Autonomous and Mobile Robotics

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Humanoid Locomotion: a demonstration

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information

- for any question: smaldone at diag.uniroma1.it
- the code of this demonstration is available at: https://github.com/FilippoSmald1/Robotis-OP3-MPC-walking
- ROS based gazebo simulation of OP3 walking
- the same implementation on the DART dynamic simulator is available upon request

the OP3 robot

- the available platform is Robotis OP3

- open source robot
https://github.com/ROBOTIS-GIT/ROBOTIS-OP3

- hardware:
  - -20 dof, position controlled
  - -encoders, imu
  - -camera
  - -main controller: INTEL NUC i3, 8 GB RAM

- the hardware necessarily constrains our solution to the problem

the OP3 robot

- software:
  - -Linux Mint 16
  - -ROS Kinetic
  - -custom real-time control manager
  - -arbitrary sampling time for motor commands
  - -C++ (convenient for real-time control), python

- the software framework gives us enough versatility for our solution in spite of the hardware

the OP3 robot

- pros:
  - -open source
  - -ROS based
  - -modular (easy to upgrade)
  - -easy maintenance
  - -easy set up
  - -GitHub issues responsiveness
  - -low cost, < 20k € in 2021

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  - -low cost, < 20k € in 2021
- cons:
  - -position controlled actuators
  - -comes without F/T sensors
  - -comes without any range sensors
  - -large and slippery feet

problem statement

- high level description: “make a humanoid navigate to reach a goal”

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  -trajectory generation
  -control
  -localization and mapping

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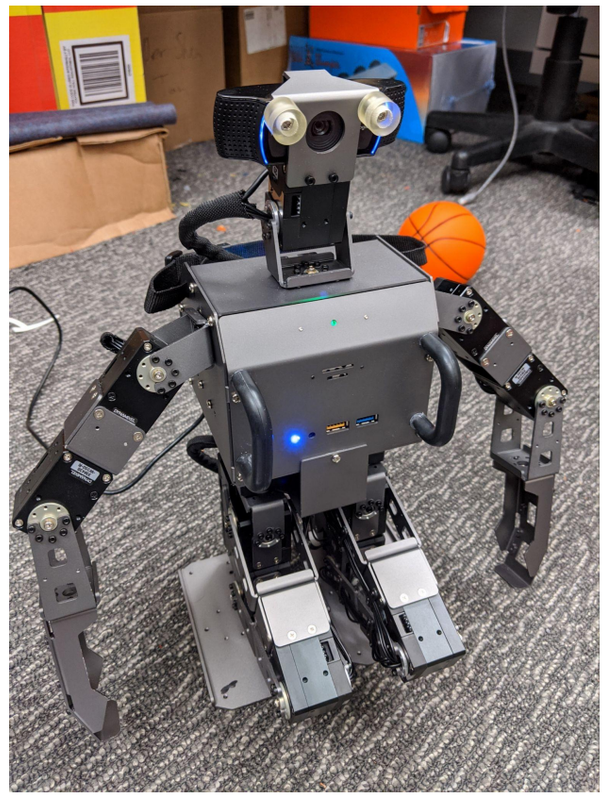
- the robot has a standard initial configuration

- the task will be realized by composing three different motions:
  - -reach a configuration to start walking
  - -walk and reach the goal
  - -come back to the initial configuration



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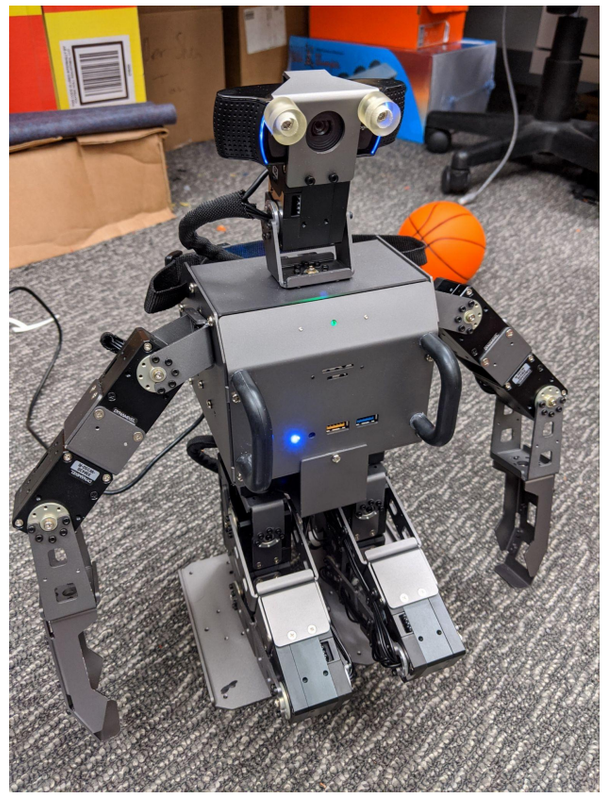


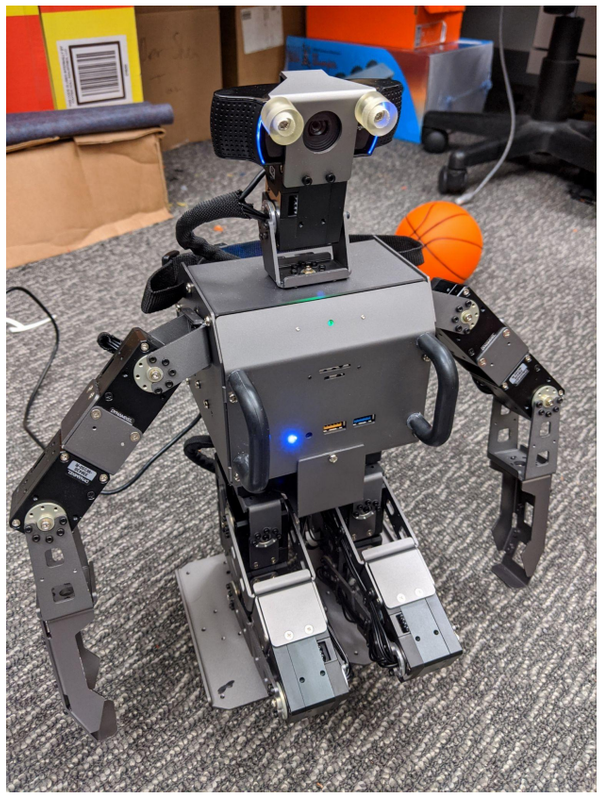
- let's keep it simple: use time pre-programmed motion modes (stand up, walk, sit down)

addressing the problem

- use a hierarchical approach

- for each motion mode generate proper body cartesian trajectories (e.g. CoM, feet, arms)

- track them with a kinematic controller



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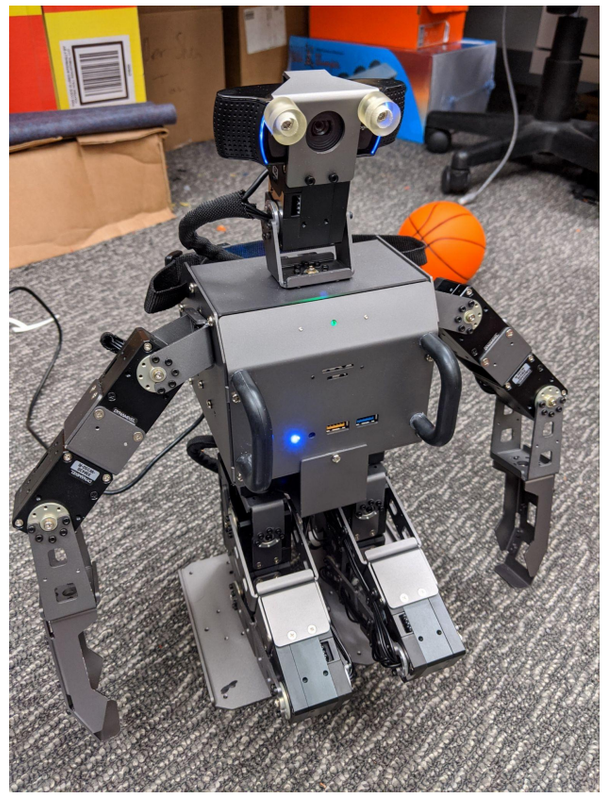

