Any-angle Tactile Sensing using Position Feedback Only

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***Abstract*— In this work, we address a problem of detecting the leg contact with the ground or obstacle for a hexapod walking robot to enable it crawling rough and irregular terrains. The proposed approach is based on a model of the leg dynamics combined with the model of the joint actuators to detect the contact whenever there is a significant difference of the real position from the estimated position provided by the model. The developed dynamic model allows reliable detection of foot-strike events using only the position feedback from the utilized servomotors, and thus it enables adaptive locomotion of the affordable hexapod walking robot without any other sensory equipment.**

I. Introduction

Timely and reliable detection of the leg contact with the ground or obstacles is a crucial ability of the legged robots to navigate in the environment safely. The inability of the robot to detect the foot-strike events leads to increase torques at the joints which may induce stress on the robot construction, and thus the actuators can be damaged, or the robot can lose its stability. Several methods for the detection of the foot-stability events have been proposed in the literature, but all share a common property of utilizing sensory feedback in the detection of foot-contact with the ground or obstacles.

The existing methods of the foot-contact detection include approaches restricted to tactile sensing only at the leg foot-tips and more general approaches not restricted to the foot-tips. The former approach includes usage of switch sensors [1]; measurement of the ground-reaction forces and torques using strain-gauges [2]; force-sensitive resistors [3]; or expensive force-torque sensors at the leg foot-tips [4]. On the other hand, methods that measure the joint torques at each joint directly [5], or estimate them using a linear model of the servomotors current [6] require expensive servomotors that are capable of measuring the joint torques. Besides, a minimalistic approach based on position feedback is proposed in [7], where a single passive compliant actuator is added into the leg morphology to detect the foot-strike events. In [8], the authors avoid the additional actuator and directly estimate the joint torques from the error between the set and measured joint angles using only the active actuators.

The herein presented any-angle tactile sensing follows on [8] but contrary to experimentally find fixed error threshold used in [8], the proposed approach utilizes a high-fidelity dynamic model of the leg to compare the actual position of the leg with its estimate position. The tactile event is detected whenever the error between the actual and estimated positions is above a given threshold. In addition to the ground detection, the proposed approach allows detecting a leg contact with an obstacle. We experimentally verify the proposed approach using an affordable hexapod walking robot built from off-the-shelf components, see Fig. 1.

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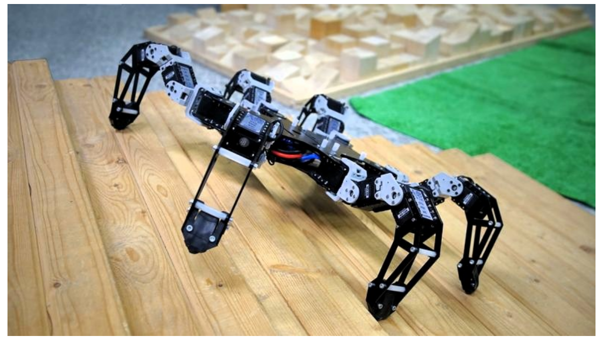

Fig. 1. Utilized hexapod walking robot with three DOF per leg.

II. Proposed Method

The proposed tactile event detection seamlessly integrates into the locomotion control as it only requires the trajectory of the leg in the joint space. The dynamic model of a single leg is used to model the behavior during the motion. The model is formulated using Euler-Lagrange formulation [9] for the vector of generalized coordinates $\mathbf{q} = \{\theta_1, \theta_2, \cdots, \theta_n\}$, corresponding to the joint angles, as

$$\boldsymbol{D}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{C}(\boldsymbol{q}, \dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{G}(\boldsymbol{q}) = \boldsymbol{\tau}, \qquad (1)$$

where $\boldsymbol{D}(\boldsymbol{q})$ is the *inertia* matrix of the chain of rigid bodies, $\boldsymbol{C}(\boldsymbol{q}, \dot{\boldsymbol{q}})$ is a tensor representing the *centrifugal* and *Coriolis* effects induced on the joints, $\boldsymbol{G}(\boldsymbol{q})$ is the vector of moments generated at the joints by the *gravitational acceleration*, and $\boldsymbol{\tau}$ is the vector of actuation torques at the respective joints. Besides, we further need to model the real behavior of the actuators that are composed of the motor and reduction gear which dynamics can be expressed as

$$J\ddot{q}^M + B\dot{q}^M + F(\dot{q}^M) + R\tau = K\,V, \qquad (2)$$

where q^M is the rotor position angle before the reduction, J is the rotor inertia, B is the rotor damping, F is the sum of the static, dynamic and viscous friction that depends on the current rotor speed, R is the gearbox ratio, τ is the servomotor torque, K is the back electromotive force, and V is the motor voltage. The appropriate value of the parameters $J, B, F, R,$ and K have to be experimentally

