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Exploiting the robot kinematic redundancy for emotion conveyance to humans as a lower priority task

Josep-Arnau Claret · Gentiane Venture · Luis Basañez

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Abstract Current approaches do not allow robots to execute a task and simultaneously convey emotions to users using their body motions. This paper explores the capabilities of the Jacobian null space of a humanoid robot to convey emotions. A task priority formulation has been implemented in a Pepper robot which allows the specification of a primary task (waving gesture, transportation of an object, etc.) and exploits the kinematic redundancy of the robot to convey emotions to humans as a lower priority task. The emotions, defined by Mehrabian as points in the Pleasure - Arousal - Dominance space, generate intermediate motion features (*jerkiness*, *activity* and *gaze*) that carry the emotional information. A map from this features to the joints of the robot is presented. A user study has been conducted in which emotional motions have been shown to 30 participants. The results show that happiness and sadness are very well conveyed to the user, calm is moderately well conveyed, and fear is not well conveyed. An analysis on the dependencies between the motion features and the emotions perceived by the participants shows that *activity* correlates positively with *arousal*, *jerkiness* is not perceived by the user, and *gaze* conveys *dominance* when *activity* is low. The results indicate a strong influence of the most energetic motions of the emotional task and point out new directions for further research. Overall, the results show that the null space approach can be regarded as a promising mean to convey emotions as a lower priority task.

Keywords Human-robot interaction · Social robotics · Emotion conveyance · Robot kinematics · Task priority · Pepper robot

Abbreviation

DOF	Degree of Freedom
JVG	Jerkiness - Activity - Gaze
PAD	Pleasure - Arousal - Dominance

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Josep-Arnau Claret
Institute of Industrial and Control Engineering, Technical University of Catalonia (UPC), BarcelonaTECH, Barcelona, Catalonia, Spain
E-mail: josep.arnau.claret@upc.edu

Gentiane Venture
Tokyo University of Agriculture and Technology, Tokyo, Japan
E-mail: venture@cc.tuat.ac.jp

Luis Basañez
Institute of Industrial and Control Engineering, Technical University of Catalonia (UPC), BarcelonaTECH, Barcelona, Catalonia, Spain
E-mail: luis.basanez@upc.edu

1 Introduction

Robotics is moving from cells of industrial manipulators to shared environments where humans and robots have to interact [10, 44]. The increasing interest in Human-Robot Interaction and social robotics [4] has naturally lead to the question of whether robots should be endowed with emotions [11] and emphatic behaviours [3, 43].

In this regard, a future is devised in which humans and robots interact on a daily basis. Several studies show a link between productivity and the emotional state of the workers, for example, happiness raises productivity [36], and anxiety impairs cognitive performance, which may ultimately lead to fatigue and degrade productivity [18]. In order to increase the probability that the operator succeeds in his/her task, a robot may want to convey an appropriate emotional state to the user (i.e., calmness, when the robot is delivering a fragile load to the human; or an appropriate degree of arousal in a situation where a robot and a human are cooperatively carrying a delicate object through a narrow passage). In this situation it is necessary to have all the possible means to induce the desired emotion to the operator. It is even more interesting if the robot can achieve this while executing another task with higher priority (grasp a fragile load while approaching the user to deliver the charge). Another situation where it can be interesting to convey emotions to humans is, for instance, when a care robot is carrying a plate and may sense that a patient is in a low mood and thus use its redundancy to convey positive emotions to him/her; or even to convey an appropriate emotion so that the robot is more accepted by the people with which it is interacting [22]. Also, for a robot gesturing with the hands while speaking, it can be interesting (and even necessary) to complement the emotional content of the voice with more emotional information, and use the redundancy to do so while the hands are occupied doing the gestures.

1.1 Related works

Different approaches have been devised in the Human-Robot Interaction field to use the robot to convey emotions to the user. An interesting approach is the modulation of the voice intonation [16, 30, 38], such that the voice carries the emotional information. Other approaches use a robot or avatar head to carry emotional information, for example, by actuating eleven servo-motors in the robot face to command the desired facial expressions through a behaviour based control [8], by integrating the head motion with the facial expression to emphasize the emotional content [12], or by generating emotionally expressive head and torso movement during gaze shifts [27].

