TUM Institute for Cognitive Systems (ICS)

OpenWalker

Module Description: Foot Compliant (FCM)

Emmanuel Dean, Florian Bergner, Rogelio Guadarrama-Olvera,
Simon Armleder, and Gordon Cheng

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1 Module Description

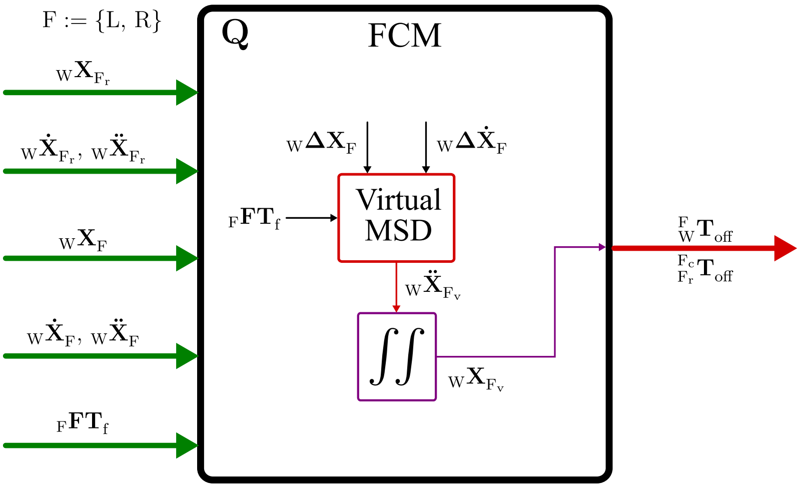

Figure 1.1: Foot Compliant module: This module implements the local zmp estimation for each leg and the combined legs ${}_{W}\mathbf{p}$, ${}_{L}\mathbf{p}$, and ${}_{R}\mathbf{p}$, respectively.

The *Foot Compliant* module (FCM) allows to modify the foot trajectories based on the conditions of the environment. The principal idea behind this module is to provide a compliant behavior for the foot to cope with uncertainties in the terrain. This compliant behavior uses the FT sensor information to generate offsets for the foot, which modify the nominal foot trajectory generated by the FTGM. The compliant behavior is generated using a virtual admittance model that is defined in the local foot coordinate frame. Admittance control is a standard control method to map forces to motion using simple virtual mass-damper dynamic systems.

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estimates the local Zero Moment Points (ZMP) for each foot and the global ZMP for both feet, ${}_{\mathrm{W}}\mathbf{p}$, ${}_{\mathrm{L}}\mathbf{p}$, and ${}_{\mathrm{R}}\mathbf{p}$, respectively. The ZMP is an important concept for dynamics and control of legged locomotion, e.g., for humanoid robots. It specifies the point where the dynamic reaction forces at the contact of the foot with the ground does not produce any moment in the horizontal direction, i.e. the point where the total of horizontal inertia and gravity forces are in equilibrium. This module requires kinematic information of the feet, dynamic information of the Center of Mass (CoM), and ground reaction forces, which can be obtained with Force/Torque (FT) sensors, for example, mounted on the feet. The ZMP calculation can be extended using IMU sensors as well. The information obtained from the ZMP analysis is extremely important for balance, which is the highest priority task for legged robots. This module also filters the signals of the FT sensors, which are used by other components of the OpenWalker framework.

2 Module Connections

2.1 Inputs

Symbol	**Name**	**Type**	**Description**
${}_{\mathrm{W}}\mathbf{X}_{\mathrm{F}} \in \mathbb{R}^7$	Foot Pose	`CartesianPosition`	This vector represents the pose of the left and right feet with respect to the world coordinate frame (wcf). The orientation is represented as Quaternions.
${}_{\mathrm{W}}\dot{\mathbf{X}}_{\mathrm{F}} \in \mathbb{R}^6$	Foot Velocity	`CartesianVelocity`	This vector represents the velocity of the foot with respect to the world coordinate frame.
${}_{\mathrm{W}}\ddot{\mathbf{X}}_{\mathrm{F}} \in \mathbb{R}^6$	Foot Acceleration	`CartesianAcceleration`	This vector represents the acceleration of the foot with respect to the world coordinate frame.
${}_{\mathrm{W}}\mathbf{X}_{\mathrm{F_r}} \in \mathbb{R}^7$	Reference Foot Pose	`CartesianPosition`	This vector represents the reference pose of the left and right feet with respect to the world coordinate frame (wcf). The orientation is represented as Quaternions. This reference pose is obtained from a trajectory generator.
${}_{\mathrm{W}}\dot{\mathbf{X}}_{\mathrm{F_r}} \in \mathbb{R}^6$	Reference Foot Velocity	`CartesianVelocity`	This vector represents the reference velocity of the foot with respect to the world coordinate frame.This reference pose is obtained from a trajectory generator.
${}_{\mathrm{W}}\ddot{\mathbf{X}}_{\mathrm{F_r}} \in \mathbb{R}^6$	Reference Foot Acceleration	`CartesianAcceleration`	This vector represents the reference acceleration of the foot with respect to the world coordinate frame.This reference pose is obtained from a trajectory generator.
${}_{\mathrm{L}}\mathbf{FT} \in \mathbb{R}^6$	Left Foot FT	`ForceTorqueSensor`	This vector contains the signals of the force/torque sensor mounted on the left foot.
${}_{\mathrm{R}}\mathbf{FT} \in \mathbb{R}^6$	Right Foot FT	`ForceTorqueSensor`	This vector contains the signals of the force/torque sensor mounted on the right foot.

