How can we achieve versatile and robust robotic walking? The concept of Divergent Component of Motion as possible candidate

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I. General thoughts about the complexity of locomotion

Legged locomotion is generally regarded as a tough problem due to its hybrid dynamics, unilaterality constraints of contact forces, the high dimensionality and nonlinearity of a robot's general dynamics and many other issues.

And yet I *hypothesize*:
Walking and most other forms of legged locomotion are probably way more simple to achieve than we think!

Looking into nature, seeing all kinds of different animals moving through their natural habitats in a very robust and versatile way and typically with an appearance of ease, and also watching those amazing videos published by Boston Dynamics[1] who thereby proof that they have (partially) achieved what we are looking for, I get the impression that **what we are missing are** neither more complex models nor brute-force computing but instead **insights and a good understanding of the fundamental aspects** of locomotion.

Regarding versatility we probably have to think about more generic ways of formulating locomotion tasks.
Just a few examples:

- If a controller allows for heel-to-toe motion when walking forward, it should automatically switch to toe-to-heel walking when walking backwards (or at least suppress the heel-to-toe pattern).
- Controllers should support variable step timing and arbitrary footstep patterns/locations.
- A walking pattern generator should decide as much as possible by itself, e.g. using some optimality criterion, instead of being tuned heuristically.

The issue of versatility seems rather related to appropriate walking pattern generators (i.e. planning), while the issue of robustness seems to be more related to the chosen control setup. It has to be noted though that finally, both the planner and the controller should work hand in hand in order to achieve the greatest possible robustness (see next section on my current research).

It seems to me that to date we are missing intrinsically stable control mechanisms. One example of such a control mechanism might be the use of impedance control instead of pure position or force control, which are most widely used in the contemporary control frameworks that I am aware of. Looking at my own simulations, the **most crucial feature** of a controller seems to be **not to make the robot explode**. This could mean: when things go wrong, the robot controller should not make them wronger (rather do nothing). This might sound obvious, but, in my eyes, should be the most important goal of our controllers, long before features such as accurate tracking or high performance/dynamics.

Looking at the different methodologies discussed in literature, I get the impression that linear methods such as LIP/ZMP control or DCM (a.k.a Capture Point) control - when embedded into optimization-based whole-body controllers - will (at least in the medium term) outperform nonlinear methods, since they exclusively allow for closed-form solutions and thus long range previews at real-time rates. This of course shall be subject to discussion!

In the next section, I will shortly recapitulate my thoughts about possible ways of achieving versatile and robust locomotion on robotic platforms, and quickly draft the control approach that I am currently working on.

II. Recent progress using the concept of DCM

The general multi-body dynamics of humanoid (or other legged) robots is quite complex. For online gait generation, it is a widely used idea to mainly focus on the robot's CoM dynamics, which covers the most prominent effects of a locomoting system, while whole-body dynamics is taken care of by a separate, typically local controller.

My personal research work [1], [2] w.r.t. walking control has always been centered around the concept of Divergent Component of Motion (DCM, a.k.a. "(instantaneous) Capture Point" [3]). The DCM is defined as

$$\boldsymbol{\xi} = \boldsymbol{x} + b\,\dot{\boldsymbol{x}} \ . \tag{1}$$

It turns out that using this state transformation, the *CoM dynamics* is found to be stable, it simply follows the DCM. Thus, - assuming sufficient friction - it *doesn't need to be considered explicitly for planning*. This drastically simplifies the process of walking trajectory generation.

Unlike the CoM, the DCM has an unstable first order dynamics and thus requires stabilization. It is pushed by the so called Virtual Repellent Point (VRP), which geometrically encodes the total force acting on the robot's CoM.

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[1]Note: if Boston Dynamics can do it, we can do it :) !

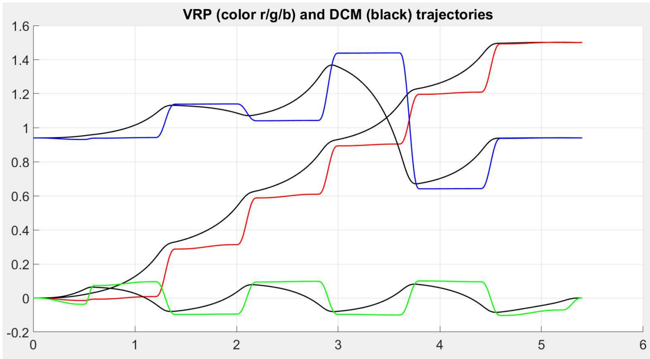

Fig. 1. Smooth and consistent VRP and DCM reference trajectories

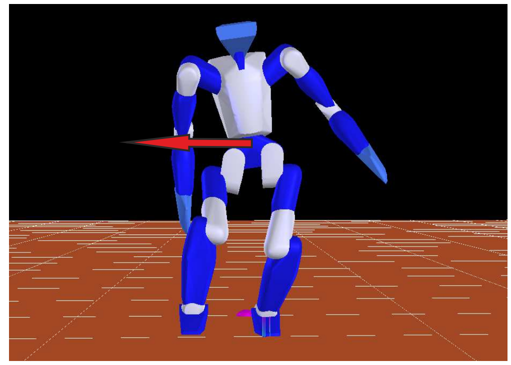

Fig. 2. Toro recovering from push by step adjustment

The basic idea of my current research is to design VRP waypoints that fit well to the previewed footholds and are smoothly interpolated. Due to the simplicity of the DCM dynamics, we can find analytical solutions for DCM reference trajectories that are consistent with the VRP trajectories and fulfill a certain terminal constraint. One of my goals is to assure perfect smoothness of both VRP and DCM reference trajectories (see Fig. 1) throughout all phases of a walking pattern (especially during start and end).

The main features of my planning framework are:

- Simple design of smooth and feasible VRP trajectories (assuming sufficient friction)
- VRP-consistent DCM trajectories computed analytically
- Multi-step preview at real-time rates

In my most recent work, I derive analytical preview matrices for several VRP and DCM related quantities. These matrices may be used to directly tell, where to step in order to perfectly compensate for the current DCM tracking error. This method works very well (see Fig. 2). Improvements that I am currently working on include perfectly smooth transitions from step to step, even after the DCM trajectories have been adjusted to compensate for disturbances.

It is an interesting question, to what extent a tracking error should be allowed to influence the reference trajectories. Adjusting the original reference trajectories just once per step leads to discontinuities during step transitions. On the other hand, if the tracking error is simply compensated by recomputing the reference such that the error vanishes, there is - apart from the stabilizing effect of the step adjustment - no more resistance to perturbations and thus, the actual tracking of the original reference is destroyed. I am currently working on a compromise that includes both an adjustment of the reference trajectories to guarantee smooth transitions and a tracking component which locally counteracts disturbances by appropriate force modulation.

Also, I am currently evaluating a momentum-based disturbance observer that will help to compensate for very strong and persistent perturbations.

III. Topics I'd like to discuss during Dynamic Walking

During the Dynamic Walking conference, I would love to talk and discuss about different aspects of versatile and robust locomotion in general and about the concept and recent progress in the field of Divergent Component of Motion (DCM) control in particular.

I'd like to discuss the following questions:

- How far are we from achieving sufficiently versatile and robust walking?
- How far are we as open research community from the performance that Boston Dynamics presents?
- What mechanisms (force modulation, step adjustment, angular momentum control) are most important for robust walking and how can we include them all in a single control framework?
- What is you guys' opinion on the concept of Divergent Component of Motion (DCM)?

Dynamic Walking is the most awesome conference ever. I'd be more than happy to be part of it this year!

Acknowledgements

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References

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