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Onboard hydraulic system controller design for quadruped robot driven by gasoline engine☆

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ABSTRACT

Featuring small size, low weight and high energy density, the hydraulic system driven by gasoline engine is an ideal solution for the actuation system of large quadruped robots. This paper studies the quadruped robot SCalf-III(SDU Calf-III) and designs a controller for the hydraulic system, which is based on the characteristics of the onboard hydraulic system and the requirements of the robot motions. The working conditions of the hydraulic system are confirmed on the basis of the robot power consumption. An engine speed control strategy is designed using the sectional PI algorithm, where the fuzzy control is implemented in the feed-forward loop. The hardware and the software designs of the controller are demonstrated, where the engine controlling and hydraulic system monitoring are implemented. Experiments on the SCalf-III robot show that the designed controller could control the engine rotating speed effectively, and ensure adequate hydraulic power for the robot.

1. Introduction

Movements of the robot are generated by the joint actuators, while different actuating modes have different performances. At present the three most common kinds of robot joint actuation modes are the electric motor, the pneumatic and the hydraulic actuations [1]. For legged robots which are used to transport materials in the wild environment, most dynamic motions are directly related to the maximum torque and velocity of the actuators. Additionally, the actuators have to resist high torque peaks produced by the impact between the feet and the ground. Furthermore, the actuators should have high power-to-weight ratio as they are mounted on the legs and thus directly added to the inertia of the legs. Compared with other alternatives of similar weight, the hydraulic actuator has higher power-to-weight ratio. The hydraulic cylinders used in the SCalf-III can go up to 7 kW/kg. It is significantly higher than the electric motors (the power-to-weight ratios of EC60-400W and TBM(S)-12913-B are 0.17 kW/kg [2] and 0.43 kW/kg [3] respectively). The temperature sensitivity of the hydraulic actuator is low, which makes it adaptable to a wide range of temperature condition. Besides, the hydraulic actuators have high bandwidth and high linearity [4], which can satisfy the requirements of the legged robots' movements. Most high performance legged robots use hydraulic actuation as their actuating modes. LS3 [5] uses hydraulic actuators and weighs 180kg. It can follow navigator and perceive terrain variation. Petman [6] and Atlas [7] are both biped robots that use hydraulic actuators to produce a large range of motion and high power.

Despite the fact that the electric motors have the characteristics of lightweight and miniaturization, the hydraulic actuators still have significant superiority in payload-to-weight ratio. The payload-to-weight ratio and actuating mode of some legged robots are shown in Table 1. It can be seen that the hydraulic actuated legged robots have large load capacity, while the electric driven robots focus more on agility.

The power source of the legged robots' hydraulic system can be a battery-electric motor or a gasoline engine. The electric powered system has a compact structure. However, the presence of large capacity batteries greatly increases the overall weight, and significantly reduces the dynamic and load capacity of the robot. For the robots used in the wild environment, the endurance and replenishment are both important. Compared with the battery, the gasoline engine has high power density, and the refuelling of the gasoline engines is much faster than the recharging of the battery [10]. Compared with the electric motor driving systems, the hydraulic systems powered by gasoline engines have several important advantages. Hydraulic systems powered by gasoline engines have high power-to-weight ratio, which make the robots more compact and have larger load capacity. The hydraulic systems driven by gasoline engines have faster dynamic response and better load stiffness than those driven by the electric motors. They could make the robots withstand the effect caused by payload variation or other external force disturbances. Besides, the hydraulic systems driven by gasoline engines are more convenient to distribute driving

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Table 1
Specification of some quadruped robots.

Robot	Weight (kg)	Payload (kg)	Payload-to-weight ratio	Actuator
SpotMini [8]	30	14	0.47	Electric
Spot [9]	75	45	0.6	Hydraulic
SCalf-II	130	140	1.08	Hydraulic
SCalf-III	200	200	1.00	Hydraulic

energy to joints according to actual needs [10]. Therefore the gasoline engine is an ideal solution for hydraulic legged robots. The BigDog robot [11] is a hydraulic actuated robot using IAME X30 kart engine as its power source. It has three active rotating joints and one passive joint for each leg, and can move on the slope of 35°.

Hydraulic systems driven by engines are widely used in engineering machineries like excavators. Casoli et al. applied the hybridization methodology based on the DP algorithm on a middle sized excavator to determine an effective hybrid system layout [12]. Zhang et al. designed an intelligent control system based on the speed detection, which could improve the power efficiency of the hydraulic excavator [13,14]. Researchers have been doing many studies on the engines and the hydraulic systems of excavators. Compared with the SCalf-III robot powered by the gasoline engine, the excavators powered by diesel engines have different working conditions.

Engine control is commonly used in the vehicle control systems. Qiu et al. have utilized the internal model controller (IMC) to control the turbocharged gasoline engines [15,16]. Huang et al. have studied the dual-loop λ control model of gasoline engines based on the unilateral time delay PI controller [17]. Vijay et al. designed a vehicle electronic control unit, which could control the engine speed by controlling the electronic injector [18]. However, the big size of the vehicle engines makes it unsuitable for robotic applications.

