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

problem statement

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

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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
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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

addressing the problem

- decompose the big problem into small problems and identify the solution for each one of them

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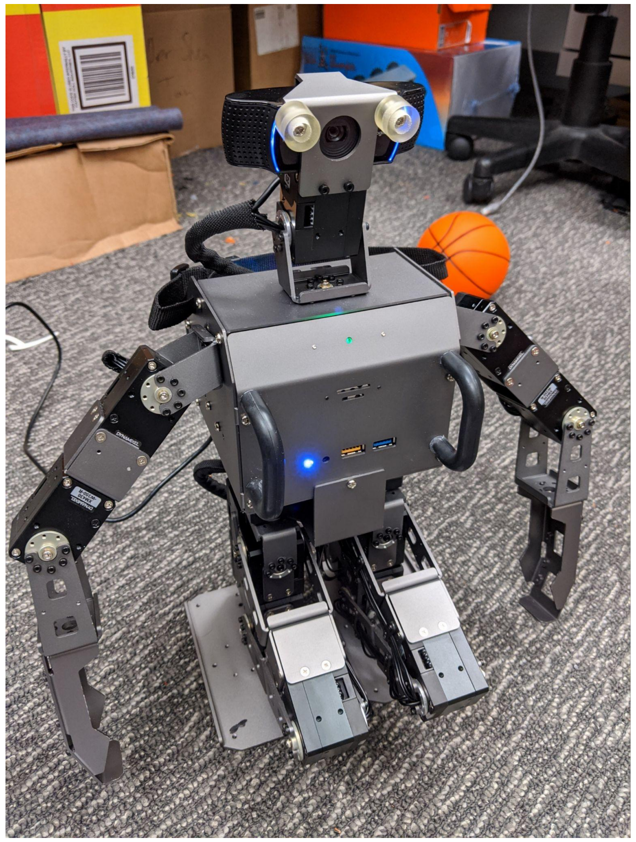

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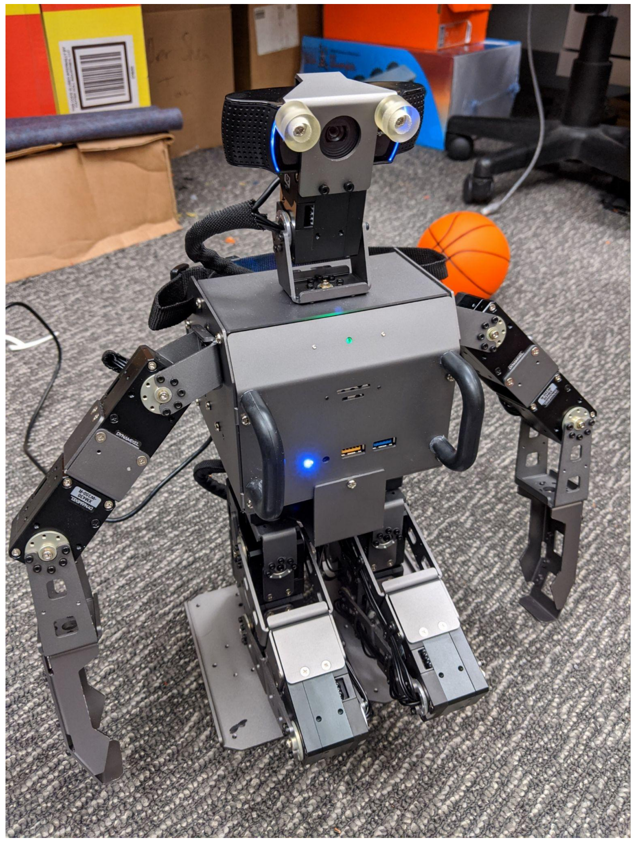

- the task will be realized by composing three different motions:
  - -reach a configuration to start walking
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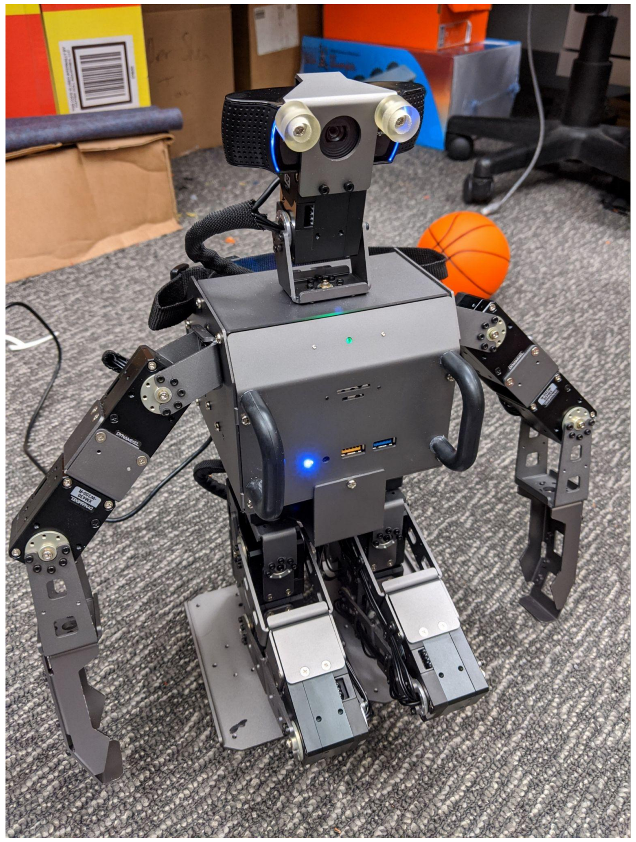
- let's keep it simple: use time pre-programmed motion modes (stand up, walk, sit down)

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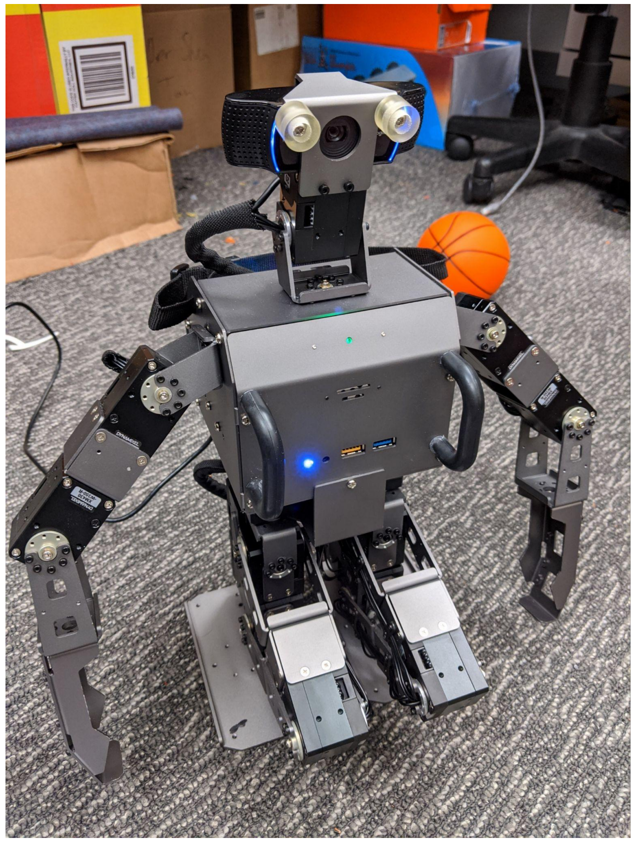
- note that:
  - -kinematic control is the most practical choice with position controlled actuators
  - -we assume that we do not need localization nor mapping
  - -there exist different solutions to this problem



