closed-form of solution to the lateral reachable workspace of the axially symmetric hexapod robots was facilitated by developing a correlation for the lateral motion of a hexapod robot using an equivalent 2-RPR planar parallel mechanism. Inside the reachable workspace of robots, considerable stability and stable workspace were formed.

There are several stability criteria that are widely used in the field of multi-legged and multi-wheeled systems. These criteria can be divided into static and dynamic types. These are further classified into five categories based on the mode of measurement which include distance-based criteria, angle-based criteria, energy-based criteria, moment-based criteria and force-based criteria.

With regard to research carried out earlier on the stability of robots, McGhee and Frank proposed the concept of the stability margin of quadruped robot crawling on a horizontal surface [25]. Messuri and Klein (1985) while considering the center of gravity of the robot defined the energy stability margin. Yoneda and Hirose (1996) conducted studies on the rollover stability zone. Subsequently Hirose (1998) introduced improved energy stability region. To generate crawling gait on the basis of the static stability, Hirose et al. [26] suggested diagonal principle. Agheli and Nestinger studied the foot force stability margin for the multi-legged wheeled robots under dynamic conditions [27]. Moreover, in many instances, the workspace and stability of robots were studied separately. The key research contribution on stable workspace came from Qu Long et al. [5]. They solved the stable workspace of 2-RPR parallel mechanisms by integrating stability into the workspace problem, assuming that the robot maintained a constant-orientation workspace. However, the proposed methodology was applied only to any planar biped robot, planar mechanism and walking machine with fixed or mobile foot contacts. This paper presents the research conducted by its authors on the stable workspace of a quadruped walking robot with hand–foot-integrated function.

Although any stability criteria could be used to derive an expression for the stable workspace of a given system, the available derivations were based on distance-based stability criterion according to the diagonal principle.

Generally, a forward kinematic analysis is necessary for solving the workspace issues of the robot. The quadruped robot studied in this paper is a reptile-like robot. Nine servo motors were installed on the three supporting legs. Of those nine, six were active drivers and the rest were redundant. The basis of forward kinematics analysis and solving workspace of the robot was acquisition of the redundant drive angles. For solving these angles, a set of 16 nonlinear equations was obtained by Professor Chen Xuedong [28] after complex deductions in the analysis of forward kinematics of the robot. Abel theorem shows that quintic equations of higher order have no general algebraic method of obtaining solutions and that they can be solved only by numerical method. As a result, the algebraic solution to forward kinematics of robot cannot be obtained by analytical method and iterative solution by the application of numerical method also encounters several difficulties. Therefore, for this type of robot, a geometric method of kinematic analysis is proposed in this paper. Based on the geometric method of kinematic analysis, the stable workspace of the robot was obtained in grid partition way, in conjunction with Matlab, VB and Solidworks software, for the robot with fixed footholds and meeting stability. The conditions of stable working for the robot were also given. The results obtained from solving workspace