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Energy Regulation for Biologically-Inspired Robotics

A robotic monkey swings through jungle trees, capturing valuable wildlife data without disturbing the local environment. In a nearby city, a robotic police dog runs through the streets, weaving through pedestrians' legs to catch a thief. It passes a traveling circus group, where robot gymnasts perform elaborate routines in front of an awestruck audience. This world sounds like science fiction, but it is truly within sight: the research we propose below will enable roboticists to accurately recreate human and animal behaviour in their robots. This world we imagined can become a present-day reality.

Background

Before we can explain how these humanoid and animal-like robots will work, we must first understand how humans and animals move. Take the example of a human gymnast who wants to do backflips around a horizontal bar. The gymnast starts by swinging their legs in a technique called a "giant" [1], during which they move their legs based on their current position and velocity [2]. This allows them to generate enough momentum to rotate around the bar.

Now imagine the gymnast is a robot, and their creator is teaching them to perform giants like a human. If the roboticist had studied classical control theory, they would plot a human gymnast's leg angle as a trajectory over time and tell the robot to synchronize its legs with this trajectory. While this is the standard approach in robotics, it is not appropriate for biologically-inspired robots: it is susceptible to timing delays, it is not robust to external disturbances, and it is *not what humans do*. After all, human gymnasts do not have an internal stopwatch telling them when to move their legs. Instead, existing research suggests that human gymnasts actually move their legs as a function of their body angle and velocity [2]. Rather than using time-based motion, a clever roboticist would attempt to emulate this natural human behaviour, which is well described by the method of virtual constraints.

There are two types of constraints on a mechanical system: *holonomic* constraints restrict position (e.g. a snake robot can slither on the ground but cannot fly), while *nonholonomic* constraints restrict both position and velocity (e.g. an autonomous car with normal wheels cannot slide sideways). It is often possible to use a robot's actuators to enforce a desired constraint which is engineered to achieve a safety or motion planning goal. Since this constraint is enforced by the robot's actuators, and not by the physics of the system, it is known as a "virtual" constraint [3]. Virtual holonomic constraints (VHCs) have been used to control walking robots [4], autonomous bicycles [5], helicopters [6], and snake robots [7], among other applications. Unfortunately, VHCs cannot adequately recreate many animal behaviours. For example, they cannot perfectly recreate the giant motion of gymnastics because they do not incorporate information about the gymnast's velocity [8]. This is where virtual nonholonomic constraints (VNHCs) are most useful.

The modern concept of VNHCs was described by Griffin and Grizzle [9] in 2015, though there are references to preliminary versions going back as early as the year 2000 [10]. VNHCs have been of most notable use in bipedal walking robots, where they show marked improvements in the robustness of walking gaits when compared to previous control techniques [11], [12]. They have also been used for error-reduction in time-delayed teleoperation [13] and in the field of human-robot interaction [14], [15]. Horn *et. al.* [16] derived the equations of motion for robots constrained by VNHCs, and they used VNHCs to improve the gait of walking robots on a variable-slope terrain [17].

Proposal

Virtual constraints have proven useful for generating biologically realistic behaviour in robotic systems. In my master's thesis I showed that VNHCs also allow for *energy regulation*, i.e., they can inject energy into (or dissipate energy from) a certain class of mechanical systems [18]. One such mechanical system is a gymnastics robot called the *acrobot*, for which I designed a VNHC that generates giant-like motion. This VNHC enables the acrobot to gain energy and perform backflips on a horizontal bar.

Using VNHCs for *energy injection* is beneficial because it allows robots to safely and reliably increase their momentum. Likewise, designing VNHCs for *energy dissipation* allows robots to safely and realistically slow down. In this PhD, I propose to further study the energy regulation properties of VNHCs. First, we will find mathematical conditions under which VNHCs are guaranteed to inject or dissipate energy in fixed-base robots. Then we will design a means of transitioning between two different VNHCs, enabling us to regulate a robot's energy in a provably safe manner. We will experimentally verify the results of this theory on the acrobot by designing a gymnastics routine which is performed solely by transitioning between different virtual constraints. Finally, we will extend the theory to mobile animal-like robots, and we will build a robotic monkey which uses VNHCs to swing on monkey bars just like a real monkey would swing through jungle trees.

The advancements in mathematics from this research will bring improvements to the control of all autonomous systems. The ability to safely transition between complex constraints by adding or removing energy will allow for more expressive motion, and may become a standard technique for controlling biologically-inspired robots.

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