block scheme

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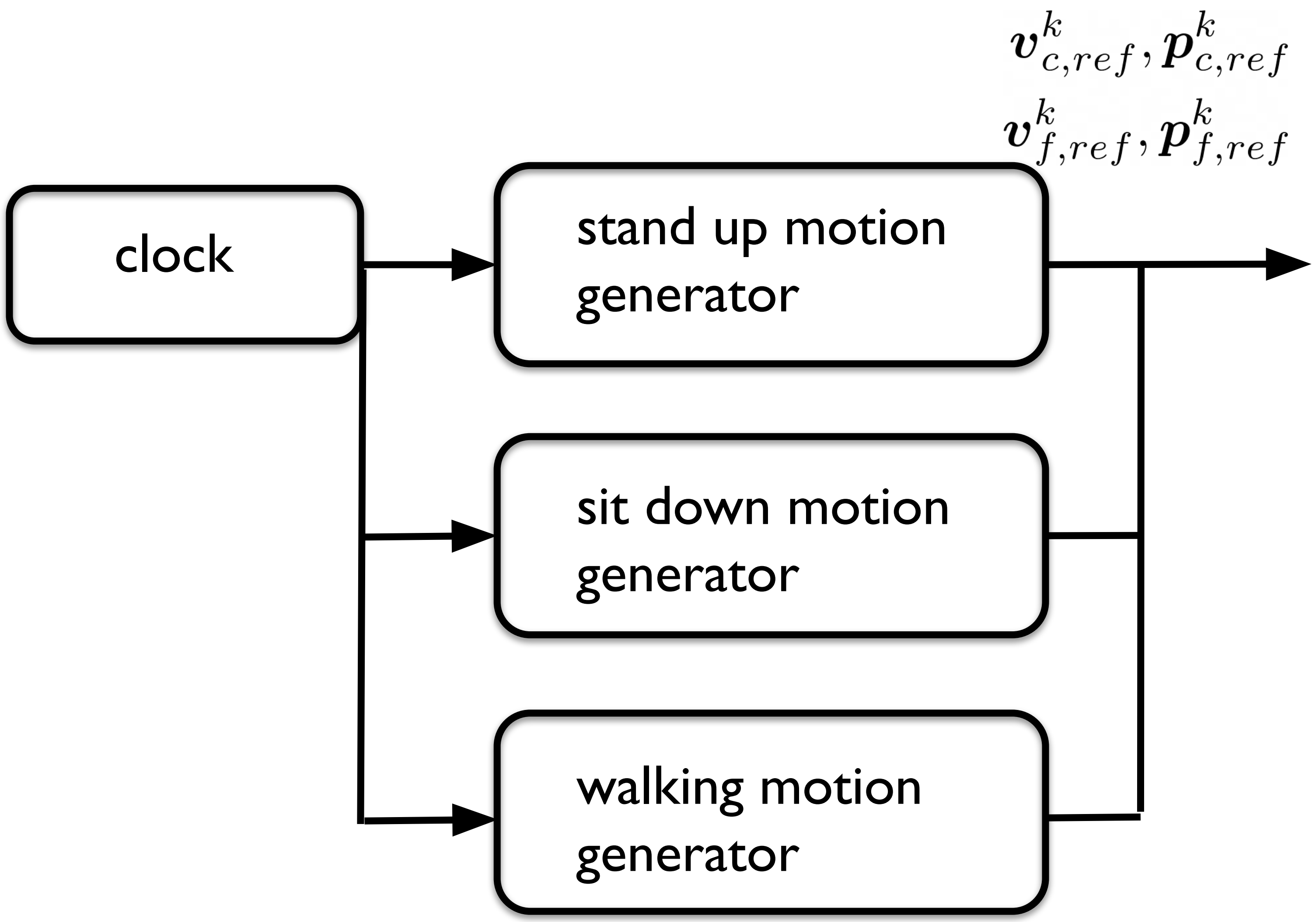

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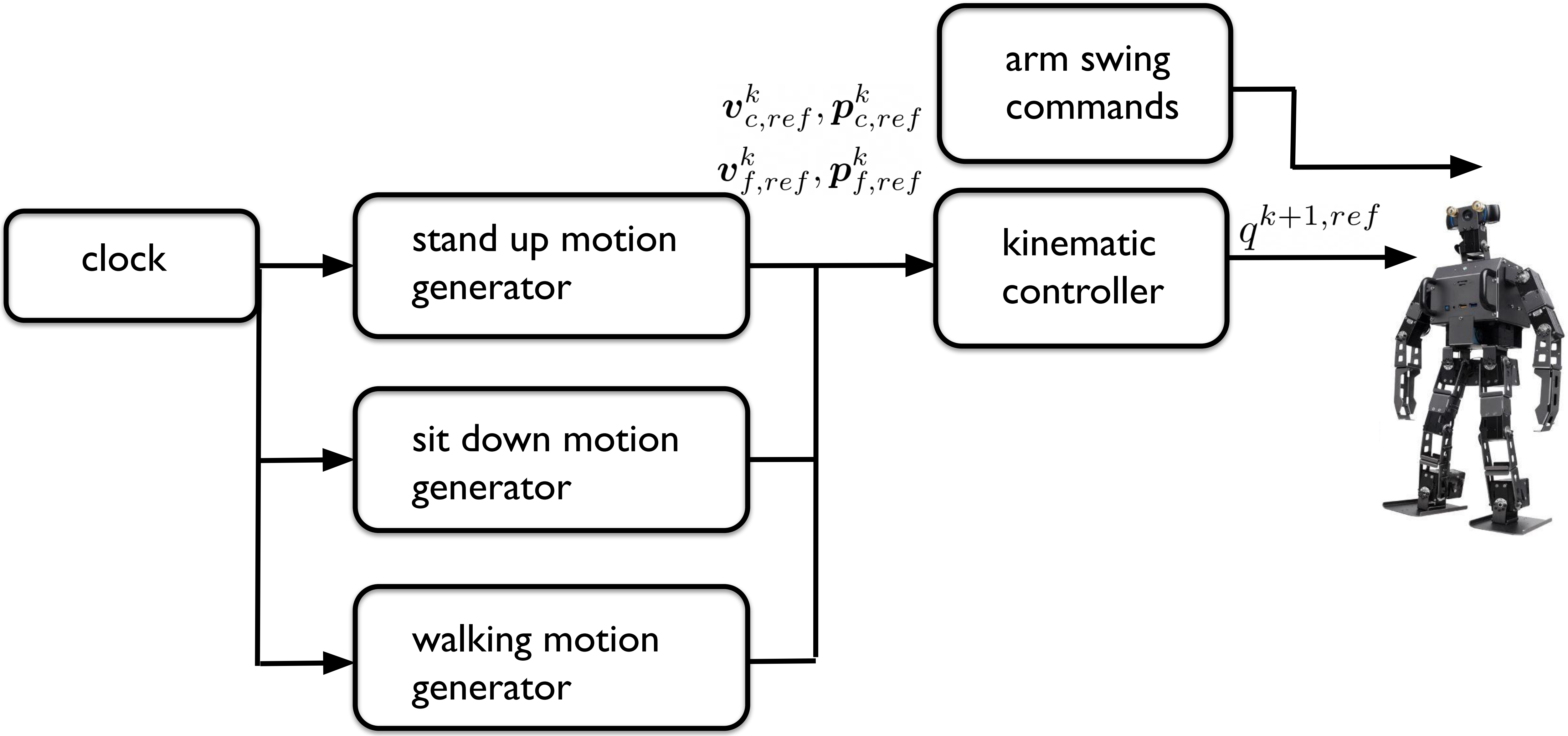

