Robotics and Autonomous Systems 70 (2015) 36–51

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

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

Pre-gait analysis using optimal parameters for a walking machine tool based on a free-leg hexapod structure

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HIGHLIGHTS

- Proposes a layout for a walking free-leg hexapod machine tool.
- Optimisation approach for tripod gait based on selected system parameters.
- Proposes an algorithm for independent walking motion based on stability.

ARTICLE INFO

Article history:
Received 11 January 2014
Received in revised form
4 March 2015
Accepted 1 April 2015
Available online 12 April 2015

Keywords:
Hexapod
Walking robot
6-axis milling machine
Robotised machine tool

ABSTRACT

The scope of this paper is to present a novel gait methodology in order to obtain an efficient walking capability for an original walking free-leg hexapod structure (WalkingHex) of tri-radial symmetry. Torque in the upper (actuated) spherical joints and stability margin analyses are obtained based on a constraint-driven gait generator. Therefore, the kinematic information of foot pose and angular orientation of the platform are considered as important variables along with the effect that they can produce in different gait cycles. The torque analysis is studied to determine the motor torque requirements for each step of the gait so that the robotic structure yields a stable and achievable pose. In this way, the analysis of torque permits the selection of an optimal gait based on stability margin criteria. Consequently, a gait generating algorithm is proposed for different types of terrain such as flat, ramp or stepped surfaces.

1. Introduction

At present, Parallel Kinematic Machines (PKMs) are primarily used in large setups to perform machining tasks such as milling [1] or manipulation of heavy components [2]; additionally, different configurations of PKM are utilised for manipulations in assembly lines [3] or accurate positioning systems [4] for astronomy installations or MEMS. However, recent work has shown that PKMs are also suitable for use in a mobile context, i.e. being moved into a location of intervention to perform various inspection/processing tasks. Yang et al. [5] have designed a quadruped robot PK machine tool, equipped with one redundant limb that is used only for walking, which can move between fixed pins fitted to the surface to be traversed; these pins react the lateral forces and ensure that the legs fall within a series of known positions, which eliminates the need for referencing the PK structure relative to the base platform. However, due to such configuration, this PKM structure walking machine cannot walk within an unprepared environment.

Guy [6] developed a robot PKM for drilling and riveting, which positions itself on the exterior of a section of aircraft fuselage using a fixed base and actuators attached to the parallel platform that can lift the base while it relocates utilising a PK mechanism. This design uses suction cups to attach the base unit to smooth, relatively flat surfaces; however, it could be noted that this solution cannot cope with complex environments, since the footprint of the system is large and therefore cannot easily avoid obstacles. It also cannot cope with terrains that are non-smooth and is not flexible enough for more general applications than working only on fuselage sections. Both Guy [6] and Yang et al.'s [5] designs have the desired mobility, but are only mobile within limited environments, rendering them ineffective for more general tasks/interventions (e.g. in-situ repair) that might require motion within uneven terrain and/or complex paths of the end-effectors. They also might exhibit a limited accuracy for performing processes such as multi-axis milling or rely on pins built into the environment; hence, neither is suitable to perform accurate automated operations in hazardous or constrained environments.

Furthermore, attempts have been made, such as that by Denton [7], to implement a tooling solution for performing machining

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http://dx.doi.org/10.1016/j.robot.2015.04.001

Nomenclature

α	Angle of slope of terrain (rad)
θ_{FS}	Foot spacing angle (rad)
R_{FS}	Foot spacing radius (m)
Ft_i	Foot *i*
g	Gravitational Coefficient 9.81 (ms^{-2})
θ_R	Hexapod rotation (rad)
$\theta_{R_{Opt}}$	Optimal hexapod rotation (rad)
M_i	Magnitude of stability margin *i* (m)
T_M	Maximum torque in system (N m)
S_{opt}	Optimal translation (m)
M_s	Overall system stability margin (m)
θ_P	Platform pitch (rad)
x_P	Platform translation (m)
Pr_i	Prismatic joint *i*
$\mathbb{Z}$	Set of integers
T_i	Torque in upper spherical joint *i* (N m)
Sph_i	Upper spherical joint *i*

with a standard hexapod robot, which uses an off-the-shelf axially symmetric configuration; this places a limit on the accuracy achievable by such a system and leads to a relatively low useful working volume. As a result, the robot would be required to walk while machining if performing operations on a large area, further reducing accuracy and repeatability.

