A decentralized cooperative transportation scheme for humanoid robots

Greta Gasbarrone, Nicola Scianca, Leonardo Lanari, and Giuseppe Oriolo

***Abstract*— We propose an MPC-based decentralized scheme for two humanoid robots that cooperate to transport an object. One robot, the *leader*, is assigned a footstep plan in order to bring the object to a desired location. The other, the *follower*, autonomously decides how to move based on the perceived interaction forces. We report dynamic simulations on two HRP-4 robots carrying a table.**

I. INTRODUCTION

A major benefit brought by the adoption of robots in many fields is the reduction the amount of heavy work that must be done by humans, whether by providing aid or by completely removing the need for humans to intervene.

Collaborative approaches between humanoid robots can make use of a *centralized* controller [1] which is better suited to determine the individual behaviors necessary to achieve the common goal. However, for retaining high flexibility in the range of possible applications, it may be useful to use a *decentralized* approach [2] which can be applied both to human-robot or to robot-robot scenarios. In this scheme, two agents are identified by their roles in the transportation. The *leader* has knowledge of the task to be executed, and can be embodied either by a human or, as in our case, by a robot with a predefined plan. The *follower* is a robot who is unaware of the task and must determine how to move based on what it perceives.

In this abstract, we propose a decentralized scheme in which controllers for both the leader and the follower are based on the Intrinsically Stable Model Predictive Control (IS-MPC) [3], featuring a *stability constraint* which we showed to be also capable of disturbance rejection [4].

II. GENERAL ARCHITECTURE

Consider two robots that must collaborate in the transport of a rigid object. Since our approach is decentralized, the leader will be directly instructed with the task, in the form of a footstep plan following a given a reference velocity profile. The follower, being unaware of the task, will experience interaction forces as soon as the leader starts moving. Knowing these interaction forces will allow the follower to determine how to move.

The architecture of the proposed scheme is shown in Fig. 1. For each robot, the measure or estimate of the force at each hand is given to an *admittance controller*, which determines the hand position based on a compliant interaction model. In the absence of any force, the hands will be in a neutral state which will be perturbed by the presence of any interaction force. For the follower, the *footstep plan generator* module adapts the step positions so to follow the movement of the hands, thus being indirectly influenced by the interaction force. Both robots hand positions and footstep plan are sent to an *MPC controller*, which generates a stable CoM trajectory. Finally a whole-body kinematic controller generates joint commands for the robot.

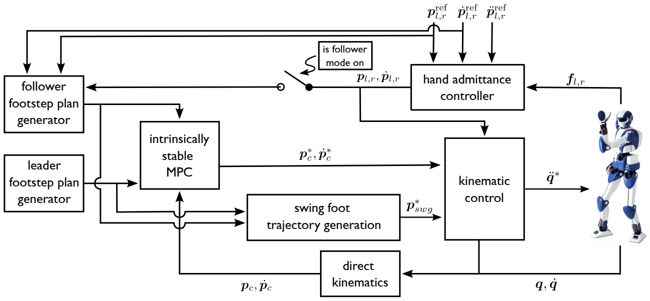

Fig. 1. Control scheme for cooperative transportation. Interactions forces cause a change in the hand position which, for the follower, robot triggers a variation in the footstep plan.

III. MODULES DESCRIPTION

This section describes the different components of the proposed scheme: the hand position admittance controller, the footstep plan generator, and the MPC.

A. Hand admittance controller

We assume the object to be held at a constant height and define a grasping reference position $\boldsymbol{p}_{l,r}^{\text{ref}} = (x_{l,r}^{\text{ref}}, y_{l,r}^{\text{ref}}, z_{l,r}^{\text{ref}})$ for each left/right hand. The admittance controller generates the hand trajectories $\boldsymbol{p}_{l,r}^{x,y} = (x_{l,r}, y_{l,r})$ in the (x, y) plane so to follow the references in a compliant way. For the x-component (analogously for the y), we impose

$$m_v(\ddot{x}_{l,r} - \ddot{x}_{l,r}^{\text{ref}}) + c_v(\dot{x}_{l,r} - \dot{x}_{l,r}^{\text{ref}}) + k_v(x_{l,r} - x_{l,r}^{\text{ref}}) = f_{l,r}^x$$

where $f_{l,r}^x$ is the x-component of the force applied on the left/right hand, and m_v, c_v, k_v are respectively the virtual mass, damping and spring parameters which determine the level of compliance.