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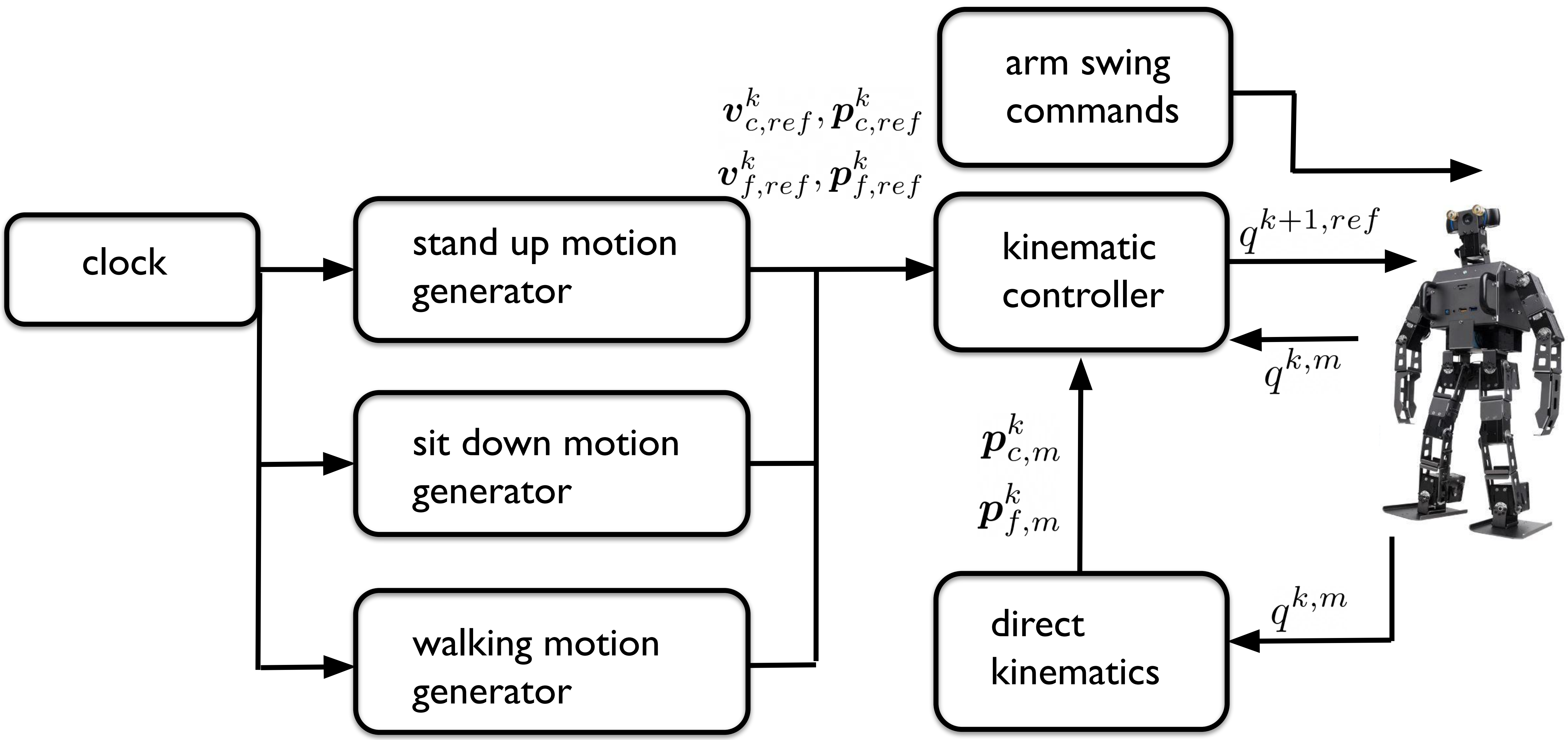
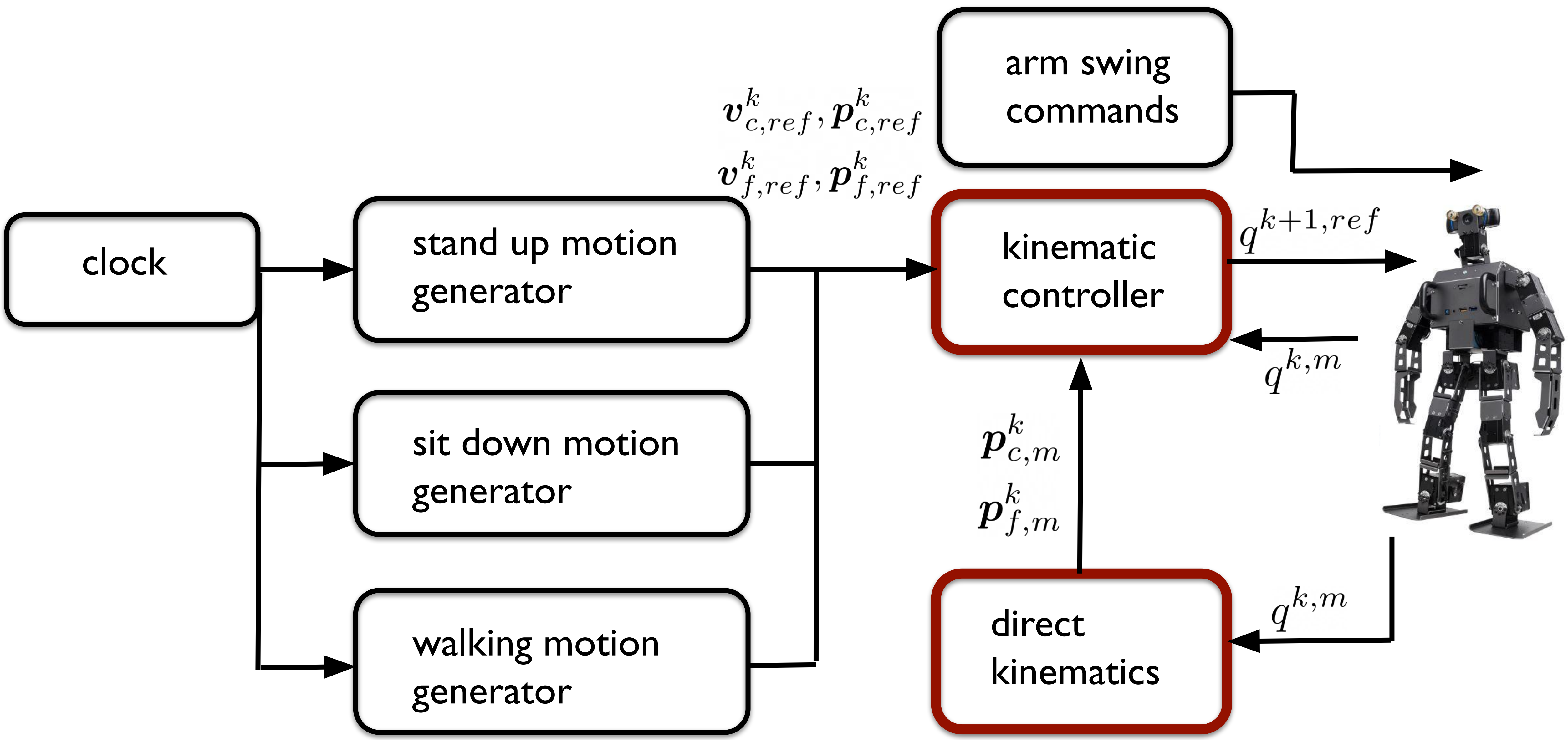


$\boldsymbol{p}, \boldsymbol{v}$ denote the pose and its time derivative

kinematic controller and direct kinematics



kinematic controller and direct kinematics

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

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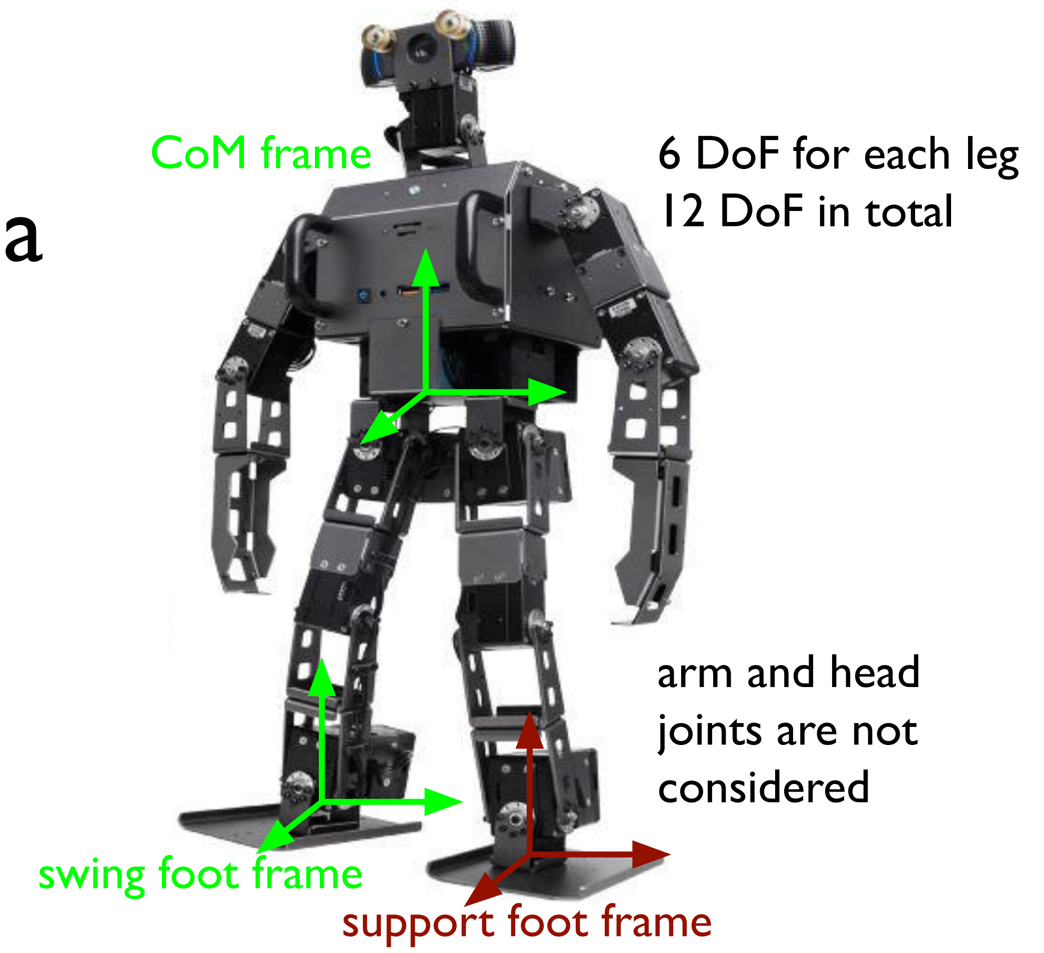
  why?
  -humanoid as fixed base manipulator where the base frame coincides with a supporting foot
  -CoM and swing foot are regarded as End-Effector frames
  -regulation via multi-task kinematic control law



