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Motion Analysis by Proper Orthogonal Decomposition: An Application to the Gait Motion of the Humanoid Robot *Lola*

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Abstract

Autonomous bipedal robot locomotion is a challenging task as it requires stable and robust walking motion planning and control under real-time requirements. Considering a real-world application, the locomotion capabilities of such robots must be highly dynamic and versatile. The humanoid robot *Lola*, see Fig. 1, is a human-sized bipedal robot developed at the Chair of Applied Mechanics at the Technical University of Munich.

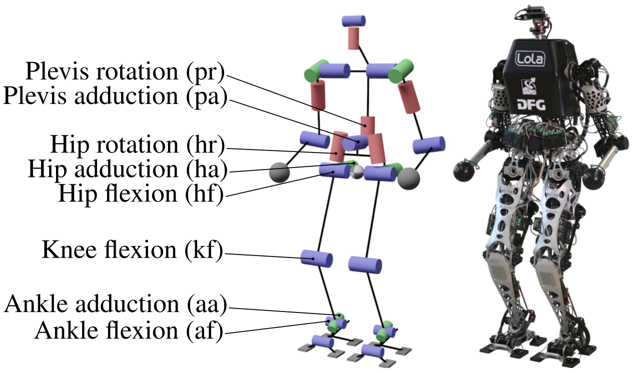


Figure 1: Human inspired kinematic topology of the robot *Lola*. A total weight of about 68 kg and a height of 176 cm, allowing a comparison with the locomotion of adult humans. *Lola* has 26 distributed, electrically actuated joints, with pelvic rotation (pr), pelvic adduction (pa), hip rotation (hr), hip adduction (ha), hip flexion (hf), knee flexion (kf), ankle adduction (aa) and ankle flexion (af) being the degrees of freedom mainly responsible for its gait.

Although [4] shows the ability to walk stable and robust in uncertain environments, *Lola*'s motion is far from being highly dynamic. A precise analysis of its walking motion is required to better understand the underlying gait pattern and to enhance the capabilities of the robot's soft- and hardware to achieve a highly dynamic gait. As humans fulfill these requirements, human gait serves as an ideal model for walking robots, and thus a comparison with the basic human gait pattern is obvious.
In this contribution we compute the underlying fundamental gait pattern of *Lola* using Proper Orthogonal Decomposition (POD), which is widely used in the characterization and model order reduction of dynamic systems [2], and applications to gait analysis can also be found in biomechanics, e.g. [1]. The POD is done by assembling the time history of the joint angles $q(t)$ of the most important joints for walking, see Fig. 1, row-wise in a so-called snapshot matrix $\boldsymbol{Q}_{\text{Lola}}$:

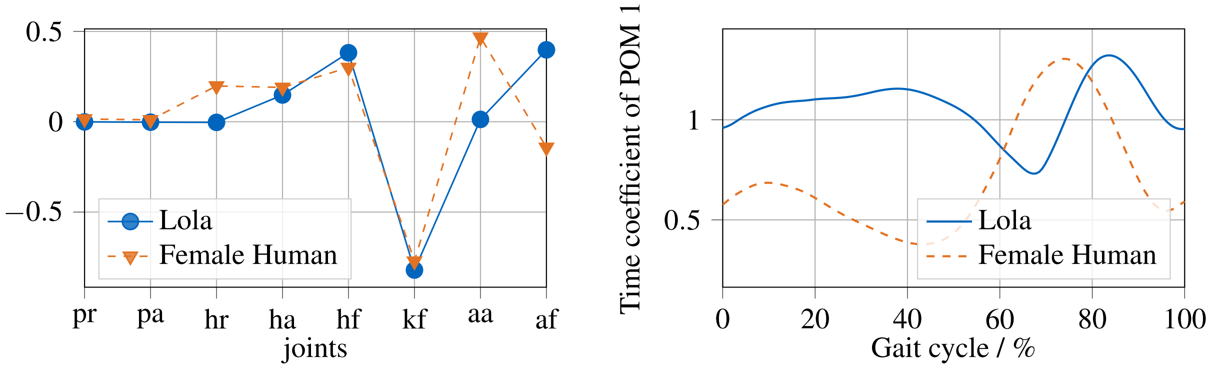
$$\boldsymbol{Q}_{\text{Lola}} = \begin{bmatrix} q_{\text{pr}}(t_0) & \cdots & q_{\text{pr}}(t_{end}) \\ \vdots & \ddots & \vdots \\ q_{\text{af}}(t_0) & \cdots & q_{\text{af}}(t_{end}) \end{bmatrix} \in \mathbb{R}^{8\times N_t} \tag{1}$$