- note that:
  - -kinematic control is the most practical choice with position controlled actuators
  - -we assume that we do not need localization nor mapping
  - -there exist different solutions to this problem

block scheme

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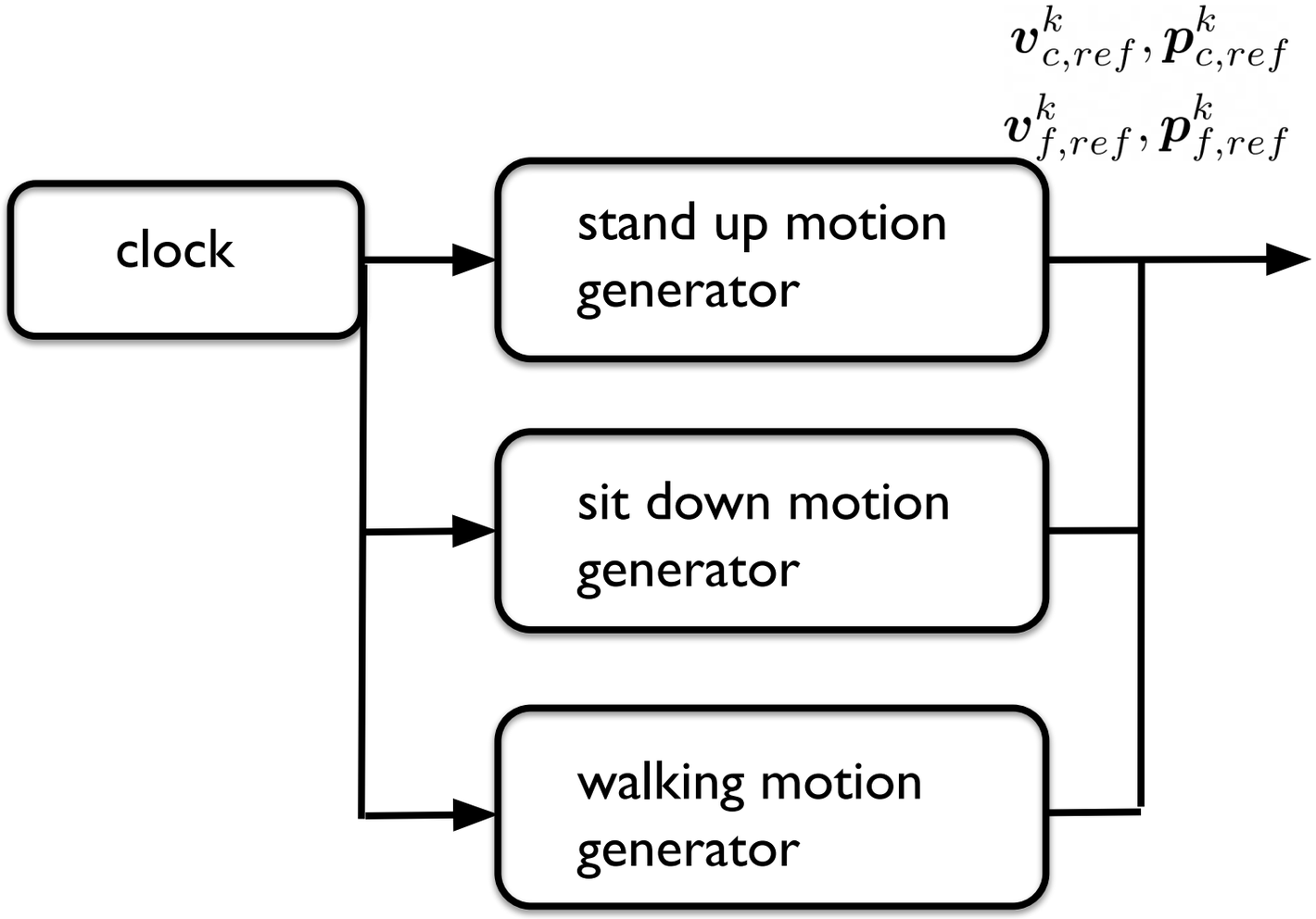

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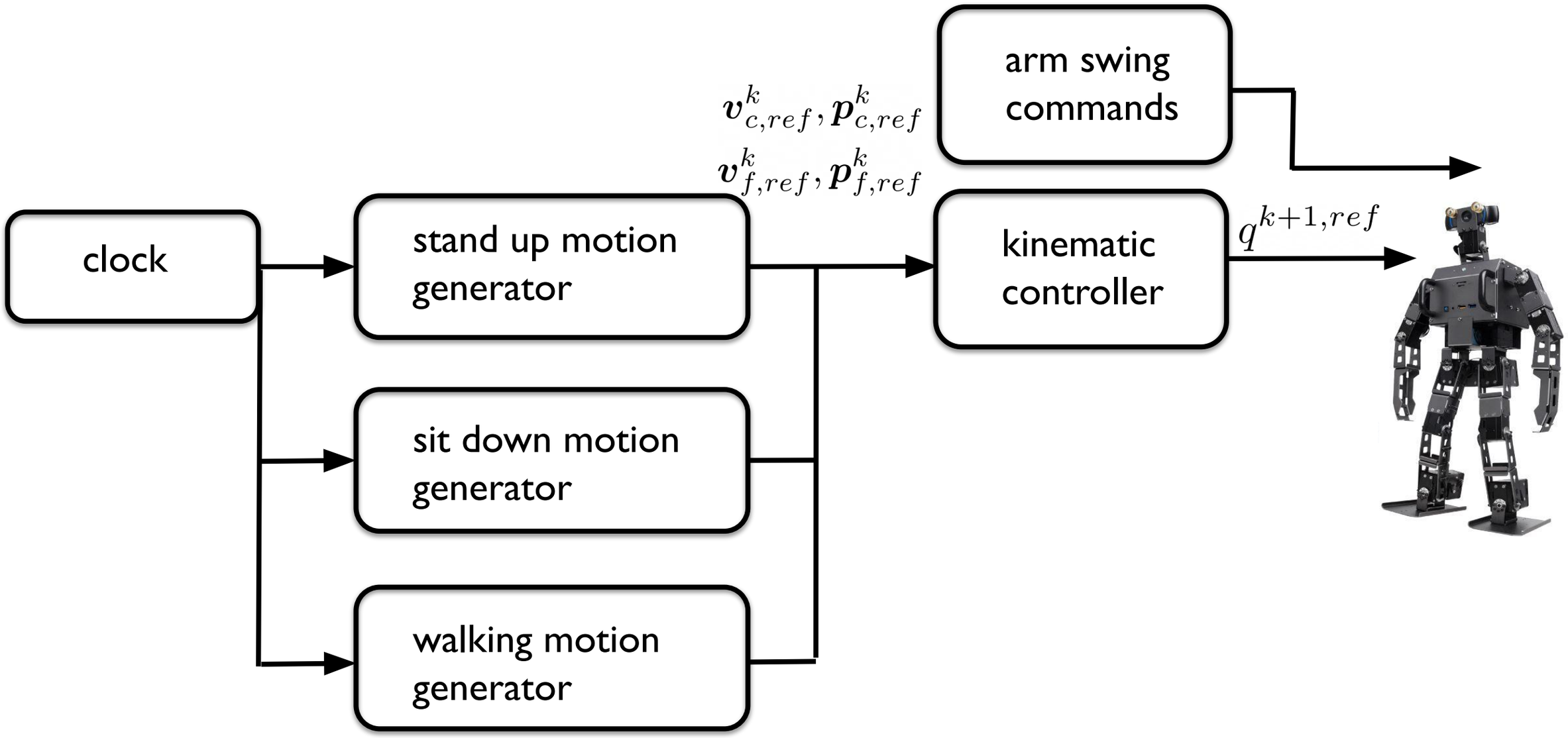