An existing Free-leg Hexapod (FreeHex) [8,9] with a PK structure that can be attached directly to the workpiece (without the need for a fixed base) for in-situ processing (e.g. machining) has been reported; this machine must be placed in location by a human operator and calibrated using an innovative methodology involving a set of gauges that must be removed prior to machining [8]. Despite this, the FreeHex was reported to be capable of achieving high accuracy, i.e. repeatable results when machining and proved to meet real industrial application needs, thanks to its design. However, in its current design, it lacks the advantage of being able to reach tight spaces or hazardous locations independently. Consequently, new strategies are required in order to allow this system to walk independently, without compromising the machining capability conferred by a PK configuration.

Prior to a redesign of the FreeHex to enable its walking capability, it is important to evaluate the stability of such structures during their motions and analyse suitable gaits in order to select suitable actuators. Therefore, it is important to consider existing walking robots, even though they may not be capable of generating 6-axis tool paths. Walking robots fall into two overall categories: statically stable [10] and dynamically stable (e.g. [11]).

Dynamically stable robots are most analogous to bipedal animals and humans, where balance must be actively maintained. Dynamically stable walking is performed by internally generating an imbalance such that the centre of mass is (usually) in front of the supporting limbs causing the subject to have the tendency to topple forwards. Thus, one leg is placed in front of the other in order to prevent the system from collapsing and so to enable its advancement. According to McKerrow [12], dynamic stability is achieved by continuously moving either the feet or body to maintain balance. Wettergreen and Thorpe [13] describe an active feedback approach to control system implementation in order to maintain the balance with respect to a required speed. By contrast, statically stable walking robots rely on maintaining a balanced pose at all stages during motion. This is analogous to the motion of many creatures with four legs and all creatures with six or more; as such, many examples of this type of robot are inspired by animals or insects.

For a robot to be able to move autonomously, reasoned decisions need to be made as to where and in what order the feet are placed; this process is referred to as gait generation analysis. The gait of a robot is the set of motions that the legs should go through in order to allow the robot to advance in a specified direction. According to Wettergreen and Thorpe [13], previous work on gait can be classified into four categories: Behavioural, Control (previously explained), Constraint-Based and Rule-Based.

Behavioural gait generation is an attempt to mimic the method of determining limb movement used by animals and insects by creating an environment for unconscious reasoning, such as a neural network. Beer et al. [14] built a walking hexapod to investigate a control network based on the neuroethology of insect locomotion, producing a range of gaits and degrees of robustness in a real robot that match quite closely with simulations. Berns et al. [15] describe an hierarchical control architecture for a walking hexapod named LAURON utilising neural network techniques; this focuses on active learning within the control system, which proved to be time intensive and not of as much practical use if the environment to be traversed is well defined.

Rule-Based gait generation involves assigning a prescribed gait based on the classification of the robot's environment, unlike the behavioural and control approaches that involved no active planning. As the robot switches between different types of terrain, the system adopts the gait that is most suitable for the current environment. Song [16] reports on an efficient wave gait that varied foot placements between terrains while retaining gait sequencing; furthermore, this was developed to allow for autonomous crossing of four major different types of obstacle: grade, ditch, step and isolated-wall [17].

Kumar [18] uses a system of control schemes to modify gait parameters including duty factors for the wave gait in order to demonstrate that robot velocity can be varied continuously even with irregular, asymmetric and changing support patterns; however, this approach showed that some problems in switching between gaits could appear. This highlights the main drawbacks of using Rule-based gait generation: (i) difficulty in generating an exhaustive list of environment scenarios; (ii) difficulty in autonomous recognition of which type of environment scenario is most appropriate for the current terrain; (iii) while the robot is transitioning between two environments, it is not fully in either environment, so the system must have a method of coping with fuzzy logic. Cruse [19,20] achieves some success in addressing these issues by means of the 'Cruse Coordination Rules', which allow the robot to adapt automatically to its environment, producing stable and reliable gait patterns. Roggendorf [21] compares this with Steinkühler and Cruse's MMC model [22] and a modified form of Porta and Celaya's approach [23], but finds that the latter produces the best performance in simulation. Belter [24] utilises an evolutionary algorithm to generate a tripod gait for the hexapod 'Ragno', reporting that there is a strong dependence on the accurate knowledge of the physical parameters in the quality of the produced gait. Buchli [25] presents an excellent control methodology for the 'LittleDog' quadruped incorporating a novel line-based COG trajectory planner which is proven to be effective in real world trials.

For complex and constrained environments, a modified standard gait is not as suitable for avoiding all obstacles. It is in these situations where the fourth category of gait generation is most useful: Constraint-based gait generation—a mid-term planning active searching gait generator. It operates in the following stages: (i) a complete list of possible moves that the robot legs and platform could make is generated; (ii) this list is reduced by eliminating all motions that are infeasible due to spatial uniqueness (e.g. clashes between legs and legs/other parts of the robot/the environment); (iii) the list is further reduced by eliminating all unstable movements and possibly by using other criteria (such as singularity