We assume symmetry and periodicity of the gait. Thus, we take only the angles of the left leg during one gait cycle (time between two consecutive initial touchdowns of the left foot) resulting in N_t timesteps to construct the snapshot matrix. The POD of the snapshot matrix is then performed by singular value decomposition (SVD):

$$\boldsymbol{Q}_{\text{Lola}} \overset{\text{SVD}}{=} \boldsymbol{U}_{\text{Lola}} \underbrace{\boldsymbol{\Sigma}_{\text{Lola}} \boldsymbol{V}_{\text{Lola}}^{\text{T}}}_{:=\boldsymbol{A}_{\text{Lola}}} = \begin{bmatrix} \boldsymbol{u}_{\text{Lola},1} & \cdots & \boldsymbol{u}_{\text{Lola},8} \end{bmatrix} \begin{bmatrix} \boldsymbol{a}_{\text{Lola},1} \\ \vdots \\ \boldsymbol{a}_{\text{Lola},8} \end{bmatrix} = \sum_{i=1}^{8} \boldsymbol{u}_{\text{Lola},i} \boldsymbol{a}_{\text{Lola},i} \tag{2}$$

The left singular vectors $\boldsymbol{u}_{\text{Lola},i} \in \mathbb{R}^{8\times 1}$ (columns of $\boldsymbol{U}_{\text{Lola}}$) are the time-independent Proper Orthogonal Modes (POMs). The product of the singular value matrix $\boldsymbol{\Sigma}_{\text{Lola}}$ and the matrix of the right singular vectors $\boldsymbol{V}_{\text{Lola}}^{\text{T}}$ is defined as $\boldsymbol{A}_{\text{Lola}}$. This matrix contains the time-dependent coefficients $\boldsymbol{a}_{\text{Lola},i} \in \mathbb{R}^{1\times N_t}$, which represent the time history of each POM. The result is thus interpreted as a decomposition of the time-spatial snapshot matrix $\boldsymbol{Q}_{\text{Lola}}$ into a sum of time-independent shape functions $\boldsymbol{u}_{\text{Lola},i}$ multiplied by a time history $\boldsymbol{a}_{\text{Lola},i}$. This separation of time and space information allows for a more comprehensive motion analysis. Furthermore, the contribution of each POM to the reconstruction of $\boldsymbol{Q}_{\text{Lola}}$ is estimated by the singular values σ_{Lola} of $\boldsymbol{Q}_{\text{Lola}}$, which are the non-zero diagonal elements of $\boldsymbol{\Sigma}_{\text{Lola}}$. This allows to neglect certain modes, thus condensing the approach to an analysis of only a small number of POMs and their respective time coefficients.

In a previous study [3] we focused on quantifying the difference between the POMs $\boldsymbol{u}_i$ of *Lola* and the one computed from human data, which showed a general similarity in the more important POMs and a decreasing similarity along the less important POMs, (see e.g. Fig. 2a). However, the time coefficients corresponding to the POMs were not taken into account for this analysis. As can be seen in Fig. 2b, the time histories of the POMs from *Lola* and those from human data can differ even though the shape of the POMs is similar. In this contribution, we address this issue by incorporating the time coefficients into the analysis. This is done by computing a Fourier transform of the time coefficients and analyzing the underlying frequencies. Furthermore, we compute the POD of Lola's gait in different walking scenarios like varying the gait speed. The results of this analysis allow us to further understand the dynamics of *Lola*'s gait and pave the way for hard- and software improvements towards a more dynamic gait.



(a) POM $\boldsymbol{u}_1$ with the highest contribution to the gait pattern. See Fig. 1 for the definition of the joints.

(b) Time coefficient $\boldsymbol{a}_1$ corresponding to the POM with the highest contribution to the gait pattern.

Figure 2: Comparison of the gait pattern computed from *Lola* with the one computed from a human. The human data is taken from [5].

References

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