Momentum control using limbs, tails in mobile robots: Challenges and tradeoffs

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***Abstract*— Cheetahs exhibit extreme mobility not only in running speed, but also in agility. In particularly, tail-assistive maneuver in chase of a gazelle shows the potential usage of tail in robotic quadruped as well. This talk presents several examples of appendage-assisted dynamic balance in nature along with hypothesized principles. Although the benefits of using additional limbs to augment the agility of the robots or Practical challenge in implementations in robot.**

I. Introduction

While most manufacturing robots are grounded and fully actuated, mobile robots are typically underactuated due to the ground contact condition. Since the foot of the robot neither can pull nor apply torque on the ground, legged robots often cannot directly control the state of the robot particularly in dynamic situations. This makes the control of mobile robot significantly far more challenging in dynamic locomotion. The magnitude of angular and linear momentum generated by ground reaction forces will be limited by the maximum force at each foot without loosing contact, whereas manufacturing robots can rely on their anchor and apply forces/moments within the actuators' capability.

In order to overcome such limitations, animals exhibit remarkable strategy of utilizing appendages to exert torques to the main body for performance enhancement. Cheetahs seem to whip their tails to enhance maneuverability and chase prays more effectively [8]. Geckos use their tail to correct the body orientations while falling [4]. Lizards use their tails to exert torque to the body in the pitch direction to regulate the body orientations while jumping [1]. Humans use arms to enhance balance and stabilize their gaze, which in turn, can improve accuracy of the motion control.

Taking ideas from biology, roboticists apply these ideas to mobile robots. A tail attached at the end of the MIT cheetah platform to improve balancing upon disturbances [3]. Changing the orientation via tail movement was demonstrated when the robot is in the air [5]. A RC car demonstrated extreme agility using the tail motion to compensate the angular momentum [9]. Dash, small hexapod demonstrate impressive turning utilizing the inertia of the tail [6]. Atlas, a humanoid robot developed by Boston Dynamics, uses the arms and a leg to recover balance from a lateral disturbance.

Despite of clear benefit of using appendages, there are several challenges in utilizing such idea in mobile robots. This talk will introduce the observations of appendage-assistive behaviors in animals and robots, and discuss practical challenges in implementation in mobile robots.

II. Appedages motion as a feed forward control

In legged locomotion, in general, the regulation of body orientation is important. In many cases, the motions of appendages can cancel the anticipated torques applied to the body. An excellent example is walking and running in humans. The upper body rotation in yaw compensates the torque fluctuation caused by the legs and ground reaction forces. The author will discuss several examples categorized in this case.

III. Challenges in using robotic tails

There are several design challenges in implementing the idea of 'robotic tail' in a real hardware. Two major challenges are as follows.

A. *Design optimization*

There are two approaches in utilizing the 'tail'. First approach is using a tail-like structure that has inertia. An effective tail can have a concentrated mass at the end of a lightweight stick to maximize the moment of inertia while minimizing the total mass of the tail. On the other hand, actuated reaction wheels at the center of mass to create pure torques [8]. This approach allows for simple tracking controller for balancing the orientation of the body because there are no parasitic reaction forces or shifted center of mass caused by the configuration change. The location of the tail and the total inertia and mass properties along with the actuator design become quite complex design challenge.

The amount of torque the robot can apply to the body depends on the scale of the actuator. The added mass of the actuators contributes the change of the dynamics of the locomotion and is directly related to the cost of transport. Design optimization of such machine involves a complex tradeoff between stability and efficiency.

B. *Complexity in control/planning*

Tails in animals are usually located at the end of the body. This configuration brings complexity in control. For example, as a quadruped apply torque at the tail in order to compensate a roll disturbance, the body will not only receive a torque in roll axis but also lateral forces caused by eccentric mass distribution of the tail depending on the tail initial angle. In addition, once the tail's velocity increases, the centrifugal force will be applied to the base of the tail. When the tail decelerates, the opposite phenomenon will occur depending on the configuration of the tail and the center of mass will be shifted unless the tail ends up returning the initial position. This will be combined with varying moment of inertia of the robot depending on the footfall pattern of the robot. The problem requires a sizable optimization to find good control policies.

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