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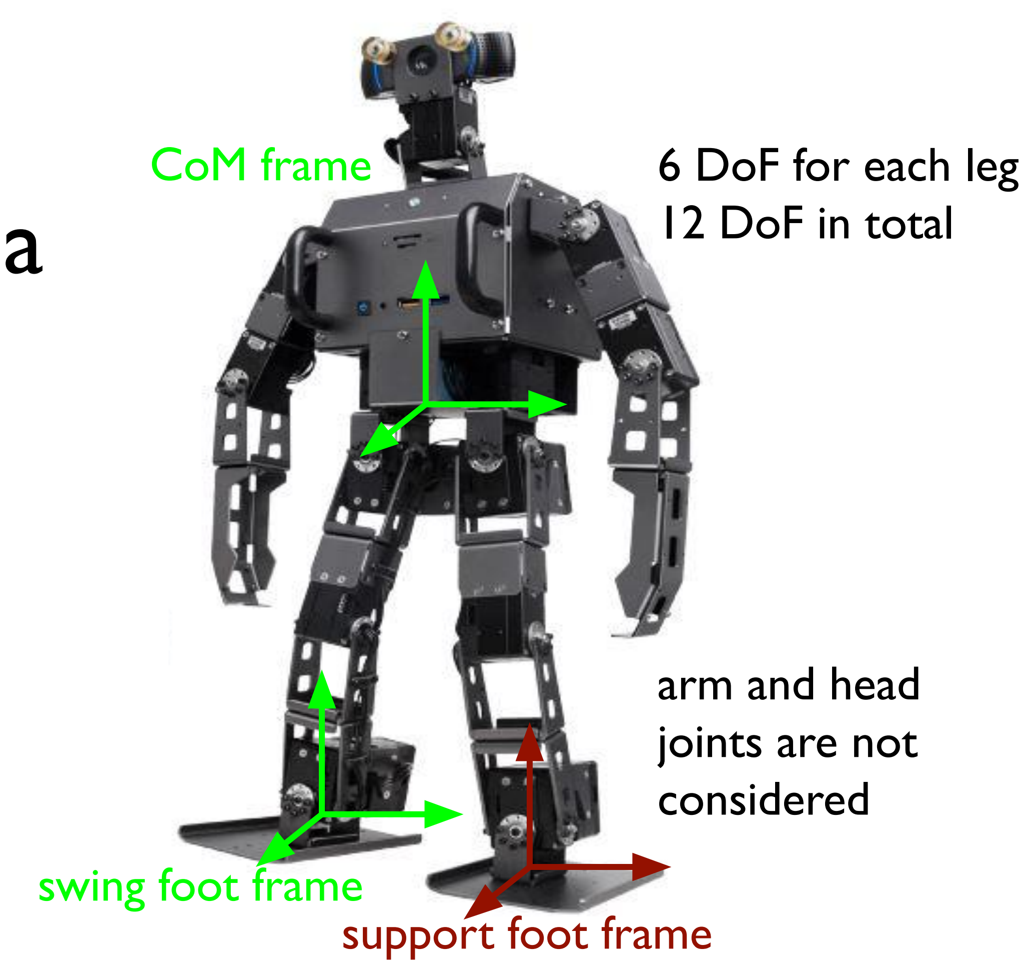

- output: joint position commands

kinematic controller and direct kinematics

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- compute the joint velocities as

$$\dot{q}^k = \underbrace{\begin{bmatrix} J^k_c \\ J^k_f \end{bmatrix}^{\#}}_{\text{damped pseudoinverse of stacked jacobians}} \left[\underbrace{\begin{pmatrix} \boldsymbol{v}^k_{c,ref} \\ \boldsymbol{v}^k_{f,ref} \end{pmatrix}}_{\text{reference velocities}} + \underbrace{\boldsymbol{K}}_{\text{position error gains}} \underbrace{\begin{pmatrix} \boldsymbol{p}^k_{c,ref} - \boldsymbol{p}^k_{c,m} \\ \boldsymbol{p}^k_{f,ref} - \boldsymbol{p}^k_{f,m} \end{pmatrix}}_{\text{position error}} \right]$$

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damped pseudoinverse of stacked jacobians

reference velocities

position error gains

position error

- 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));
```

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

```
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;
```

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

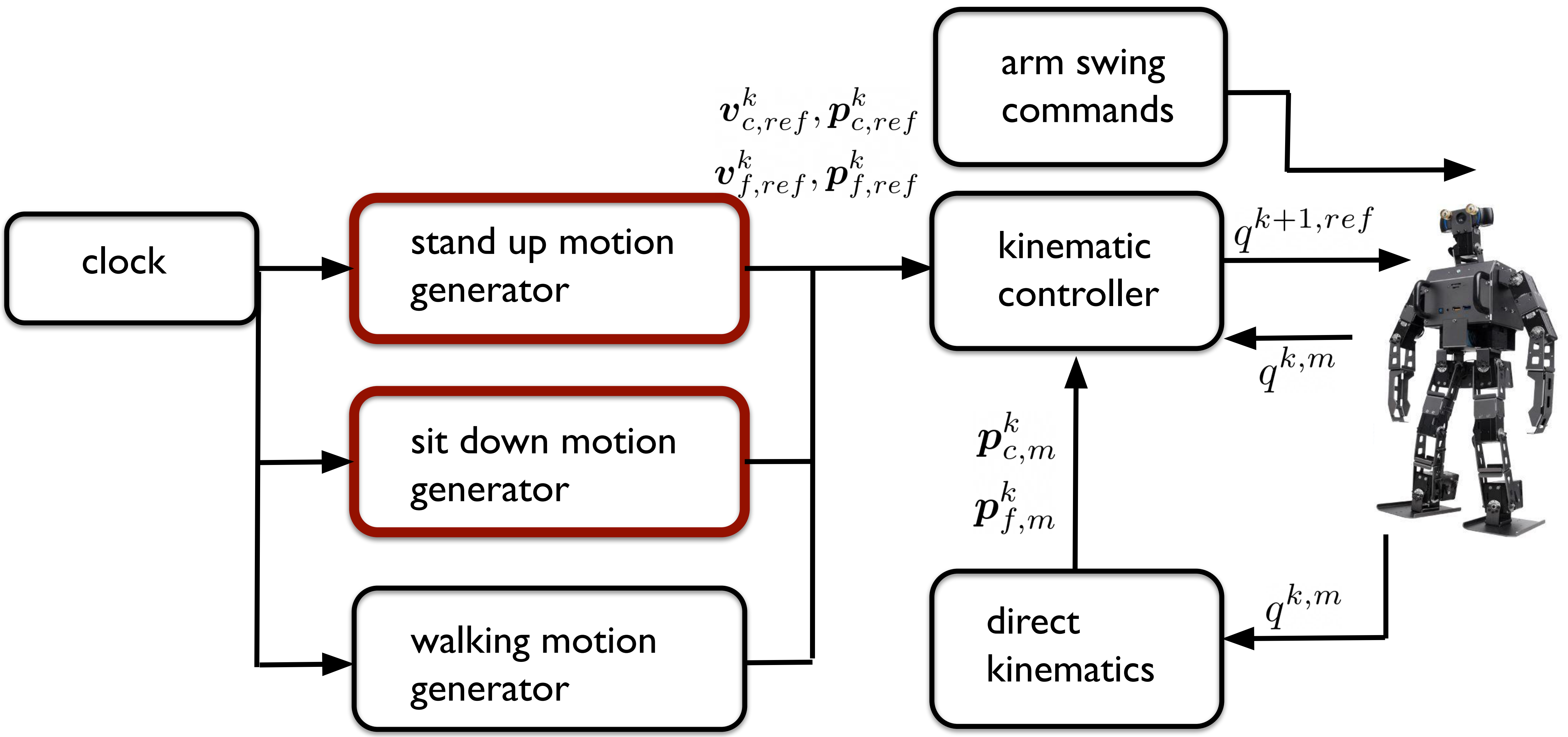
```
if (left_foot_to_right_foot_jacobian_solver->JntToJac(q0_sf_to_swg, J_leftf_to_rightf_leg) < 0) {
  ROS_ERROR( "jacobian error");
}
J_left_leg_to_right = J_leftf_to_rightf_leg.data;
if (left_leg_jacobian_solver->JntToJac(q0_left_leg, J_left_leg) < 0) {
  ROS_ERROR( "jacobian error");
}
J_left_leg_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