Some researchers have designed engine controllers for robots. Xu et al. [19] designed a controller for the rotor of a mini autonomous helicopter, which used the fuzzy control to tune the PI parameters. It is a PI controller essentially, and the load shock of the helicopter rotor is much smaller than the hydraulic driven legged robot. The quadruped robot JINPOONG used prediction control to control the rotating speed of the gasoline engine [20]. The JINPOONG has almost the same control requirement with the SCalf-III, but its size is smaller. Compared with the controller of JINPOONG, the controller in this work has simplified the design of rotating speed measuring circuit, so the stability and the integration of the controller are improved. Besides, an upper debug interface has been designed to monitor the condition of the power system, which makes it convenient to tune the parameters.

The main purpose of this work is to design a controller for the hydraulic system of the legged robot SCalf-III. The controller can control the gasoline engine and the hydraulic pump according to the working conditions and the power requirements of the robot. The kinematics of the SCalf-III is studied and the hydraulic flow required by the robot is estimated, in order to obtain the required engine rotating speed. The controller uses a sectional PI algorithm in the feedback loop and establishes a feed-forward loop based on the fuzzy control, which can control the engine rotating speed effectively. In the meantime, the controller can monitor the conditions of the onboard hydraulic system, and can supply feedback to the operator in real-time.

2. An overview of SCalf-III

In 2017, the Robot Research Center of Shandong University has built a quadruped robot named SCalf-III(SDU Calf-III), as shown in Fig. 1. The length and width of the robot are 1.4 m and 0.75 m respectively, and the overall weight is 200 kg. The power of the robot movements are supported by an onboard hydraulic system, which is powered by the ROTAX 582UL gasoline engine. The whole system power is from the gasoline engine.

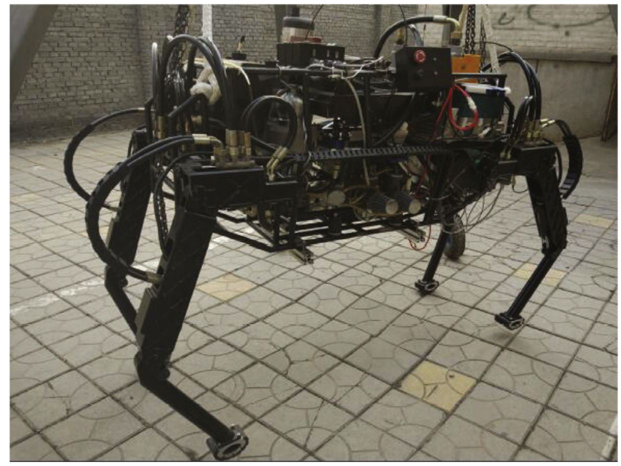

Fig. 1. The quadruped robot SCalf-III from Shandong University.

To ensure the robot can move flexibly and steadily, the onboard hydraulic system has to provide sufficient and stable power output. This paper analyzes the working conditions of the hydraulic system based on the existing robot platform. As the power source is the gasoline engine, the design of the controller is focused on the engine control, which ensures the engine can provide enough power with a steady speed. The engine is controlled by constantly adjusting the throttle opening to adapt to the load variation, in order to maintain the engine speed at a given value. During the operation, as the engine encounters a lot of disturbance and uncertain factors, the relationship between the throttle opening, load and the rotating speed is rather complicated. In addition, the relationship is also influenced by the environment and the operating time. Therefore, the control of the gasoline engine is a keypoint for the onboard hydraulic system of legged robots.

2.1. Mechanical structure

As shown in Fig. 2, the SCalf-III consists of a trunk and four legs. The control system and the hydraulic system are placed inside the trunk. Each leg of the robot has a rolling hip joint, a pitching hip joint and a pitching knee joint. With this structure, the endpoint of the foot can move in a three-dimension workspace with the hip joint as its origin.

There are different ways of attaching the four legs to the torso. The two hind and the two front legs are always built in pairs and can either be mounted in a forward configuration (where the knee joint points to the front of the robot) or in a backward configuration (where the knee joint points to the back of the robot) [1]. This results in four combinations as shown in Fig. 3.

To make the robot easy to control, the symmetric structure is used to

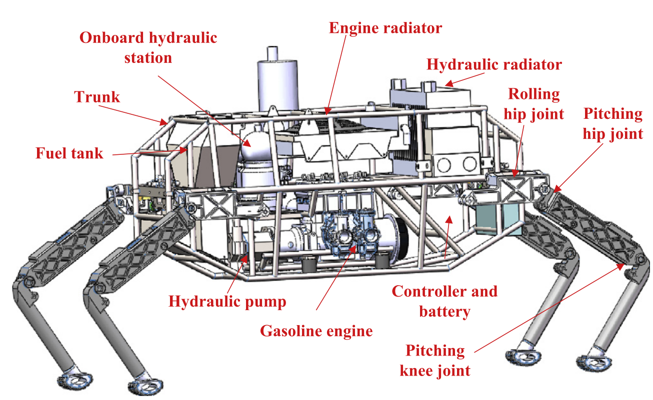

Fig. 2. The overall structure of the SCalf-III.