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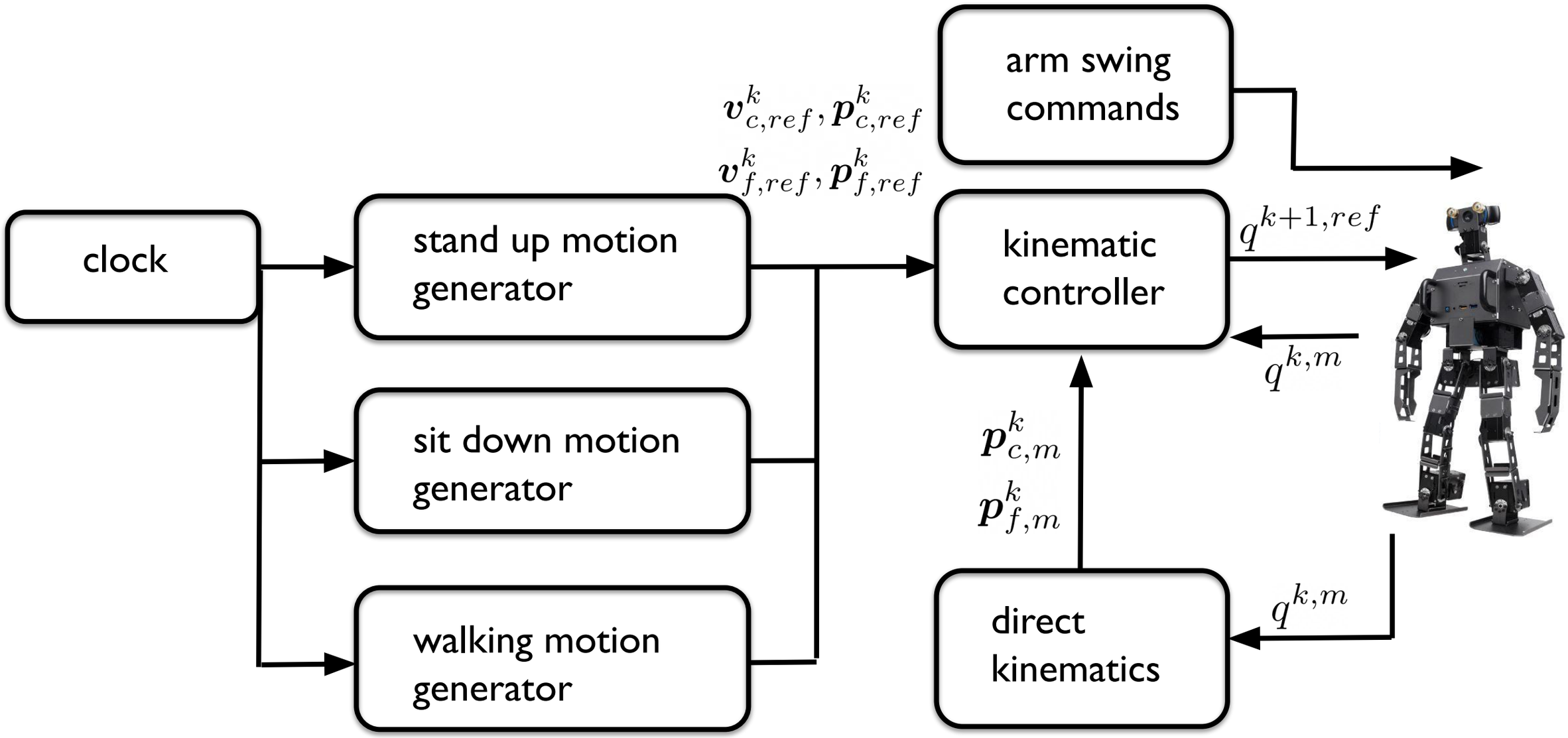
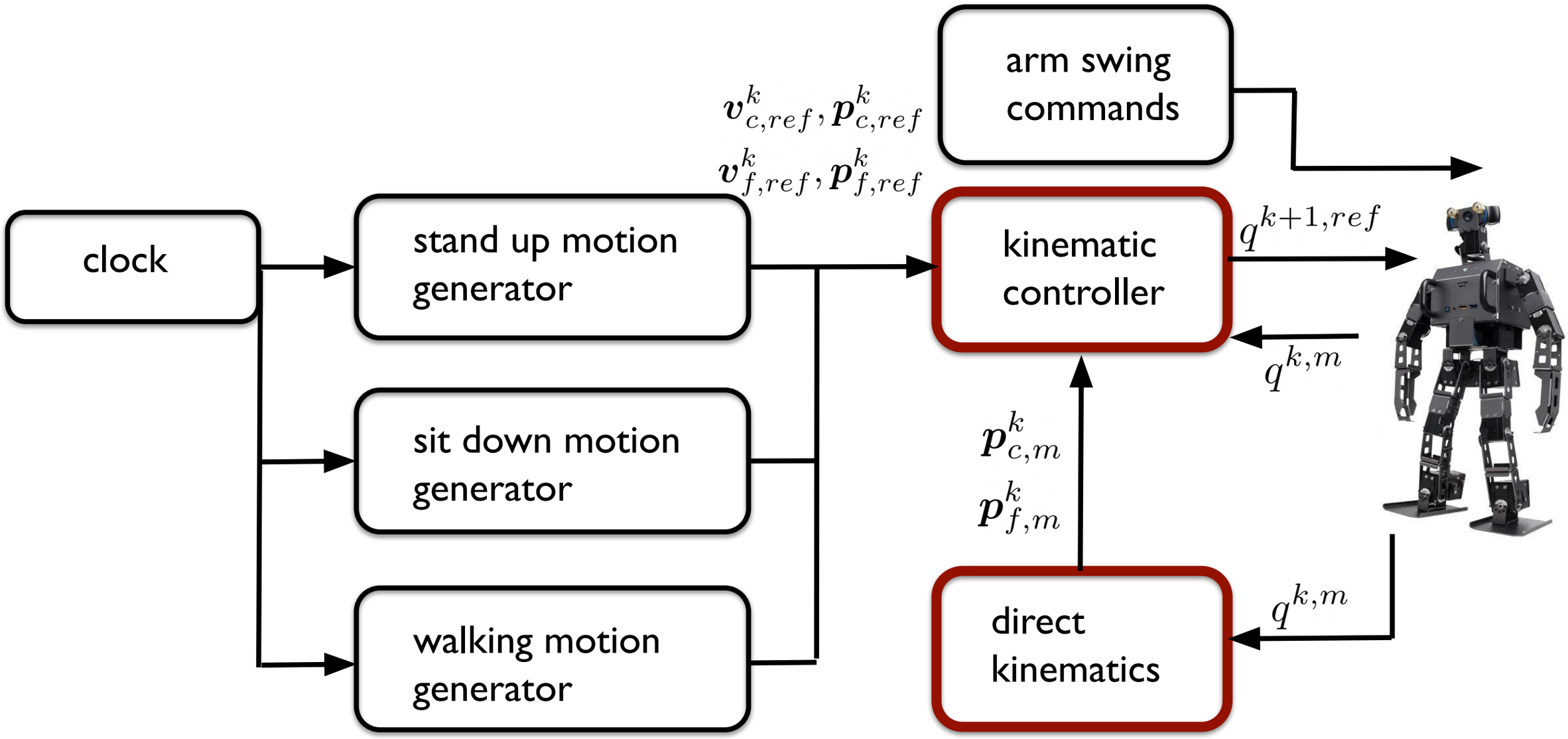


p, v denote the pose and its time derivative

kinematic controller and direct kinematics



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- input: reference pose and velocity of CoM and a foot (left or right), denoted as swing foot