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

```
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);
...
```

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 $\boldsymbol{p}^0$ and reach a target pose $\boldsymbol{p}^1$ in T seconds

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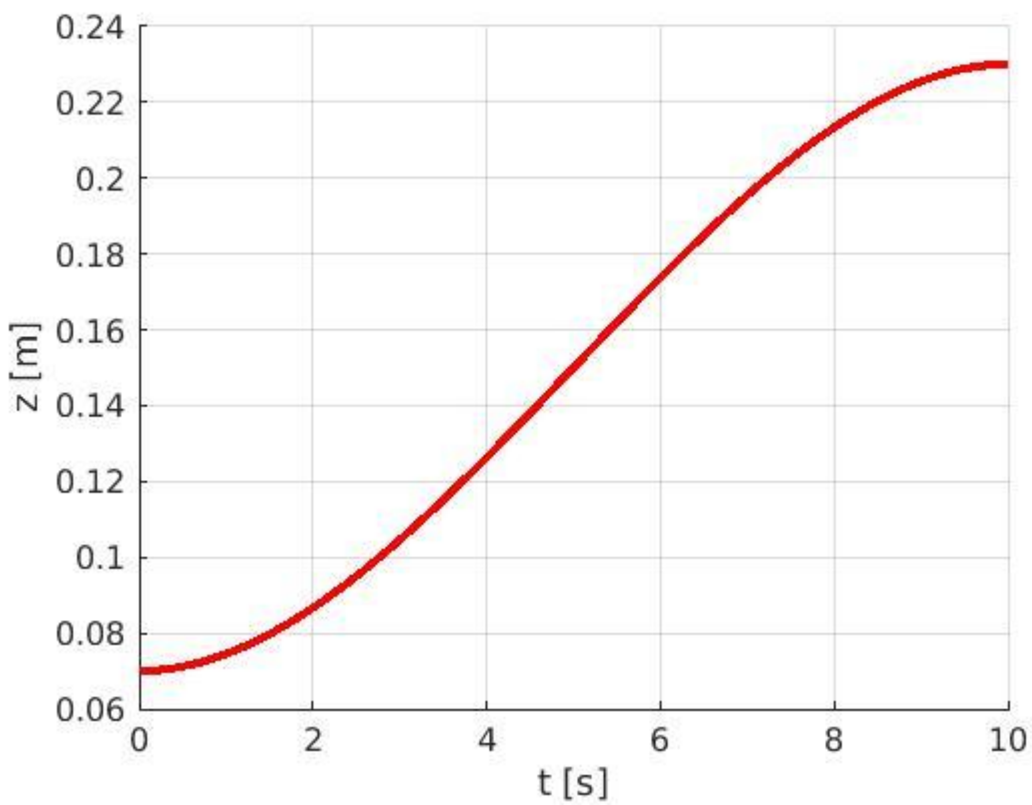
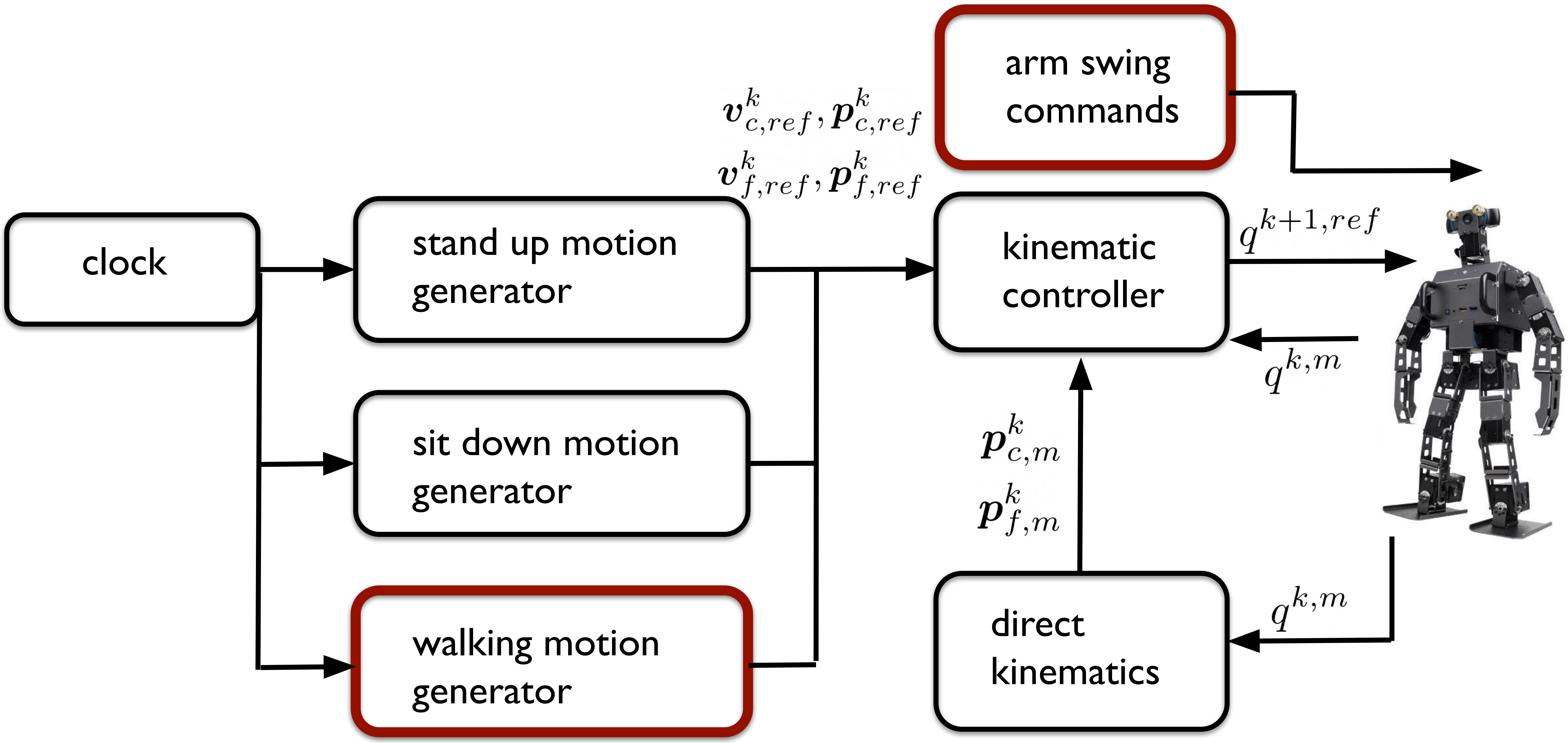


- in practice, it is only required a trajectory for the vertical CoM component

- 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

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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 position and timings (step duration)

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- single and double support alternate during locomotion

