Tasks prioritization for whole-body realtime imitation of human motion by humanoid robots

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Abstract. This paper deals with on-line motion imitation of a human being by a humanoid robot using inverse kinematics (IK). First, the human observed trajectories are scaled in order to match the robot geometric and kinematic description. Second, a task prioritization process is defined using both equality and minimized constraints in the robot IK model, with four tasks: balance management, end-effectors tracking, joint limits avoidance and staying close to the human joint trajectories. The method was validated using the humanoid robot NAO.

1 Introduction

Kinematics conversion for motion imitation focuses on the manner the motion is performed. It basically consists in scaling the human joint trajectories and velocities to generate a motion compatible with the robot kinematic constraints (joint position and velocity ranges, self collision or singularities avoidance) [2, 4, 3, 13–15]. Because of the dynamics differences between human and humanoid systems, kinematics conversion does not allow respecting humanoid task constrains such as end-effector position or robot balance, unless another controller dedicated to balance is used [6, 8, 9].

Task-based priority uses the first order IK model and takes advantage of the robots redundancy to define a stack of tasks to be performed simultaneously according to a level of priority [5, 16, 11]. The task for static balance as an equality constraint was successfully performed for on-line motion imitation using NAO [10] or HRP-2 [12]. Still, great delay remain between the human and the robot motions. Both approaches dealt with the balance problem by constraining the robot feet to remain flat in double support and the COM projection to superpose to a fixed target on the floor.

Our approach also uses an IK-based tasks stack to generate on-line whole-body motion imitation. It uses both equality and optimization constraints [11, 6], and we will show that it is sufficient to set the priority of optimization constraints by tuning a coefficient which only depends on the task desired priority. NAO robot was used to validate experimentally the approach, with the four following tasks: respect robot joint angles boundaries; meet the balance constraint; track the robot end-effectors (two hands and the free foot) and minimize human-humanoid joint angle positions.

2 Method

2.1 Inverse kinematics (IK)

The inverse kinematic model gives the generalized coordinate vector $\dot{\mathbf{q}}$ for an operational coordinate vector $\dot{\mathbf{X}}$: $\dot{\mathbf{q}} = \mathbf{J}^{+}\dot{\mathbf{X}}$, where $\mathbf{J}^{+}$ $(n \times m)$ denotes the pseudo-inverse of the Jacobian matrix $\mathbf{J}$. In what follows, index r holds for *robot* and index h for *human*. Solving for $\dot{\mathbf{q}}_r$, the IKM giving the robot generalized vector taking the human kinematics into account is obtained as follows.

$$\dot{\mathbf{q}}_r = \mathbf{J}_r^{+}(\alpha\ \mathbf{J}_h\ \dot{\mathbf{q}}_h) = \mathbf{J}_r^{+}(\alpha\ \dot{\mathbf{X}}_h) \quad (1)$$

where $m_r = m_h$. The human joint trajectories may be easily measured using a motion capture system, but the human Jacobian matrix cannot be obtained precisely. The use of the human Cartesian trajectories gives a simple access, easily measurable, to task data: the components of $\dot{\mathbf{X}}_h$ are obtained by measurements, the components of α are float numbers matching the human to humanoid scaling as described in the next subsection, and the components of the matrix $\mathbf{J}_r$ are known according to the robot kinematics description.

2.2 Scaling matrix $\alpha(t)$

The diagonal scaling matrix α is a square matrix of dimension $m_r \times m_r$ and its components vary with time. They depend on the systems parameters (segments length, joint positions, dof) and configuration (joint angles values). The scaling matrix is set in two steps at each instant (Fig. 1):

1. Scaling of the human into humanoid joint positions (joint space);
2. Matching the end-effectors positions in the global frame (task space).

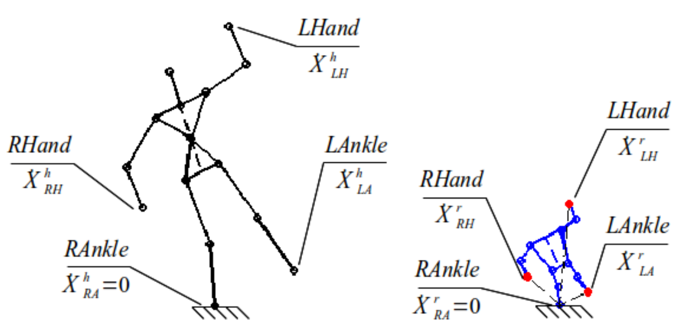

Fig. 1. Scaling process from human body (left) to humanoid robot (right). Step 1: human to humanoid joint positions (blue); Step 2: end-effectors positions (red).

2.3 Tasks specification

Let us use the robot redundancy to specify additional constraints in its motion. *Task specification* allows adding terms to the IKM forcing the robot configurations into desired ones or minimizing additional terms [1, 7, 11]. Let us consider four tasks: Cartesian trajectory tracking (index r); Balance constraint (index c); Avoiding robot joints limits (index ℓ) and Joints trajectories tracking (index h). The resulting generalized vector $\dot{\mathbf{q}}_r$ (23 $\times$ 1) is then modified as in Eq. 2.

$$\dot{\mathbf{q}}_r = \mathbf{J}_c^+ \dot{\mathbf{X}}_c' + (\mathbf{J}_r \mathbf{P}_1)^+ (\alpha \dot{\mathbf{X}}_h - \mathbf{J}_r \mathbf{J}_c^+ \dot{\mathbf{X}}_c') + \mathbf{P}_2^a (\kappa_\ell \nabla f_\ell + \kappa_h \nabla f_h) \tag{2}$$

$$\text{with } \mathbf{P}_1 = \mathbf{I} - \mathbf{J}_c^+ \mathbf{J}_c \text{ and } \mathbf{P}_2^a = \mathbf{I} - \begin{pmatrix} \mathbf{J}_c \\ \mathbf{J}_r \end{pmatrix}^+ \begin{pmatrix} \mathbf{J}_c \\ \mathbf{J}_r \end{pmatrix}$$