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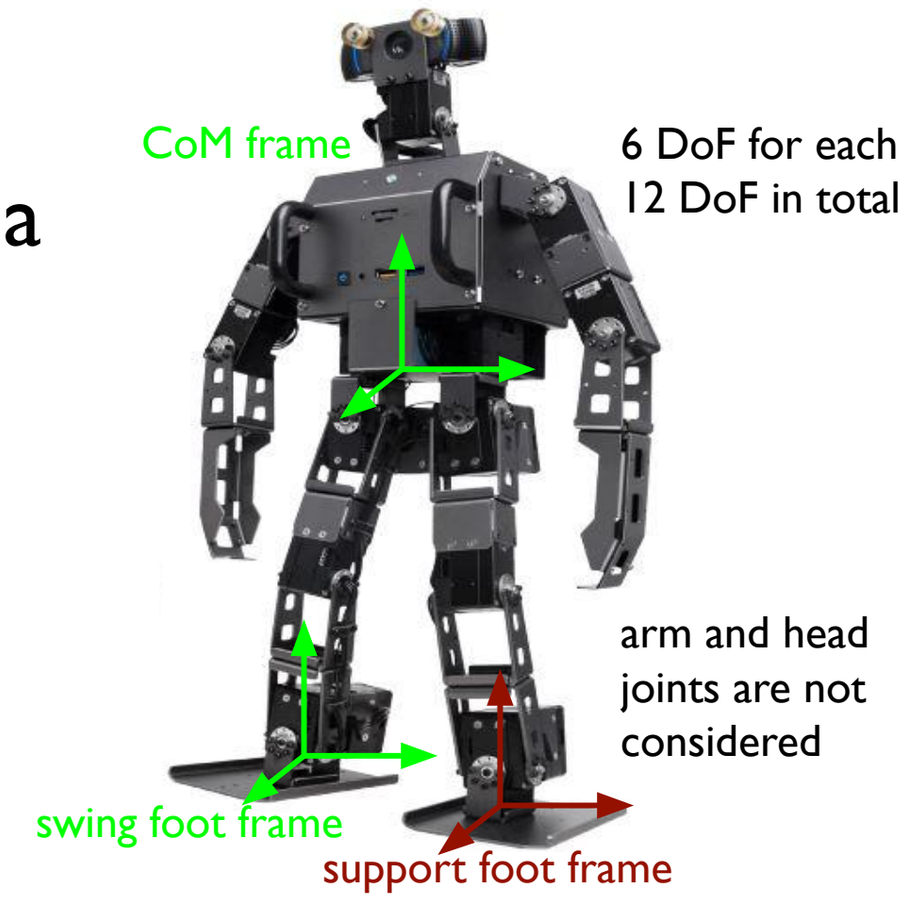
why?

-humanoid as fixed base manipulator where the base frame coincides with a supporting foot

-CoM and swing foot are regarded as End-Effector frames

-regulation via multi-task kinematic control law



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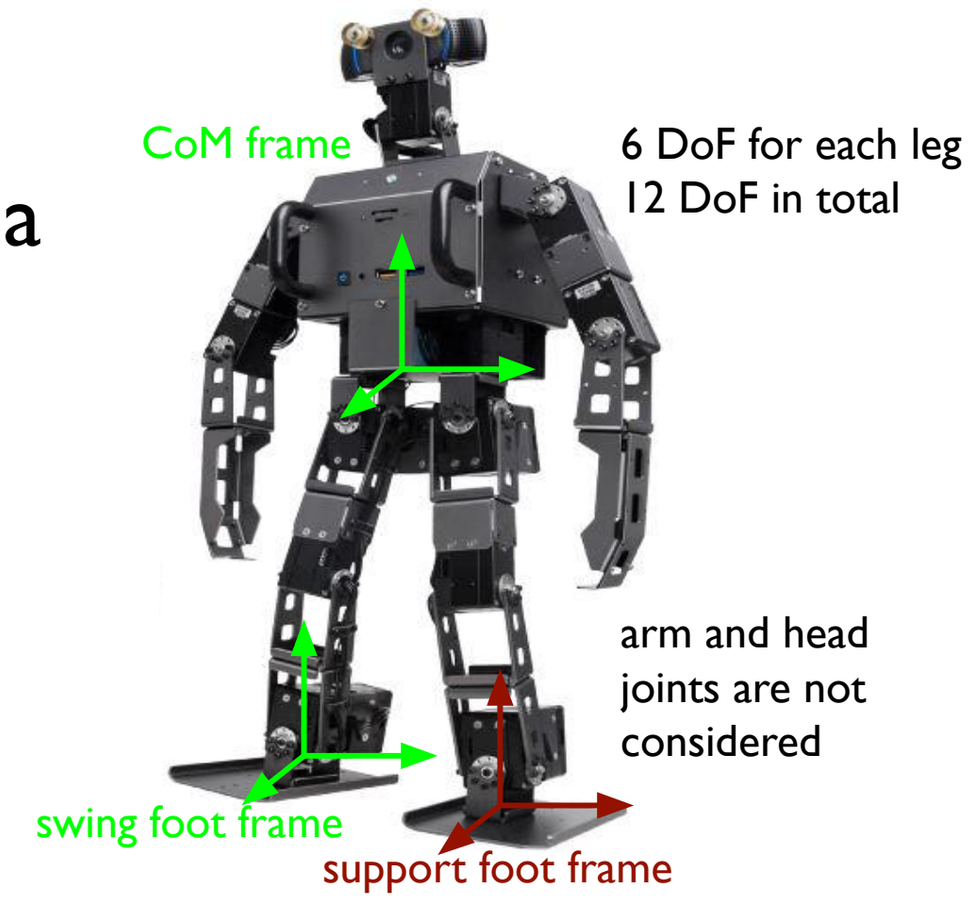

- output: joint position commands

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- compute the joint velocities as

$$\dot{q}^k = \begin{bmatrix} J^k_c \\ J^k_f \end{bmatrix}^{\#} \left[\begin{pmatrix} \boldsymbol{v}^k_{c,ref} \\ \boldsymbol{v}^k_{f,ref} \end{pmatrix} + \boldsymbol{K} \begin{pmatrix} \boldsymbol{p}^k_{c,ref} - \boldsymbol{p}^k_{c,m} \\ \boldsymbol{p}^k_{f,ref} - \boldsymbol{p}^k_{f,m} \end{pmatrix} \right]$$

damped pseudoinverse of stacked jacobians

reference velocities

position error gains

position error

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- integrate to get the joint position commands

$$q^{k+1,ref} = q^{k,m} + \delta \dot{q}^k$$

sampling time

kinematic controller and direct kinematics

- damped least squares to prevent singularity issues

- the direct kinematics and the Jacobians are computed with efficient recursive algorithms which use the robot URDF (Unified Robot Description Format), provided by the manufacturer