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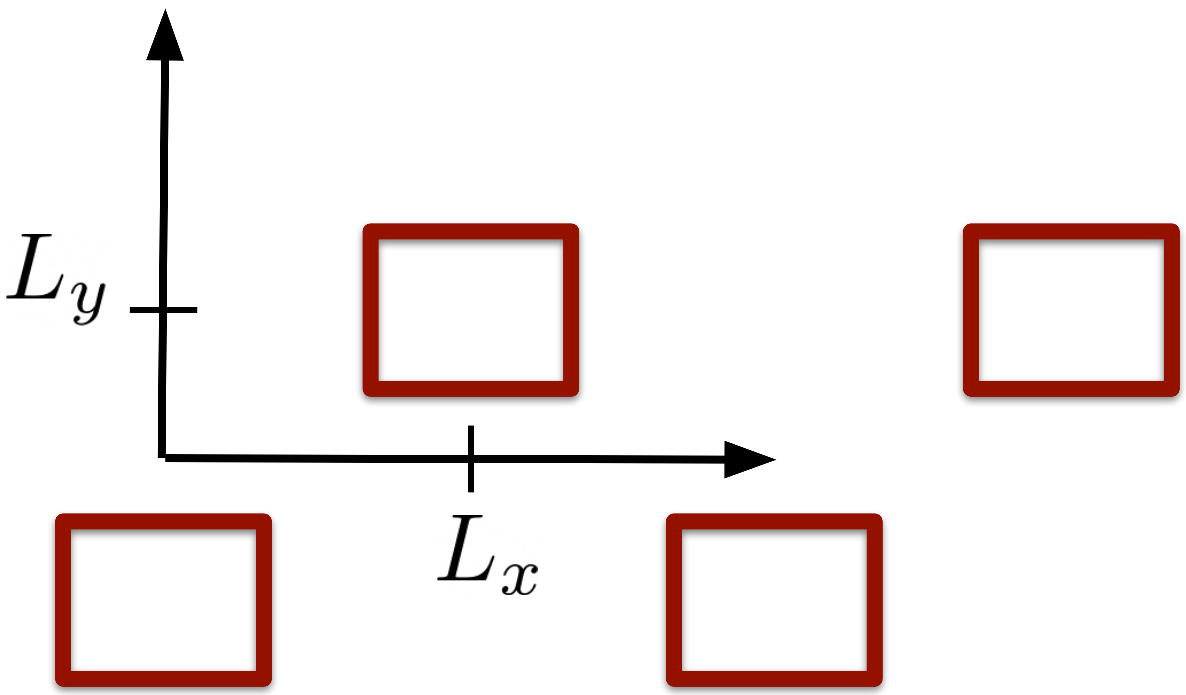
- let's keep it simple:
    - -assign a step duration, e.g., $T_s = T_{ss} + T_{ds}$(single and double support duration)
    - -choose a sagittal reference velocity v_x
    - -the stride length on the x component is obtained as $L_x = v_x T_s$
    - -the y component of the footsteps, named as L_y, alternates (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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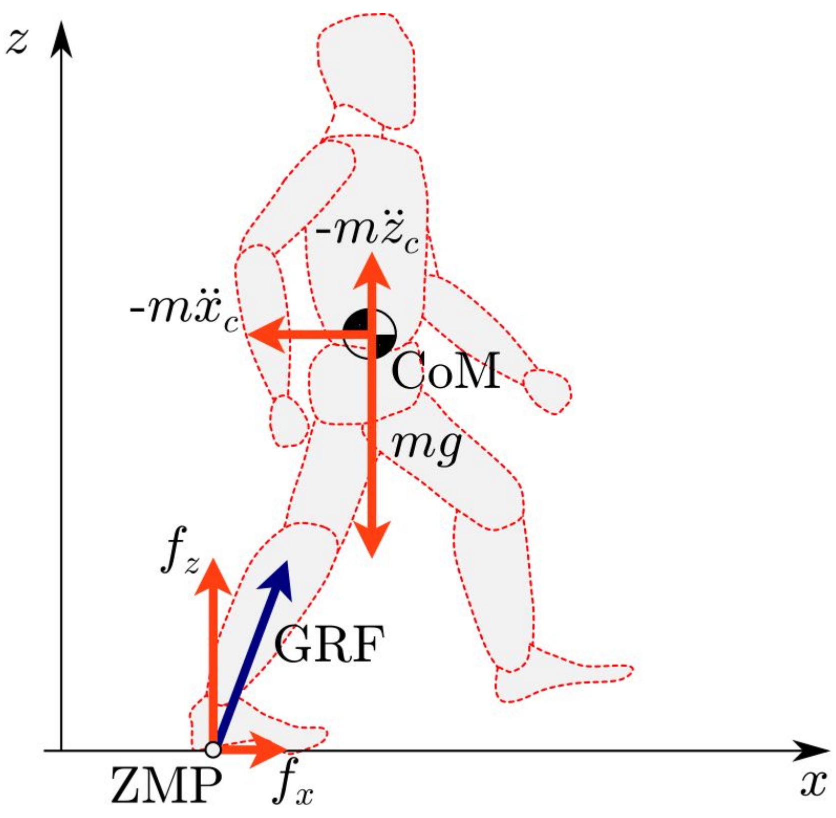
- use a simplified model: the Linear Inverted Pendulum (LIP)
- forward walking motion with constant footstep orientation: the sagittal and coronal components are decoupled



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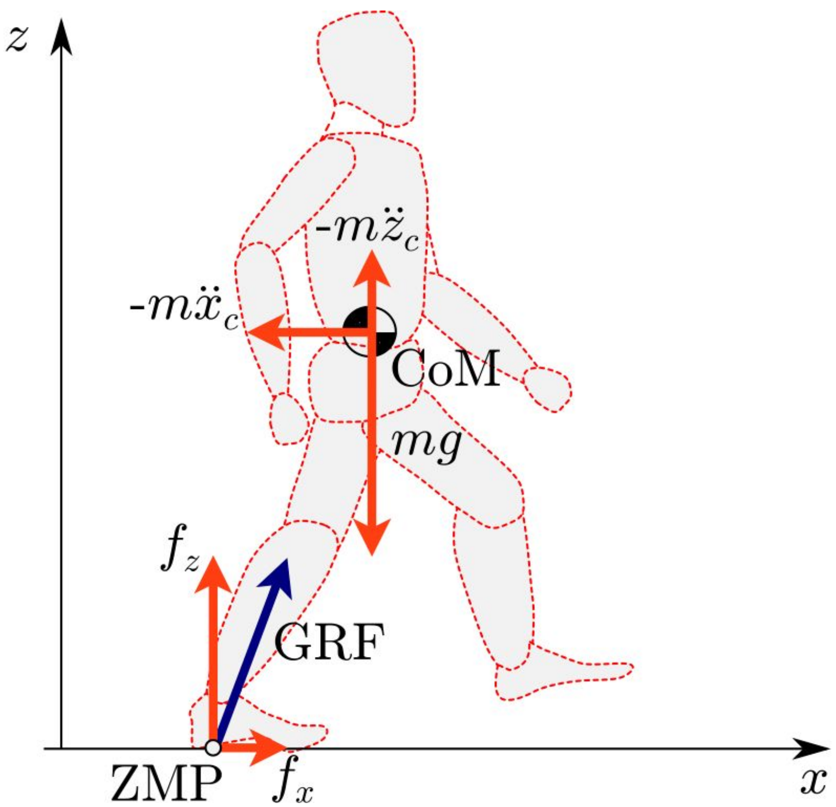

$$\ddot{x}_c = \eta^2 (x_c - x_z)$$
$$\ddot{y}_c = \eta^2 (y_c - y_z)$$

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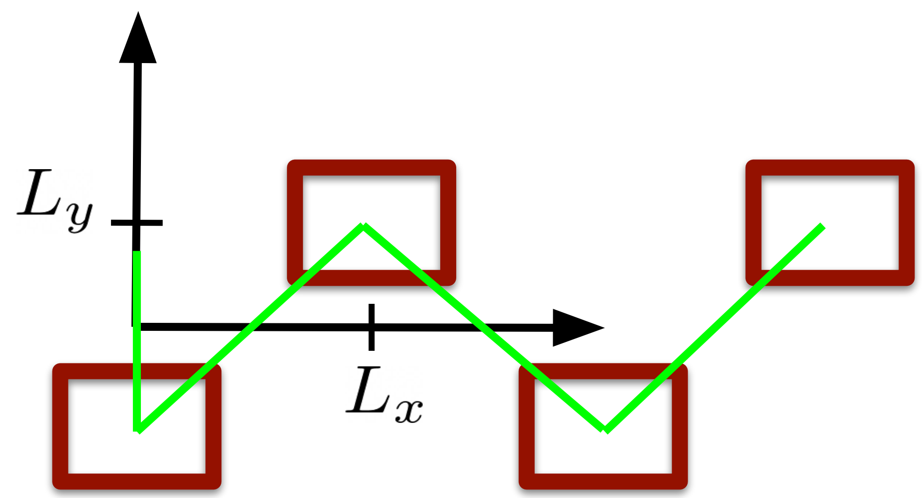
- solve at each iteration a quadratic program (QP) with linear constraints