B. Follower footstep plan generator

The mechanism for positioning the footsteps differs between the leader and the follower. The footstep plan of the leader is solely based on the commanded reference velocity, whereas that of the follower is adapted online.

Initially, the follower is commanded to step in place. Then, at each instant, the step length Δx^{step} is modulated in such

---

The authors are with the Dipartimento di Ingegneria Informatica, Automatica e Gestionale, Sapienza Università di Roma, via Ariosto 25, 00185 Roma, Italy. E-mail: {lastname}@diag.uniroma1.it.

Nicola Scianca has been fully supported by PNRR MUR project PE0000013-FAIR.

a way that the pace adequately follows the movement of the hands. Δx^{step} is obtained by averaging the following values:

$$\Delta x^{\text{step}}_{l,r} = k_{p,x}(x_{l,r} - x^{\text{ref}}_{l,r}) + k_{d,x}(\dot{x}_{l,r} - \dot{x}^{\text{ref}}_{l,r}).$$

The lateral displacement Δy^{step} is computed analogously.

C. Model predictive controller

The prediction model is a *perturbed LIP*, relating the position $\boldsymbol{p}_c = (x_c, y_c, z_c)$ of the CoM to the position $\boldsymbol{p}_z = (x_z, y_z, 0)$ of the ZMP in the presence of a disturbance:

$$\ddot{\boldsymbol{p}}_c^{x,y} = \eta^2(\boldsymbol{p}_c^{x,y} - \boldsymbol{p}_z^{x,y}) + \frac{\boldsymbol{f}^{x,y}}{m} + \boldsymbol{R}\frac{\boldsymbol{n}^{x,y}}{mz_c}. \tag{1}$$

Here η is the pendulum frequency, m the robot mass, $\boldsymbol{f} = (\boldsymbol{f}_l + \boldsymbol{f}_r) = (f^x, f^y, f^z)$ the force applied at the hands, $\boldsymbol{R}$ a $\pi/2$ rotation matrix, and $\boldsymbol{n}$ represents the moment of $\boldsymbol{f}$ with respect to the CoM. The system is dynamically extended to have ZMP velocity as input. The pendulum frequency $\eta = \sqrt{(mg - f^z)/(mz_c)}$ depends on the vertical component of the force, which we assume to be equal to half the weight of the table.

To guarantee contact stability, we constrain the ZMP to be within a *moving box*, i.e., a region of fixed shape and size, whose center $(x_{\text{mc}}, y_{\text{mc}})$ moves in such a way to always be within the support polygon.

To ensure a stable CoM trajectory, we enforce a *stability constraint* on the Divergent Component of Motion (DCM). The constraint along x (and similarly for y) is derived from the *stability condition*

$$x_u(t_k) = \eta \int_{t_k}^{\infty} e^{\eta(t_k - \tau)} x_z(\tau)\, d\tau - \frac{1}{\eta}\int_{t_k}^{\infty} e^{\eta(t_k-\tau)} w_x(\tau)\, d\tau, \tag{2}$$

where $x_u = x_c + \dot{x}_c/\eta$ is the x-component of the DCM, and w_x is the disturbance (last two terms of eq. (1)) along x. As shown in [4], this condition can be turned into a constraint using the available preview information and a measure or estimate of the disturbance.