- state of the art C++ libraries for these computations: kdl, rbdl, pinocchio

- the choice of the gain matrix is crucial

- the choice of the sampling time is also crucial

kinematic controller and direct kinematics

a quick look at the code - left support foot

```
...
left_leg_fk_solver->JntToCart(q0_left_leg, x_left_leg_fk);
for (int i = 0; i < 12; i++) {
  if (i<6) q0_sf_to_swg(i) = q0_left_leg(i);
  else q0_sf_to_swg(i) = q0_right_leg(11-i);
}
left_foot_to_right_foot_fk_solver->JntToCart(q0_sf_to_swg, x_sf_to_swg);
CoM_pose_meas.segment(0,3) = Eigen::Vector3d(x_left_leg_fk.p(0),x_left_leg_fk.p(1),x_left_leg_fk.p(2));
swg_pose_meas.segment(0,3) = Eigen::Vector3d(x_sf_to_swg.p(0),x_sf_to_swg.p(1),x_sf_to_swg.p(2));
x_left_leg_fk.M.GetRPY(CoM_pose_meas(3),CoM_pose_meas(4),CoM_pose_meas(5));
x_sf_to_swg.M.GetRPY(swg_pose_meas(3),swg_pose_meas(4),swg_pose_meas(5));

sf_pose << desired.leftFootPos, desired.leftFootOrient;
CoM_pose_des << desired.comPos, desired.torsoOrient;
CoM_pose_des(2) = CoM_pose_des(2);
swg_pose_des << desired.rightFootPos, desired.rightFootOrient;
CoM_pose_des = vvRel(CoM_pose_des, sf_pose);
swg_pose_des = vvRel(swg_pose_des, sf_pose);
CoM_pose_des(0) = CoM_pose_des(0);

Eigen::VectorXd v_des, pos_des, pos_meas;
v_des = Eigen::VectorXd::Zero(12);
v_des.segment(0,3) = desired.comVel;
v_des.segment(6,3) = desired.rightFootVel;
pos_des = Eigen::VectorXd::Zero(12);
pos_meas = Eigen::VectorXd::Zero(12);
pos_des << CoM_pose_des, swg_pose_des;
pos_meas << CoM_pose_meas, swg_pose_meas;

if (left_foot_to_right_foot_jacobian_solver->JntToJac(q0_sf_to_swg, J_leftf_to_rightf_leg) < 0) {
  ROS_ERROR( "jacobian error");
}
J_left_leg_to_right = J_leftf_to_rightf_leg.data;
if (left_leg_jacobian_solver->JntToJac(q0_left_leg, J_left_leg) < 0) {
  ROS_ERROR( "jacobian error");
}
J_left_leg_ = J_left_leg.data;
J_stacked << J_left_leg_, Eigen::MatrixXd::Zero(6,6), J_left_leg_to_right;

Eigen::VectorXd q_dot = J_stacked.transpose() * (J_stacked*J_stacked.transpose() + Id*sigma).inverse() * (v_des + gains*(pos_des-pos_meas));
for (int i = 0; i < 6; i++) q_left_leg(i) = q0_left_leg(i) + (1.0/rate)*q_dot(i);
for (int i = 0; i < 6; i++) q_right_leg(5-i) = q0_right_leg(5-i) + (1.0/rate)*q_dot(i+6);
...
```

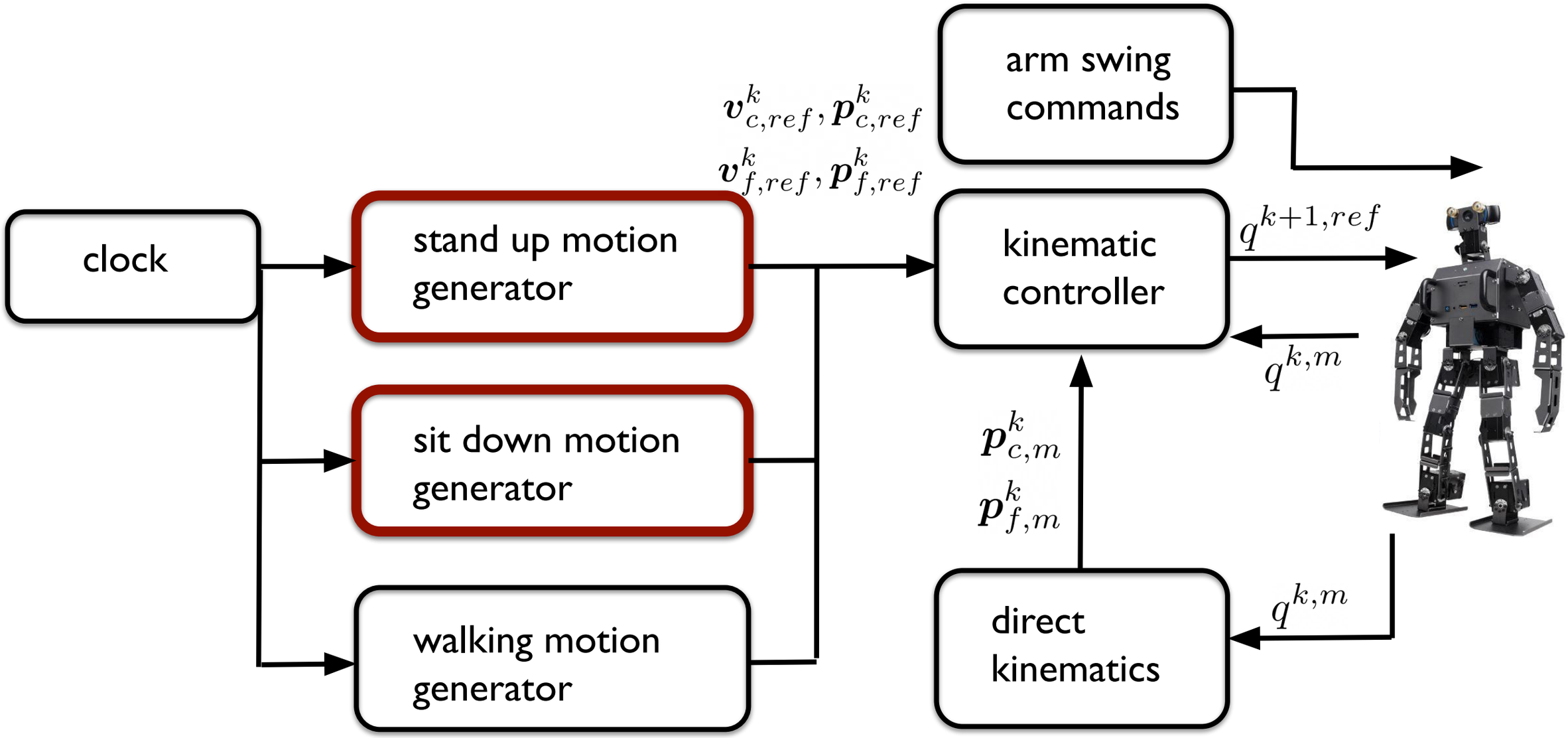
use kdl forward kinematic routine to compute the current CoM and swing foot pose

stack the measurements, the reference poses (in the current support foot frame) and velocities