2.2 Outputs

Symbol	**Name**	**Type**	**Description**
${}^{\mathrm{F}}_{\mathrm{W}}\mathbf{T}_{\mathrm{off}} \in \mathbb{R}^{4\times 4}$	Global Foot Offset	`HomogeneousTransformation`	This homogeneous transformation provides the offset of the feet relative to the world coordinate frame.
${}^{\mathrm{F_c}}_{\mathrm{F_r}}\mathbf{T}_{\mathrm{off}} \in \mathbb{R}^{4\times 4}$	Local Foot Offset	`HomogeneousTransformation`	This homogeneous transformation provides the offset of the commanded feet relative to the reference foot coordinate frame.

2.3 Inter-Connections

The inputs of the FCM come from the FTGM which provides reference trajectories for the feet, $\left({}_{\mathrm{W}}\mathbf{X}_{\mathrm{F_r}}, {}_{\mathrm{W}}\dot{\mathbf{X}}_{\mathrm{F_r}}, {}_{\mathrm{W}}\ddot{\mathbf{X}}_{\mathrm{F_r}}\right)$, where $\mathrm{F} = \{\mathrm{L}, \mathrm{R}\}$. The FKM produce the current foot state $\left({}_{\mathrm{W}}\mathbf{X}_{\mathrm{F}}, {}_{\mathrm{W}}\dot{\mathbf{X}}_{\mathrm{F}}, {}_{\mathrm{W}}\ddot{\mathbf{X}}_{\mathrm{F}}\right)$. Finally, the ZMPM provides the filtered FT sensor signals $\left({}_{\mathrm{F}}\mathbf{FT}_{\mathrm{f}}\right)$ needed to compute the offsets.

The generated offset will be used in CMDGENM to compute a commanded trajectory for the feet.

2.4 Common Methods

2.4.1 Admittance based on Virtual Dynamics

The standard admittance method is based on a virtual mass-damping system, defined as [1]:

$$\mathbf{M}\,{}_{\mathrm{W}}\ddot{\mathbf{X}}_{\mathrm{v,F}} + \boldsymbol{\beta}\,{}_{\mathrm{W}}\dot{\mathbf{X}}_{\mathrm{v,F}} = {}_{\mathrm{W}}\mathbf{FT}_{\mathrm{F}} + {}_{\mathrm{W}}\mathbf{W}_{\delta,\mathrm{F}} \tag{2.1}$$

where $\mathbf{M} = \mathbf{M}^{\top}$ is a mass matrix, $\boldsymbol{\beta}$ is the viscous friction diagonal matrix, and ${}_{\mathrm{W}}\mathbf{FT}_{\mathrm{F}}$ is the FT sensor signals of the foot F, relative to the world coordinate frame. ${}_{\mathrm{F}}\mathbf{W}_{\delta}$ is a virtual attractor wrench generated with the error between the current foot pose and the reference foot pose, i.e.

$${}_{\mathrm{W}}\Delta\mathbf{X}_{\mathrm{F}} = {}_{\mathrm{W}}\mathbf{X}_{\mathrm{F}} - {}_{\mathrm{W}}\mathbf{X}_{\mathrm{F_r}} \tag{2.2}$$

This second order system can be integrated to generate virtual velocities and positions, ${}_{\mathrm{W}}\dot{\mathbf{X}}_{\mathrm{F_v}}$ and ${}_{\mathrm{W}}\mathbf{X}_{\mathrm{F_v}}$ respectively. Finally, the offset between the reference frame pose

$${}_{\mathrm{W}}\Delta\mathbf{X}_{\mathrm{off}} = {}_{\mathrm{W}}\mathbf{X}_{\mathrm{F_r}} - {}_{\mathrm{W}}\mathbf{X}_{\mathrm{F_v}} \tag{2.3}$$

is used to generate the pose matrices ${}^{\mathrm{F}}_{\mathrm{W}}\mathbf{T}_{\mathrm{off}}$ and ${}^{\mathrm{F_c}}_{\mathrm{F_r}}\mathbf{T}_{\mathrm{off}}$.

References

[1] Keemink, A. Q., van der Kooij, H., Stienen, A. H. Admittance control for physical human–robot interaction. The International Journal of Robotics Research, 37(11), 1421–1444, (2018).