- 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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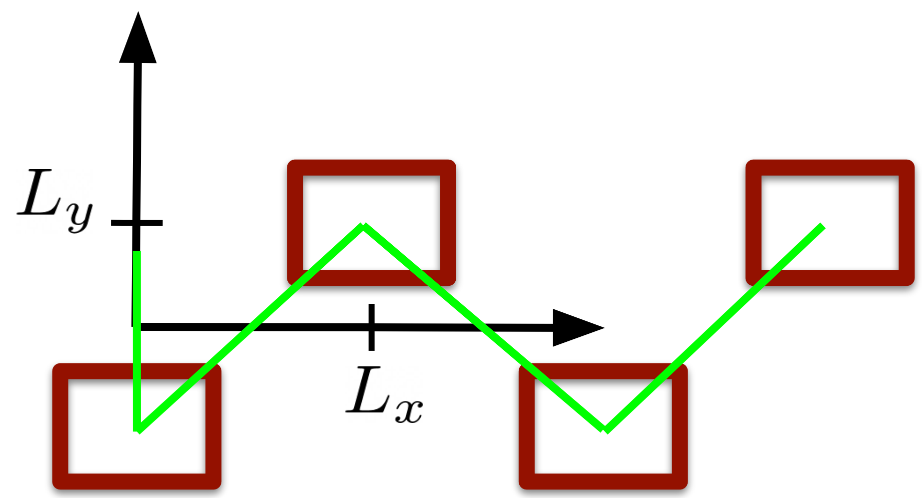

- dynamic balance: ZMP inside the support polygon, formulated as a linear inequality constraint

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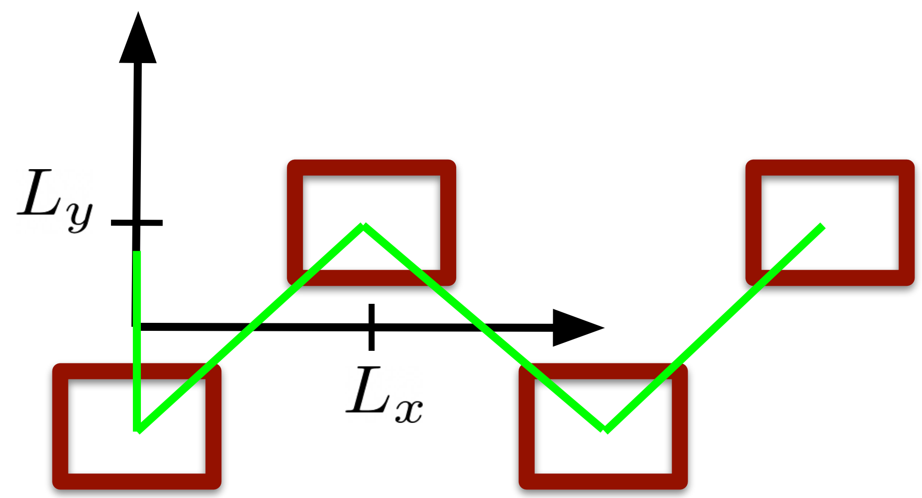

- dynamic balance: ZMP inside the support polygon, formulated as a linear inequality constraint

- 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 $\Delta X_z = [x_z^1 - x_z^0, x_z^2 - x_z^1, \dots]^T$

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solve at each time step the following QP is solved:

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

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 $\boldsymbol{v}_{c,ref}^{k}, \boldsymbol{p}_{c,ref}^{k}$

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 $\boldsymbol{v}^k_{c,ref}, \boldsymbol{p}^k_{c,ref}$

- generate a swing foot trajectory to reach the next target footstep during single support phases $\boldsymbol{v}^k_{f,ref}, \boldsymbol{p}^k_{f,ref}$

- use for instance a third order polynomial for the x and y components of the swing foot trajectory

- use a parabolic trajectory for the z component

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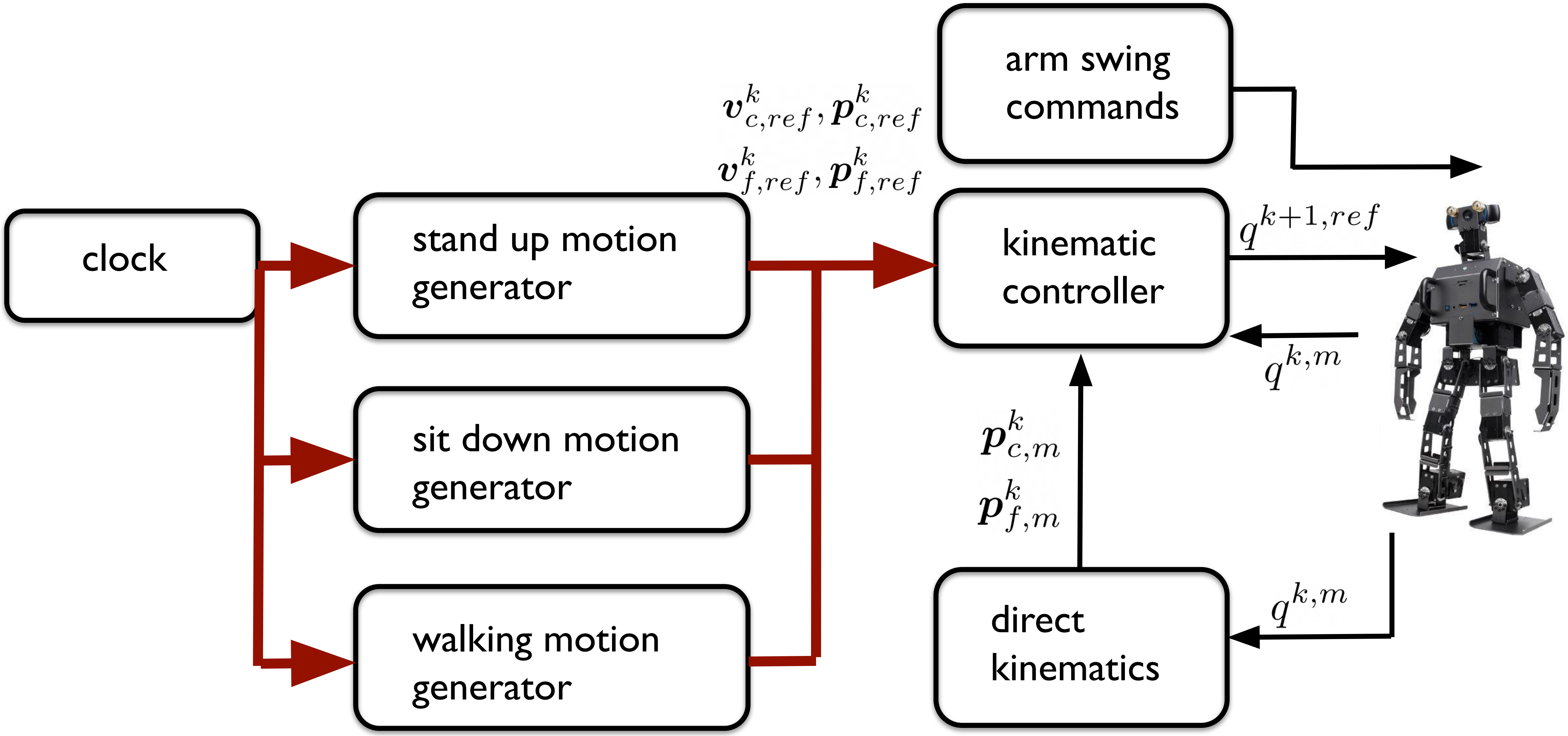
- arm swing commands: sinusoidal trajectory for the shoulder joint