Conveying emotions through the body motions has been studied in the animation and computer graphics community for decades [2, 23, 45], and it is only recently that efforts have arisen in the robotics community [26, 35, 39]. In [6] new emotional expressions are generated by interpolating between key robot configurations associated to specific emotional expressions. Some other approaches add an offset motion (in terms of position and its derivatives) on a known gesture: for instance, in [30] the final position and the velocity of a base gesture are modified depending on the emotional information to be conveyed by a humanoid robot, and, similarly, in [34] the intermediate points and the velocity of a given trajectory are transformed to incorporate affective nuances. Interestingly, the field is capturing increasing attention and maturing, and a survey can already be found [24].

Although there is a rich corpus of literature dealing with the emotion conveyance through the body motions of the robot, to the authors knowledge, the available approaches exclusively use the joints of the robot to carry the emotional information as the unique task. An obvious limitation arises when the robot is already executing a given task and a need to use the robot body motions to carry emotional information is detected. Then a decision has to be made of whether use the robot for the given task or stop it and switch to the emotional task.

Is it possible to execute both tasks simultaneously?

The present work intent is to push the boundaries of the current state of the art in robot emotion conveyance through the body motions of a humanoid robot and do a step forward in answering this question. In this regard, a framework to integrate the given task and a desired emotional task is presented when the former has the highest priority. To do so, the kinematic redundancy of the robot is exploited.

The use of the Jacobian null space [29] of a robot is a well known mean to exploit the kinematic redundancy of the robot to execute simultaneous tasks, whether at a kinematic or dynamic level. Further improvements of this concept lead to the multi priority frameworks [14, 17, 31, 41], where several tasks can be imposed to the robot with different levels of priority. These solutions have been widely applied to manipulators, mobile manipulators [46] and more recently to humanoid robots [40].

The aim of this work is to explore the null space of a robot as a mean to convey emotions to humans. The first objective is to develop a function to convey emotions through the motions of a Pepper robot (Fig. 1) using its null space; as a sub-objective, it is desirable that the proposed solution be extendible to any humanoid robot. The second objective is to present the results of a user study that has been conducted and its interpretation. The aim of this study has been twofold: to evaluate the conveyance quality of the proposed solution, and to analyse at a deep level the interactions between the different physical emotional features of the robot and the emotions perceived by the users.

1.2 Contributions

The main contribution of this work is to present the first approach, to the authors knowledge, for a humanoid robot to simultaneously execute a kinematic task and convey emotions to the users with its body motions, and the first evidence that the null space is a promising mean to convey the emotions as a lower priority task. To do so, a map is presented that transforms emotional information to kinematic features of the robot. The approach has been implemented in a Pepper robot and is extendible to other humanoid robots. As another contribution, the conclusions of a user study that

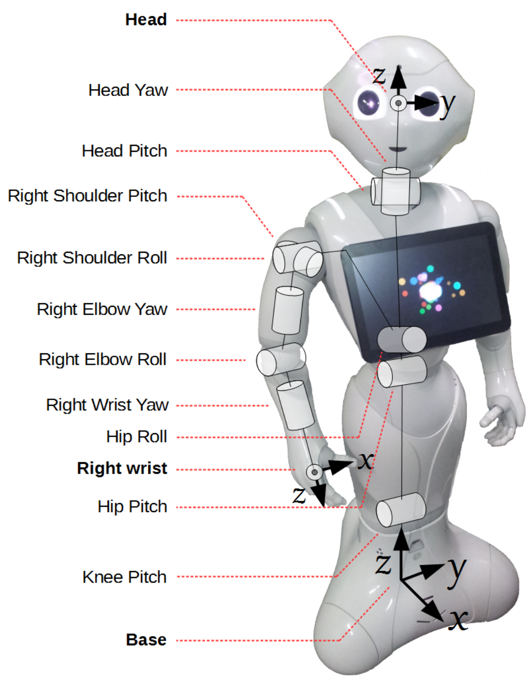


Fig. 1 The Pepper robot, with the *base*, *right wrist* and *head* frames in relief, the joints of the common trunk, and of the head and right arm chains. The left arm joints and the *left hand* frame, omitted for ease of visualization, follow by symmetry.

analyses the interactions between the robot kinematic features and the perceived emotions are presented.