use kdl jacobian solver to compute the Jacobians and then stack them

compute kinematic control law and integrate to get reference joint positions

stand up and sit down motion



stand up and sit down motion

- start from a pose p^0 and reach a target pose p^1 in T seconds

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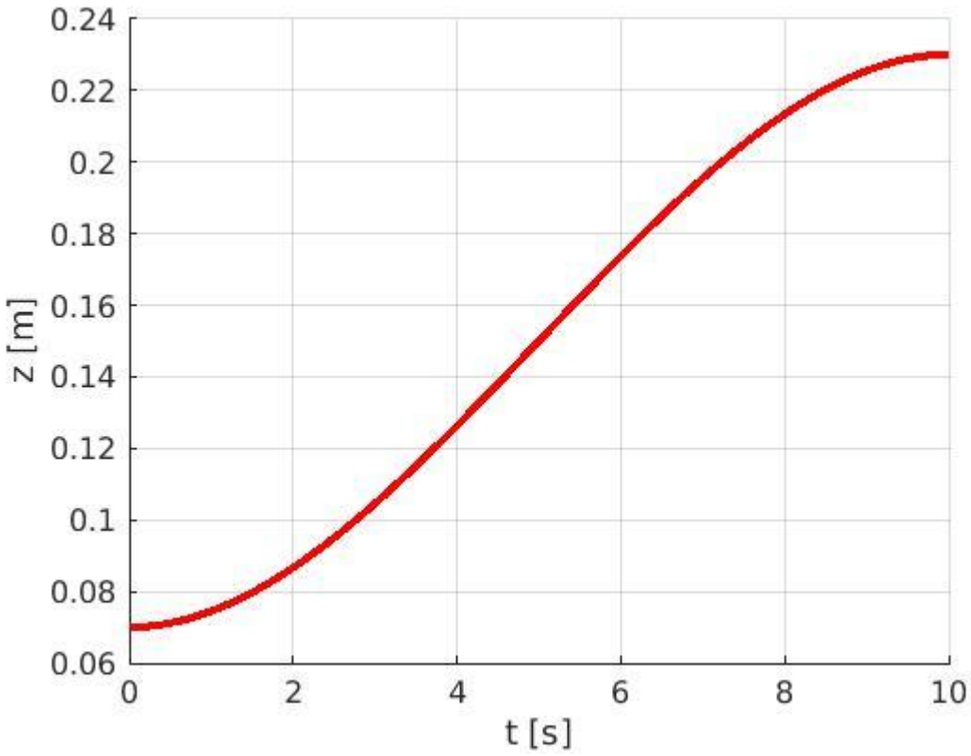
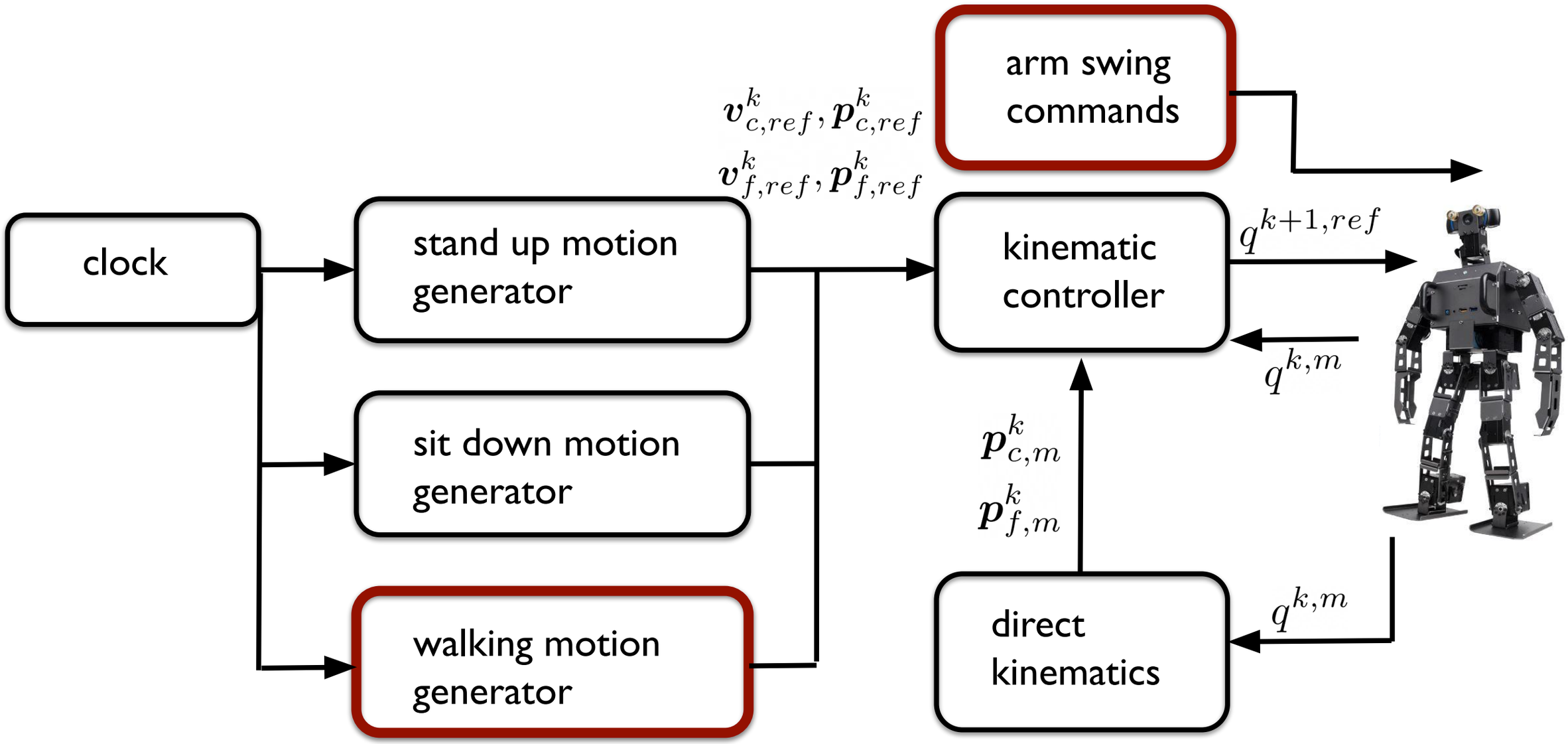


- use for instance a third order polynomial to reach a target pose with zero velocity in $t = T$

- at each time t_k the output of these blocks is $\boldsymbol{p}_{c,ref}(t_k), \boldsymbol{v}_{c,ref}(t_k)$

walking motion



walking motion

- objective: walk to reach the goal (planar ground)

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- forces are exerted through foot contact with the ground

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- approach:

  -plan suitable contacts, i.e. design a footstep plan
  -generate CoM and ZMP trajectories to realize a dynamically balanced gait over the footstep plan
  -generate also swing foot trajectories

walking motion - footstep plan

- footstep plan: cartesian positions and timings (step duration)

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- single and double support alternate during locomotion

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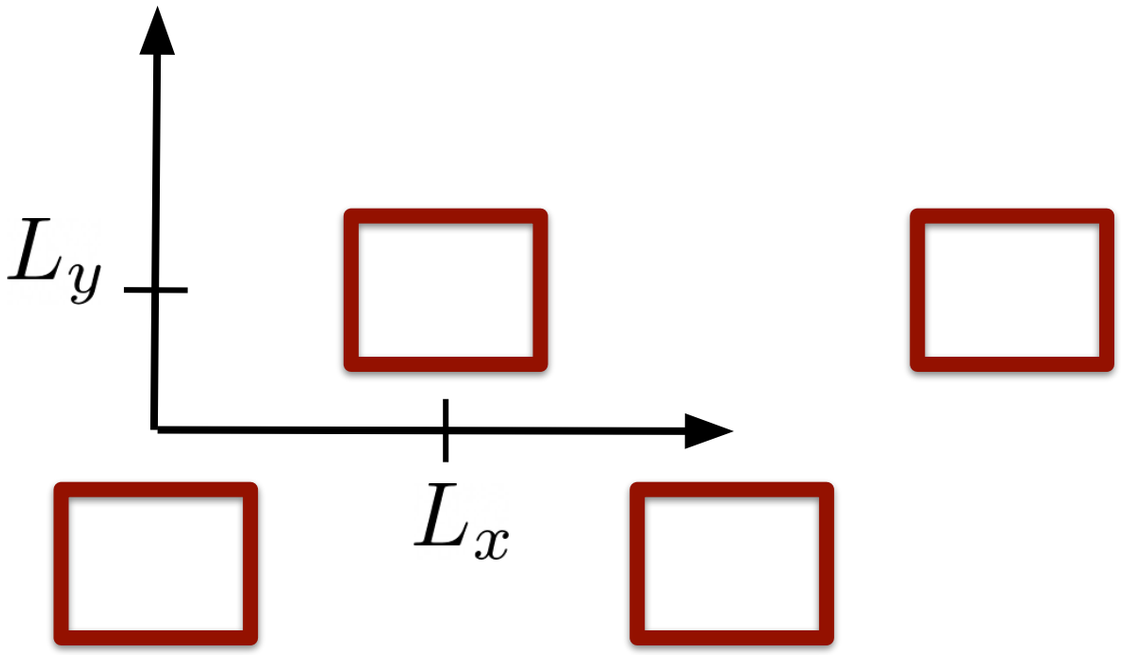
- left and right feet alternate during locomotion
- single and double support alternate during locomotion
- let's keep it simple:
  - -assign a step duration, e.g., $T_s = T_{ss} + T_{ds}$(single and double support duration)
  - -choose a sagittal reference velocity v_x
  - -the stride length on the x component is obtained as $L_x = v_x T_s$
  - -the y component of the footsteps, named as L_y, alternates (left and right support foot)

walking motion - footstep plan

in world frame coordinates



x	y	t
0	-Ly	0
Lx	Ly	Ts
2Lx	-Ly	2Ts
3Lx	Ly	3Ts
...	...	...