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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- Sim-To-Real gap: if it works in simulation, it is not 100% guaranteed that it works on the real robot
- robotics is mainly open source, but sometimes not well documented
- possible improvements:

  -footstep planner

  -3D ground

  -more sophisticated whole body controller

  -localization

experiment time

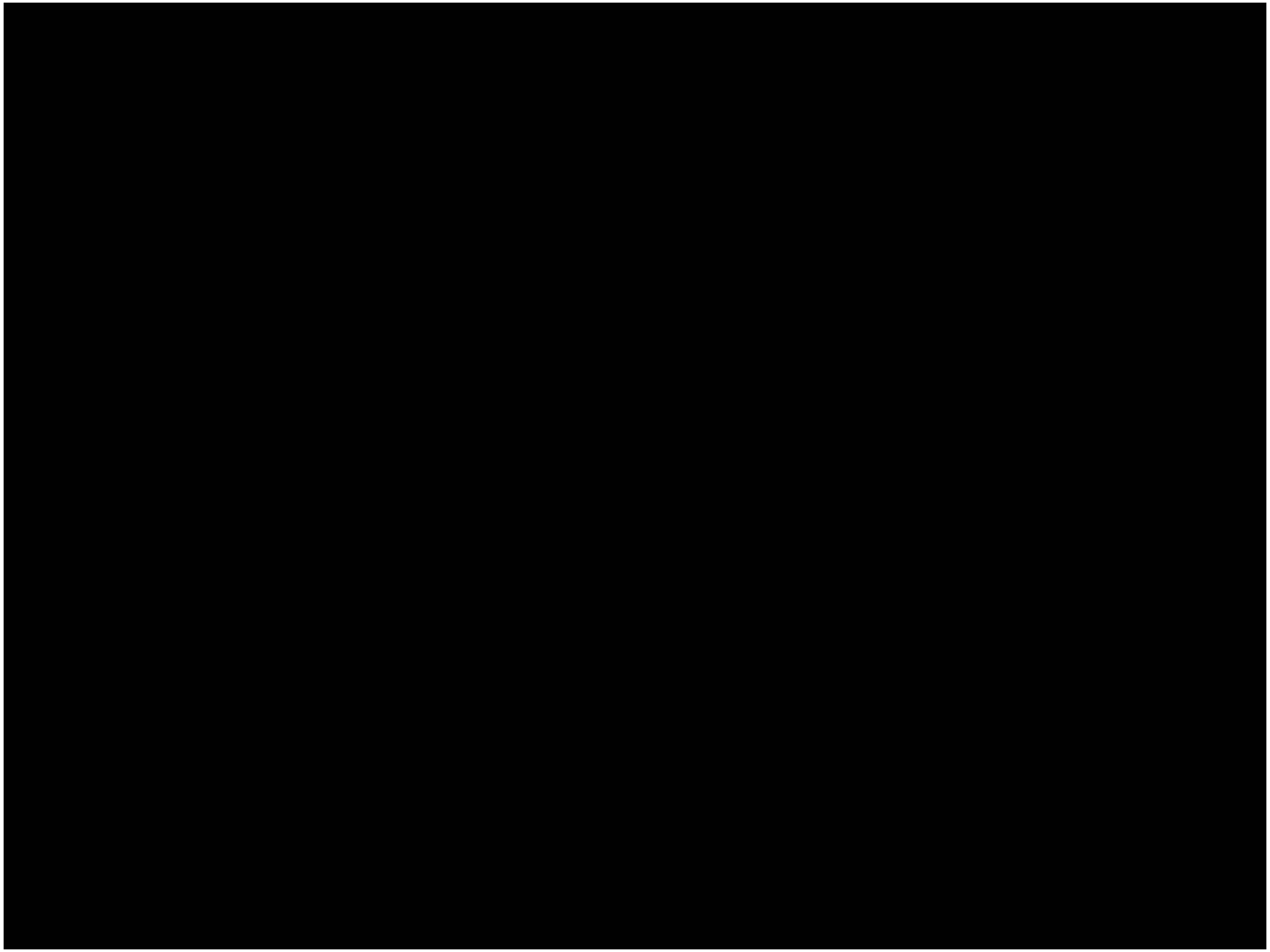
on going research - robust gait generation

- 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)

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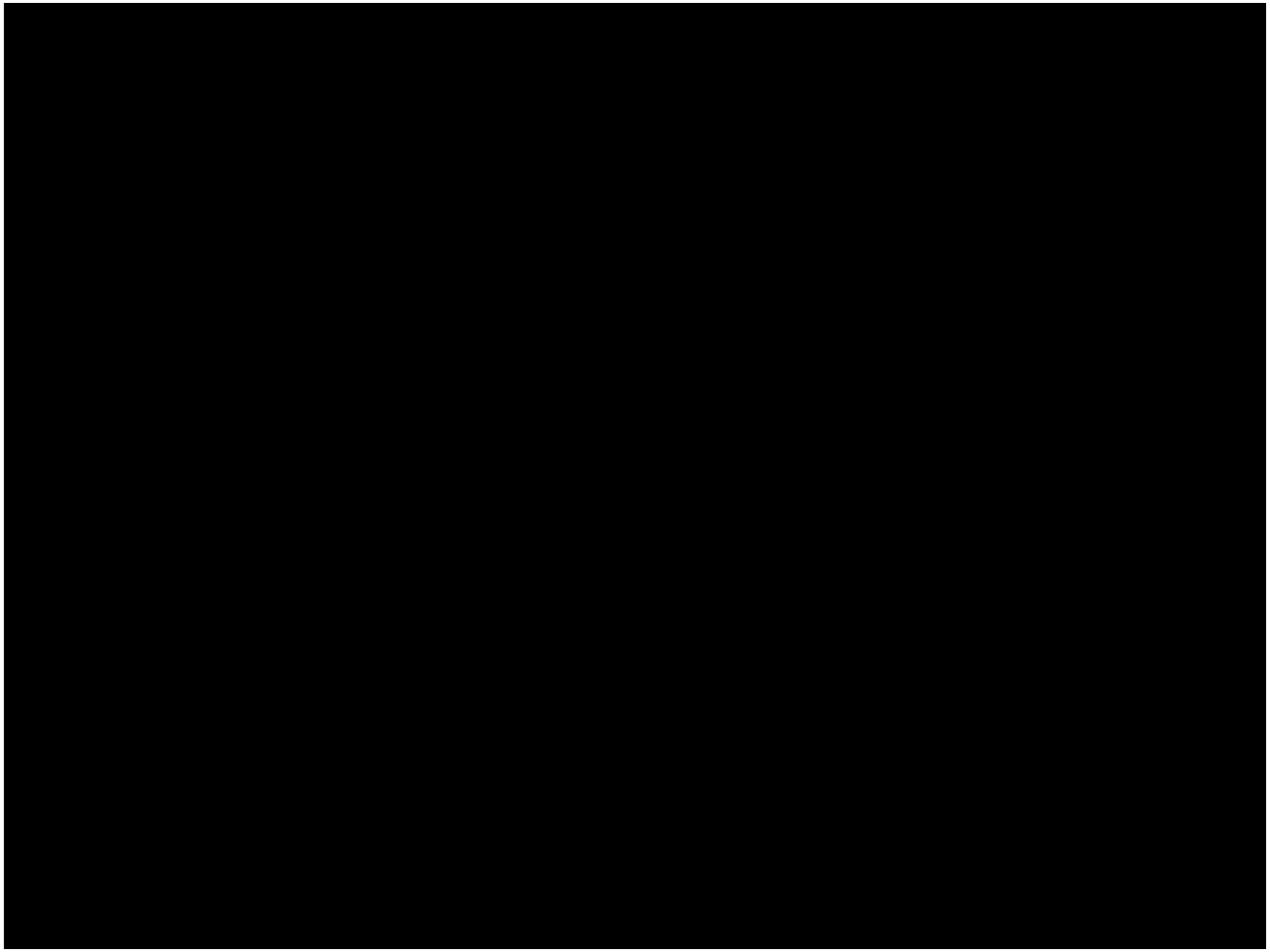

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