This paper is organized as follows. Section 2 introduces the basic features of the Pepper robot. In Section 3 the emotion conveyance approach is presented, divided into the emotion conveyance functions and the task priority inverse kinematic algorithm. Section 4 presents the implementation of this approach. The description of the user study and its results are shown in Section 5. Section 6 discusses the interpretations of the results, current limitations of the proposed approach and open questions. Finally, Section 7 addresses the conclusions and future work.

2 The Pepper Robot

Pepper is a social humanoid robot (Fig. 1) designed by Softbank Robotics [1]. It is composed by a body with two arms on top of a three-wheeled omnidirectional platform. The body is divided by the waist in the torso and a lower part, which can be seen as a single leg, connected to the platform with what resembles a knee. It weights 28 kg and has a height of 1.2 meters, thus has the gross stature of an 8 year old child. From a kinematic point of view the Pepper robot can be seen as a tree with three branches, the head and the two arms, that share a common chain composed by the leg and the torso. The leg and torso chain has 3 Degrees of Freedom (DOF), the head has 2 DOF in the neck, and each arm has 5 DOF in the joints of the arm and an additional DOF in an open-close motion of the fingers. 3 more DOF are due to the mobility of the omnidirectional platform, thus making an overall of 20 DOF.

For this work the hands are of no interest so a 18 DOF (platform, 3; leg and torso, 3; head, 2; right arm, 5; left arm, 5) kinematic model of the Pepper robot is used. The origin of the reference frame of each arm chain is on its wrist and the origin of the reference frame of the head is located between the eyes (as in Fig. 1). The corresponding DH parameters of the Pepper robot can be found in Table 1.

Joint	a_i	α_i	d_i	θ_{i_0}	$\theta_{i_{min}}, \theta_{i_{max}}$
Base	0	$-\pi/2$	339	0	Fix
Knee Pitch	268	0	0	$-\pi/2$	-0.51, 0.51
Hip Pitch	79	$-\pi/2$	0	0	-1.04, 1.04
Hip Roll	0	$-\pi/2$	0	$-\pi/2$	-0.51, 0.51
Head Yaw	0	$-\pi/2$	309	$-\pi/2$	-2.09, 2.09
Head Pitch	0	0	0	0	-0.71, 0.61
Hip Roll	226	$\pi/2$	-57	0	-0.51, 0.51
R. Sh. Pitch	0	$\pi/2$	-150	$\pi/2$	-2.09, 2.09
R. Sh. Roll	0	$-\pi/2$	0	$-\pi/2$	-1.56, 0.01
R. Sh. Yaw	1	$\pi/2$	181	0	-2.09, 2.09
R. El. Roll	0	$-\pi/2$	0	0	0.01, 1.56
R. Wr.Yaw	0	0	150	0	-1.82, 1.82
Hip Roll	226	$\pi/2$	-57	0	-0.51, 0.51
L. Sh. Pitch	0	$\pi/2$	150	$\pi/2$	-2.09, 2.09
L. Sh. Roll	0	$-\pi/2$	0	$-\pi/2$	-1.56, 0.01
L. Sh. Yaw	1	$\pi/2$	181	0	-2.09, 2.09
L. El. Roll	0	$-\pi/2$	0	0	0.01, 1.56
L. Wr. Yaw	0	0	150	0	-1.82, 1.82

Table 1 DH parameters of the Pepper robot, with angles in radians and lengths in millimetres. The first set of rows corresponds to the transformations of the common trunk of the kinematic tree. The second set extends the common trunk with the head transformations; the third, with the right arm; and the fourth, with the left, as in Fig. 1. R = Right, L = Left, Sh = Shoulder, El = Elbow, Wr = Wrist.