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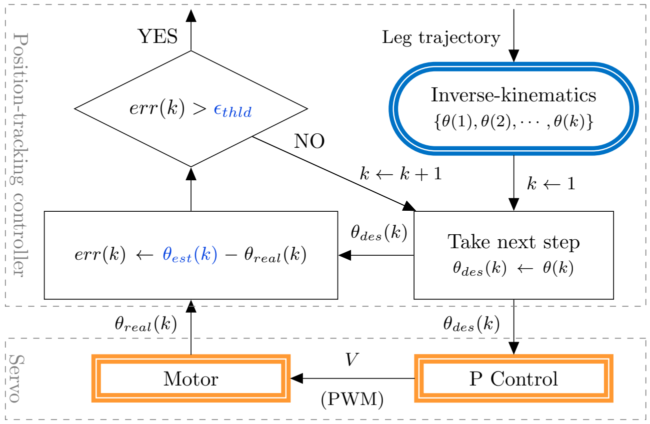

Fig. 2. Utilized position tracking controller for a single joint. The actuator is iteratively commanded with a new desired position θ_{des} and the tracking continues until the difference between the real measured position θ_{real} and the position estimated by the model θ_{est} is higher than the threshold ϵ_{thld}.

identified using the real servomotor or the values specified in the manufacturer data sheet can be utilized. The used P-type position controller influences the voltage $V = k_P \cdot err$, where k_P is the controller gain, and err is the difference between the set position and the current position of the actuator, which is internally updated in the servomotor with 1 kHz frequency.

The desired complete dynamics of the leg in the joint angles can be derived by substituting (2) into (1). The model is used in the position tracking controller which executes the leg trajectory step-by-step. At each step, the controller reads the joint angles and compares them with the ones provided by the model as it is visualized in Fig. 2. If the difference between the real measured position θ_{real} and the position estimated by the model θ_{est} is higher than the threshold ϵ_{thld}, the tactile event is recognized.

III. Experimental Evaluation

The proposed approach has been experimentally verified using a real walking robot with six legs, each with three joints in yaw-pitch-pitch configuration actuated by the Dynamixel AX-12A actuators. The respective lengths of the individual links are 5.5 cm, 7.2 cm and 10.4 cm. During the experiment, the leg follows a circular trajectory of 10 cm in diameter, regularly sampled to 100 points within 1 s. Note, such a trajectory involves motion of all joints. Each 10 ms time-step consists of setting a new setpoint θ_{des} to all the servomotors and reading back all the current positions θ_{real}.

A record of the position error from the experimental deployment is shown in Fig. 3, where the position errors between the desired θ_{des} and real θ_{real} joint angles of the actuators during a rapid any-angle swing might be significant (up to 50 ticks in our experiments). However, the dynamic model of the leg provides a high-fidelity estimation of the positions, and we can set the threshold to be ten times lower, i.e., $e_{thld} = 5$, and thus reliably detect contact of the leg with an obstacle. The reported results on successful detection of

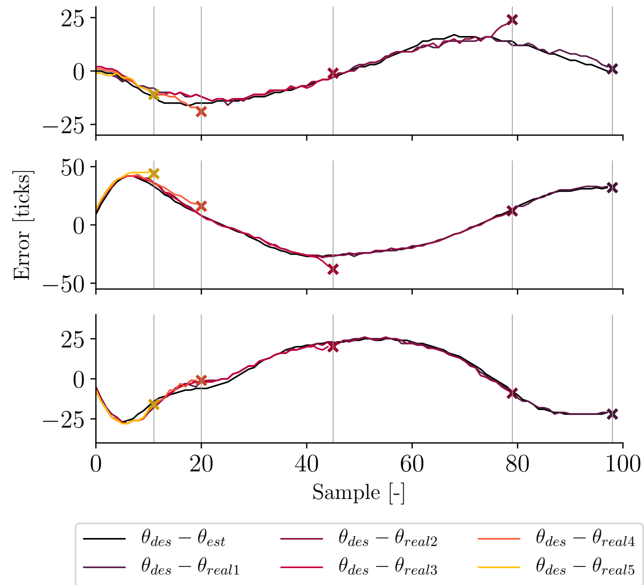

Fig. 3. The position error of each individual joints in experimental verification of the proposed any-angle tactile detection on a circular trajectory using $e_{thld} = 5$ and estimated error θ_{est} from the dynamic model. Beside the obstacle-free trajectory denoted θ_{real1}, there are four trials with an obstacle at different part of the trajectory denoted $\theta_{real2}, \ldots, \theta_{real5}$.

the obstacle support the proposed method allows any-angle tactile sensing using only position feedback.

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