walking motion - gait generation

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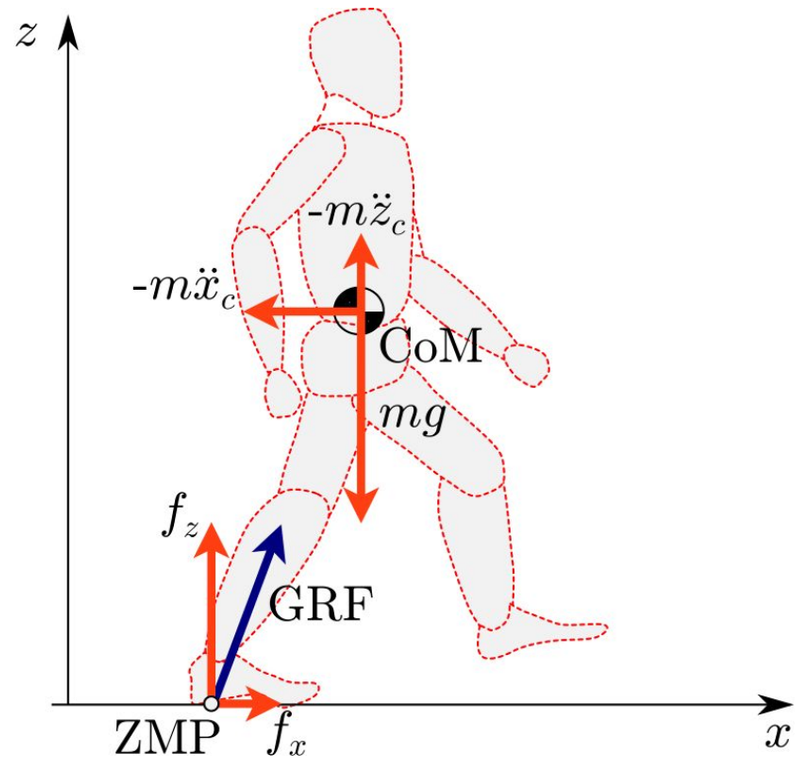

- use a simplified model: the Linear Inverted Pendulum (LIP)
- forward walking motion with constant footstep orientation: the sagittal and coronal components are decoupled

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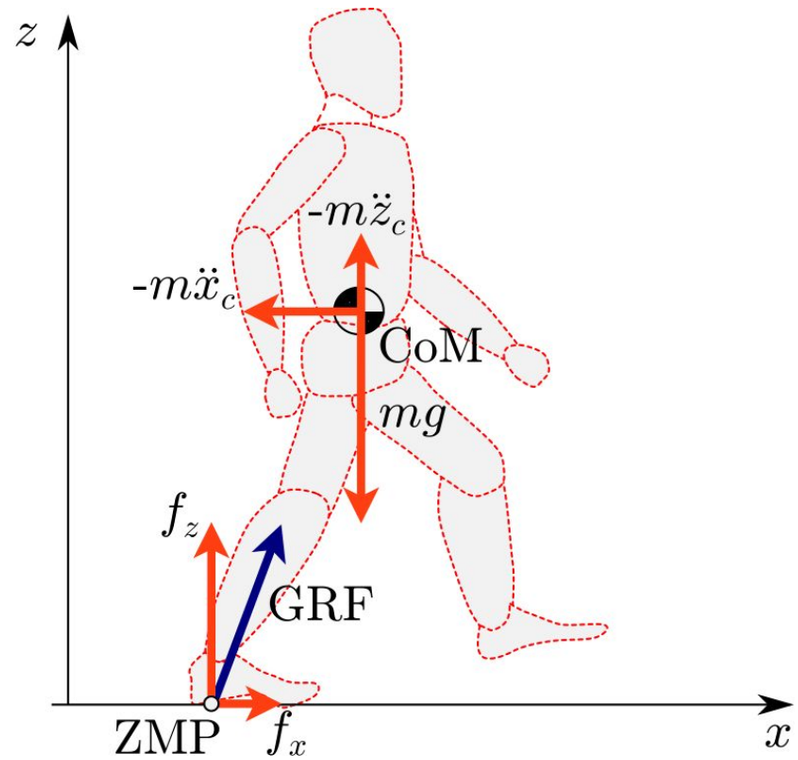

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$$\ddot{x}_c = \eta^2(x_c - x_z)$$
$$\ddot{y}_c = \eta^2(y_c - y_z)$$

natural frequency — CoM — ZMP

$$\eta^2 = \frac{g}{h}$$

walking motion - gait generation

- linear MPC formulation

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- ZMP as decision variable

- formulation: track a reference ZMP trajectory, while maintaining dynamic balance and ensuring that the CoM is bounded with respect to the ZMP (the LIP is unstable!)

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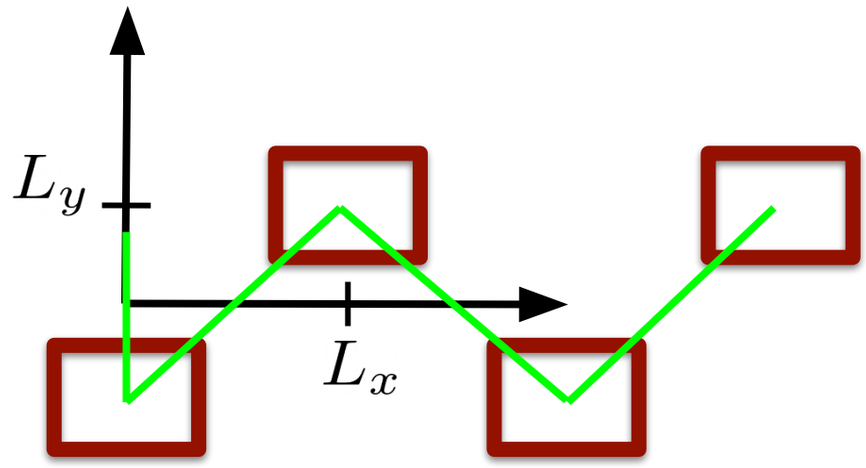
- solve at each iteration a quadratic program (QP) with linear constraints

- efficient state of the art solvers are available, e.g., hpipm https://github.com/giaf/hpipm

walking motion - gait generation

- reference ZMP trajectory:



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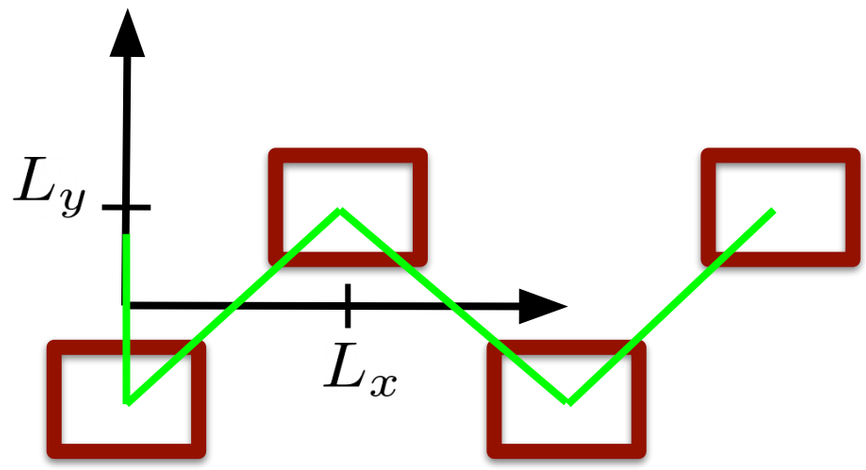

- dynamic balance: ZMP inside the support polygon, formulated as a linear inequality constraint

walking motion - gait generation

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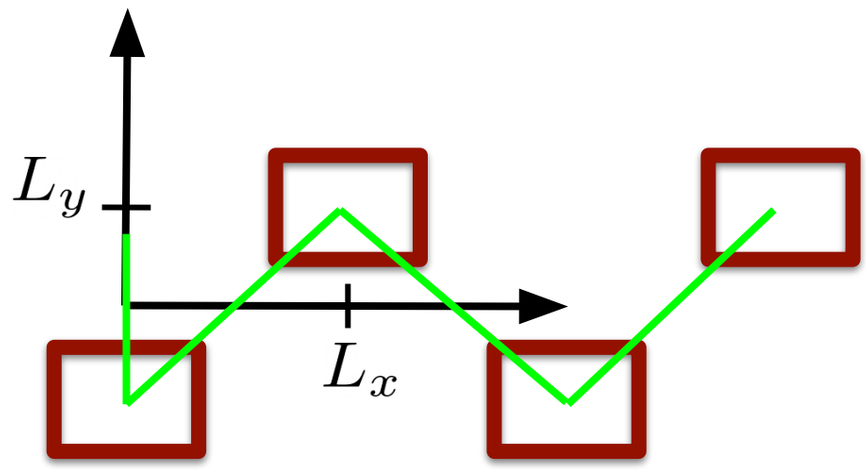

