Motion synthesis for legged-wheeled robotic creatures

Moritz Geilinger, Sebastian Winberg, Stelian Coros
ETH Zurich

Fueled by a recent surge in sensing and artificial intelligence (AI), robotics has the potential to profoundly impact our daily lives. Indeed, with applications ranging from personal assistance and social companionship to inspection and search-and-rescue, the socioeconomic promise of this field is unquestionable. To accelerate the seamless integration of robots into our technology-driven society, our goal is to develop algorithmic foundations that will shape the way future generations of robots are made. More specifically, towards the goal of ubiquitous robots, our recent work focuses on customizability and accessibility by promoting an engineering meets AI methodology.

Our design system, which is presented in detail in [1], enables bespoke robots to be easily created with the aid of specialized software. To enable user-created robots to learn how to move, we developed an efficient trajectory optimization formulation that is tailored to hybrid legged/wheeled robots of arbitrary designs. Through a unified treatment of feet and wheels, our model automatically generates stable walking, rolling and skating motions.

To validate our work, we designed a variety of robotic creatures and corresponding motions, all of which were tested using off-the-shelf physics-based simulators. We further fabricated some of our designs to assess the degree to which physical prototypes match our simulation results.

1 Overview

1.1 Robot Designer

Our robot design tool allows users to create unique robot designs by connecting together different types of mechanical components in a mix-and-match manner. This design process is illustrated in Fig. 1. The database of components we use for all our results consists of servomotors, 3D printable connectors and three types of end effectors: actuated wheels whose angular speed is controlled by motors, passive wheels that can spin freely about their rotation axis, and welded wheels that afford no motion relative to the body part they are attached to. Welded wheels are used to model feet that roll on the ground as the robots are moving, and when their radii are set to 0, they become equivalent to the point foot model commonly used by motion planning algorithms.

1.2 Motion Generation

Once the robot morphology has been designed, a robot model is created: servomotors correspond to actuated joints, connectors define the geometric shape of each rigid link of the robot, and end-effectors specify the mechanical behavior of the components that will come into contact with the environment as the robot moves. This input defines the parameters used in our motion generation model which builds on trajectory optimization techniques that reason in terms of a robot’s centroidal dynamics [2]. This simplified dynamics representation can be easily complemented by geometric constraints to ensure that the generated motions are consistent with the robot’s kinematics [3].

The robots interact with the environment through their end-effectors, which we assume to be wheels described by their radii, mounting locations on the body part of the robot, and the wheels’ rotation axes. Our motion generation model supports passive and actuated wheels, as well as feet, which can be modeled as wheels with zero radii. We introduce a set of auxiliary variables to describe the end-effectors, such as the wheel’s speed and orientation. This allows us to effectively formulate constraints that describe the wheel’s implications on the resulting motion. For example, one component needed to model passive wheels is to ensure that ground reaction forces in the direction along which the wheel is free to move vanish. To satisfy this criterion, we formulate a constraint that is only satisfied when the wheel is oriented perpendicular to the ground reaction force: $\mathbf{f} \cdot \mathbf{t}(\alpha) = 0$, where $\mathbf{f}$ are the forces at the contact point between the wheel and the environment and $\mathbf{t}(\alpha)$ is a function returning the direction of the wheel given its orientation $\alpha$. 

Figure 1: Left: A new robot design can be easily created by combining different mechanical components. Right: Thanks to a very general robot model, the motion generator can create compelling motions for a wide variety of robot morphologies. And can then be authored using the interactive motion editor.
In addition to the constraints that arise from centroidal dynamics, robot’s kinematics and the interaction of the robot and its environment at the end effectors, we define the following set of constraints: 

- **consistency constraints** that guarantee the between centroidal coordinate frame and the set of auxiliary end effector variables; 
- **collision constraints** that prevent the end effectors from colliding; 
- **fabricational constraints** that ensure the range of motion and angular velocity of each joint is within the capabilities of the physical actuators; and 
- **boundary constraints** that enforce either periodic motions or motions with predescribed start and end states.

Valid motions satisfy all these constraints and fulfill some user specified high level goals. Motions are thus generated by solving this constrained optimization problem using Newton’s method and a penalty-based approach for the constraints. In an interactive motion editor, Fig. 1, users can set and edit these high level goals and choreograph the robot to perform motions such as walking, rolling, gliding or skating motions, that are agile and compelling, yet physically-valid and stable. The generated motions are validated using an off-the-shelf physical simulator [4].

2 Results

Thanks to our interactive design and motion synthesis system, it is very easy to create a variety of different robot morphologies and generate corresponding motions. All motions emerged automatically as a function of the morphological design of each robot. Users provided only high-level guidance in the form of a desired moving speed, or optionally, in the form of a sparse set of targets for the robot’s body and/or end effectors over time.

Our system allows the flexibility to combine legs and wheels. While the wheels provide the robot with an efficient way to locomote, the legs enable increased agility. This makes it for example possible to quickly accelerate and then halt. In order to not lose balance and topple over, the robot extends its front legs forward to maintain the center of pressure within the support polygon. It is worth noting that the optimization process discovers this strategy by itself, without any intervention from the user.

Passive wheels also provide ample opportunities for efficient locomotion, skating being the prime example. Skating is an elegant and highly efficient form of human locomotion. Even at high speeds, muscles move slowly and can thus exert a large amount of force for propulsion. A similar motion where all passive wheels never lose contact with the ground is called swizzling. As for the skating motion, the swizzling motion is automatically synthesized by our system given just high level goals, such as reaching a target location in a given time frame and that all wheels shall be on the ground.

To validate the robotic designs and its generated motions, we designed a four legged robot that can either have one actuated, or two passive wheels per end effector, Fig. 2. A large variety of compelling motions were generated and easily transferred to the physical prototypes. Thanks to the fabricational constraints that respect the motors.

3 Conclusions

We presented a novel design system for a rich class of hybrid legged/wheeled robotic creatures. Thanks to the versatile trajectory optimization formulation, physically-valid walking, rolling, gliding and skating motions arise naturally as a function of the design characteristics of different robots. Our tools allow designers to interactively choreograph a large variety of compelling motions. We fabricated two physical robots with actuated and passive wheels to demonstrate that our system generates agile motions that perform just as well in the real physical world.

References