IS-MPC solves at each time step the following quadratic program:

$$\left\{\begin{array}{l} \min\limits_{\boldsymbol{u}_k} \displaystyle\sum_{i=k}^{C-1} \left(\dot{x}_z^i\right)^2 + \left(\dot{y}_z^i\right)^2 + \alpha\left(\left(x_z^{i+1} - x_{\text{mc}}^{i+1}\right)^2 + \left(y_z^{i+1} - y_{\text{mc}}^{i+1}\right)^2\right) \\ \quad \text{subject to:} \\ \quad \bullet \ \text{stability constraint,} \\ \quad \bullet \ \text{ZMP constraints} \end{array}\right.$$

where $\boldsymbol{u}_k = (\dot{x}_k, \ldots, \dot{x}_{k+C-1}, \dot{y}_k, \ldots, \dot{y}_{k+C-1})$ collects the decision variables, and α is a weight that modulates the relative importance of the second term, whose role is to bring the ZMP close to the center of its available region.

IV. RESULTS

We simulated two HRP-4 robots using the DART environment, transporting a table of mass $m_o = 17$ kg.

In the first simulation (Fig. 3, left), the two robots walk in a straight line. The reference velocity is initially set to 0.1 m/s, then halved, and then set back to the initial value. As clearly visible in the plots of Fig. 2 (left), both robots react to variations in the reference. Each time, the leader reaches the set-point first, and the follower shortly after, reacting to the hand displacement caused by the admittance.

In the second simulation (Fig. 3, right), the reference velocity commands the leader to move backwards at the start, then diagonally, and then backwards again. The follower correctly reacts to the perceived forces, both in the x and y direction.

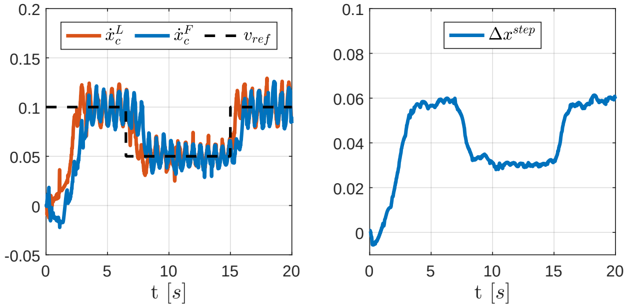

Fig. 2. Left: CoM velocity (x-component) of the leader (red) and follower (blue), compared to the reference velocity given to the leader. Right: the follower step length, generated to follow hand movements.

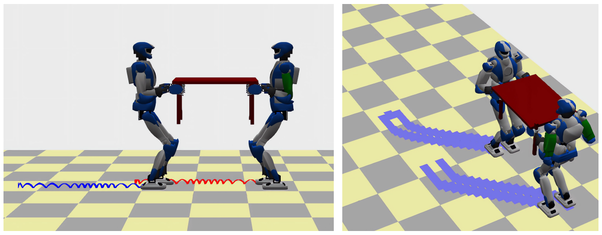

Fig. 3. Left: snapshot of a simulation with variable reference velocity for the leader; lines on the ground show the right foot trajectories of each robot. Right: snapshot of a simulation where the leader reference velocity changes direction.

V. CONCLUSIONS

We presented preliminary work on a decentralized cooperative transportation framework. Future work will include:

- allowing the robots to freely determine rotations based on differential force measurements;
- allowing the leader to lift or lower the object, e.g., to pass over an obstacle.

REFERENCES

[1] L. Hawley and W. Suleiman, “Control framework for cooperative object transportation by two humanoid robots,” *Robotics and Autonomous Systems*, vol. 115, pp. 1–16, May 2019.

[2] D. J. Agravante, A. Cherubini, A. Sherikov, P.-B. Wieber, and A. Kheddar, “Human-humanoid collaborative carrying,” *IEEE Trans. on Robotics*, vol. 35, no. 4, pp. 833–846, 2019.

[3] N. Scianca, D. De Simone, L. Lanari, and G. Oriolo, “MPC for humanoid gait generation: Stability and feasibility,” *IEEE Trans. on Robotics*, vol. 36, no. 4, pp. 1171–1188, 2020.

[4] F. M. Smaldone, N. Scianca, V. Modugno, L. Lanari, and G. Oriolo, “Gait generation using intrinsically stable MPC in the presence of persistent disturbances,” in *2019 IEEE-RAS Int. Conf. on Humanoid Robots*, 2019, pp. 651–656.