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- bounded CoM w.r.t. the ZMP through a stability constraint (Scianca et al, "MPC for Humanoid Gait Generation: Stability and Feasibility", T-RO, 2020), formulated as a linear equality constraint

walking motion - gait generation

- let X_z and Y_z be vectors collecting the decision variables over the prediction horizon
- let X_z^{ref} and Y_z^{ref} be vectors collecting the sampled reference ZMP trajectory over the prediction horizon
- let $\Delta X_z = [x_z^1 - x_z^0, x_z^2 - x_z^1, \dots]^T$

walking motion - gait generation

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solve at each time step the following QP is solved:

$$min_{X_z,Y_z} \|X_z - X_z^{ref}\|^2 + \|Y_z - Y_z^{ref}\|^2 + \beta\|\Delta X_z\|^2 + \beta\|\Delta Y_z\|^2$$

subject to:

- ZMP constraints
- stability constraint

walking motion - gait generation

- integrate over a sampling interval the LIP dynamics using the first decision variable obtained from the QP and get the reference CoM position and velocity $\boldsymbol{v}_{c,ref}^{k}, \boldsymbol{p}_{c,ref}^{k}$

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- use a parabolic trajectory for the z component

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- arm swing commands: sinusoidal trajectory for the shoulder joint

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a quick look at the code

```
...
decisionVariables_x = solveQP_hpipm(costFunctionH_xy, costFunctionF_x, A_ineq_xy, Zmin_x, Zmax_x, Aeq_x, beq_x);
decisionVariables_y = solveQP_hpipm(costFunctionH_xy, costFunctionF_y, A_ineq_xy, Zmin_y, Zmax_y, Aeq_y, beq_y);
…
```

compute QP using hpipm

```
...
state_x = A_xy*state_x + B_xy*decisionVariables_x(0);
state_y = A_xy*state_y + B_xy*decisionVariables_y(0);
```

integrate LIP to get next CoM reference

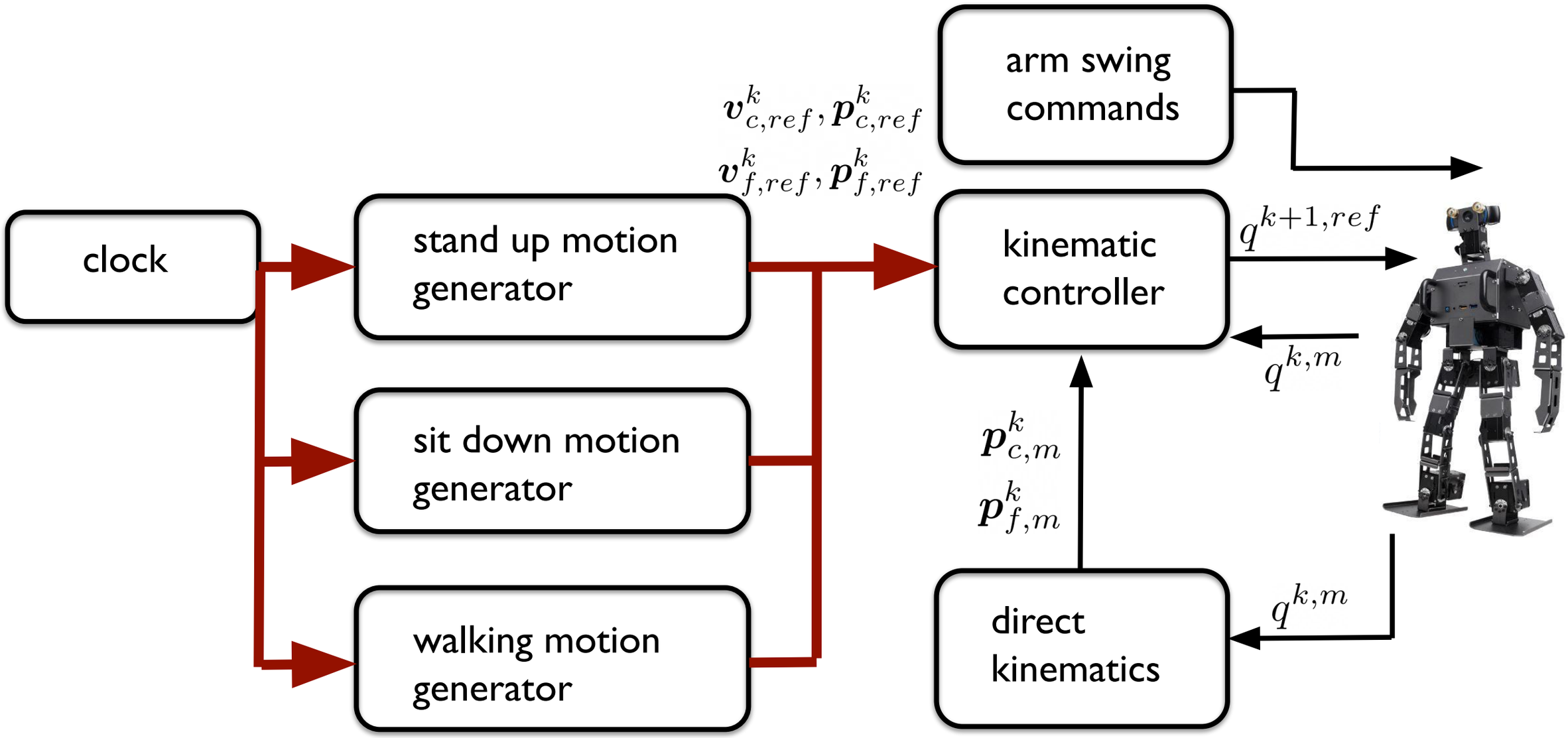
```
next.comPos << state_x(0), state_y(0), comTargetHeight;
next.comVel << state_x(1), state_y(1), 1.0;
next.comAcc << eta*eta * (state_x(0) - decisionVariables_x(0)), eta*eta * (state_y(0) - decisionVariables_y(0)), 1.0;
next.zmpPos << decisionVariables_x(0), decisionVariables_y(0), 1.0;
```

store the reference states into a useful data structure

```
if (walkState.footstepCounter > 1 && walkState.footstepCounter <= n_steps+1)
   next = WalkingSwingFoot(current, next, walkState, ftsp_and_timings);
```

compute swing foot trajectory

motion modes management



motion modes management

- motion modes change at fixed times
- wait some time t_{start} before starting the motion
- stand up motion is executed until time t_{stand} is reached
- walking motion is performed until time t_{walk} is reached (required time to physically execute the footstep sequence)
- the robot reaches its original configuration by executing a sit down motion, concluded at time t_{sit}

concluding remarks

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- robotics is mainly open source, but sometimes not well documented
- possible improvements:
  - -footstep planner
  - -3D ground
  - -more sophisticated whole body controller
  - -localization

experiment time

on going research - robust gait generation

- disturbances in MPC can cause constraint violation: in humanoid gait generation this can imply the loss of dynamic balance and instability

- different ways to address the problems: disturbance observers for persistent perturbations, constraint restriction for robustness to uncertainties, step position and timing adaptation for push recovery

- we published a contribution for each of the different methodologies and we are now working on a unified framework

on going research - robust gait generation

on going research - 3D walking and running

- LIP model assumes constant CoM height: for 3D motions such as stair climbing and running, this assumption must be removed

- use the Variable Height Inverted Pendulum (VH-IP)

- this model is non-linear

- we address the problem by computing the vertical motion first and then solving for the horizontal dynamics, considering them as a time-varying linear system

- simple but effective method (real time implementation on OP3)

on going research - 3D walking and running

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