Experiments showed that respecting the robot joint angles limits should have a very high priority, so a compromise was defined through the setting of the gains κ_ℓ and κ_h, as will be explained next.
The task here consisted in tracking the scaled human trajectories of the two hands and the left foot, the right foot remaining in flat contact with the ground. The operational vector contained 9 coordinates: 3 position coordinates for each free end-effector.

$$\mathbf{X}^{(9\times1)} = [\mathbf{X}_{LH}^{(3\times1)}, \mathbf{X}_{RH}^{(3\times1)}, \mathbf{X}_{LF}^{(3\times1)}]^T.$$

3 Experimentation with NAO robot and Kinect camera

The on-line imitation was performed using a Kinect camera and the humanoid robot NAO. The setting of κ_ℓ (joint angle limits) was set high enough to be considered first. As a consequence, the trajectory tracking and the balance management tasks dealt with already admissible trajectories. The imitation showed good results in terms of all four tasks. Fig. 2 shows the hands and foot simultaneous trajectories of scaled human (blue) and humanoid (red) movements during on-line tracking. The distances are in [mm] for the left hand (top), the right hand (middle) and the left foot (bottom). The Cartesian values were synchronized in time, which means that the robot motion was performed 1) at the same velocity as the human motion and 2) the human movement coordination was respected. All the optimized tasks are in the kernel of the last Jacobian, which means they have equivalent priority in the proposed model. The only way to modify the order of priority is the tuning of the gains κ_ℓ and κ_h. Let us also point out that the two proposed minimized tasks: keep far from the robot joint limits and keep as close as possible to the human joint angles, may sometimes be contradictory. A fixed compromise was set: the most important task is to respect the robot joint limits, as if not, no satisfactory solution may be obtained in the whole body trajectory generation. The gains were set to κ_ℓ = -0.1 and κ_h =-0.02.

To evaluate the global manner the motion was performed, root mean square error (RMSE) between the human scaled reference trajectories and obtained humanoid trajectories during on-line imitation was calculated for the controlled

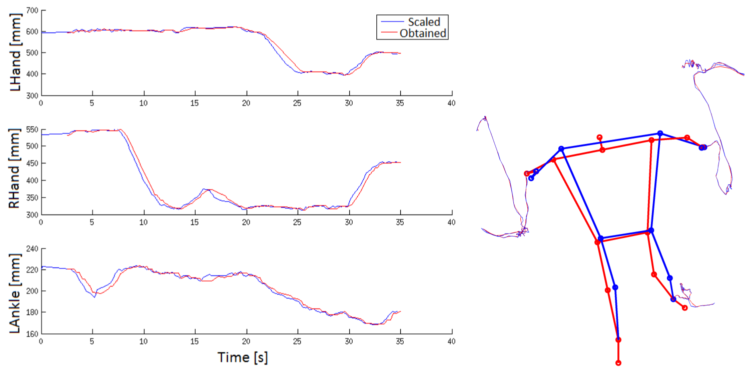

Fig. 2. Hands and left foot Cartesian positions of scaled human and humanoid movements, on-line tracking.

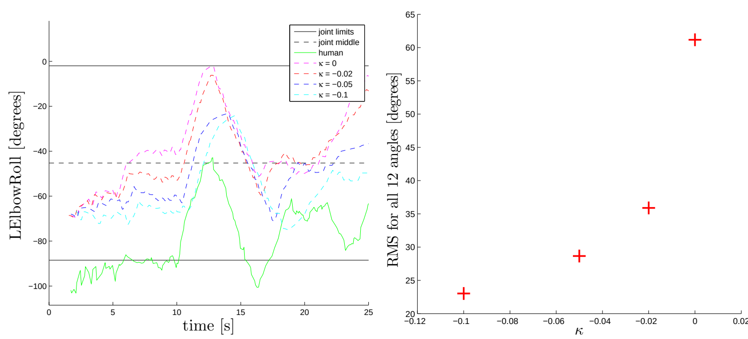

Fig. 3. Influence of κ_h on the manner the motion is performed. Example on the elbow roll angle (left) and RMSE values for different κ_h for the 23 tracked joint angles (right).

joint angles. The influence of the tuning of κ_h was compared using the RMSE values, the results can be observed in Fig. 3-left for a 2 minutes experience replayed offline. When $\kappa_h = 0$, RMSE value was high due to the offset mentioned in Fig. 3. The compromise obtained after the tuning of κ_h allowed lowering the RMSE value and generating trajectories very close to the human reference.

4 Conclusion

A general framework was proposed to realize human on-line motion imitation with a humanoid robot. IK was formulated using the pseudo inverse of the Jacobian matrices for exact tasks and minimization process for minimized tasks. Then according to the humanoid robot NAO used for experiment, 4 tasks were described to reproduce the human reference motion: balance (CoM projection); end effectors trajectories; keep away from robot joint limits and close to human joint positions. A filtering process of the human raw trajectory was also described. The scaling was absolutely necessary to ensure fluid motion of the robot and balance keeping while tracking correctly the end effectors trajectories. The proposed method showed very good results even at faster velocities and promises nice applications in the area of human motion imitation performed by humanoid robots.

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