From now on, let q be a configuration of the robot given by:

$$q = [\, x \;\; y \;\; \phi_z \;\; \Theta \,]^T \tag{1}$$

where:

– $x, y \in \mathbb{R}$ are the spatial coordinates of the position of the centre of the omnidirectional platform w.r.t. an inertial reference frame (see Fig. 1).

[1] `https://www.ald.softbankrobotics.com`

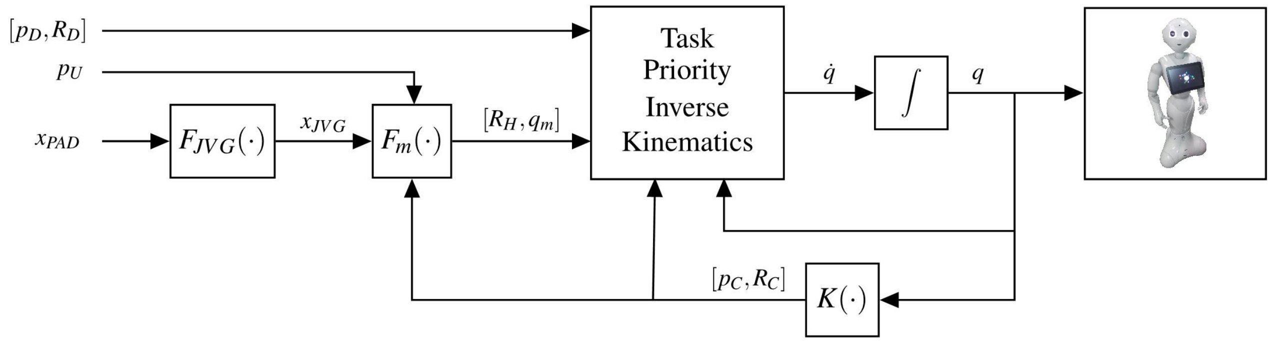


Fig. 2 Block diagram of the proposed solution

- $\phi_z \in SO(2)$ is the rotation angle of the platform around the Z axis of the inertial reference frame.
- $\Theta = [\theta_i] \in \Re^{15}$ is the vector of the joint values of the robot body, the *body configuration*, with i as the index of the joints in the following order: Knee Pitch, Hip Pitch, Hip Roll, Head Yaw, Head Pitch, Right Shoulder Pitch, Right Shoulder Roll, Right Elbow Yaw, Right Elbow Roll, Right Wrist Yaw, Left Shoulder Pitch, Left Shoulder Roll, Left Elbow Yaw, Left Elbow Roll and Left Wrist Yaw.

3 Emotion Conveyance

The main question that is being addressed in this work can be stated as:

Can a humanoid robot convey emotions to the user as a low priority task?

In order to answer this question a model is presented that, for a given emotion, generates specific kinematic motions in the null space of the Pepper robot (Sect. 3.1). The emotion conveyance using the null space and the kinematic motions has been tested through a user study (Sect. 5.1) and an analysis of its quality and degree of emotion conveyance is presented (Sect. 5.2 and 6).

3.1 Proposed approach

Given a scenario with a user, a humanoid robot with its main task, and a desired emotion, the goal of this work is to execute the given task while the robot exploits its redundancy to convey the desired emotion to the user.

In the proposed approach an emotion is defined as a point in a three dimension emotion space, which dimensions are Pleasure, Arousal and Dominance. The values in each dimension corresponding to the desired emotion are transformed into the kinematic features *jerkiness*, *activity* and *gaze*, which are ultimately mapped to a continuous range of body configurations. Thus, our approach does not generate a single configuration of the robot per emotion, but a whole range of body configurations. Also, each emotion is not conveyed by a single body part or kinematic feature, but by the combination of the three kinematic features.

Finally, each one of the continuous range of body configurations becomes the input of the null space of the robot. Thus, the main task will be accomplished and the desired emotion will be conveyed by exploiting the remaining kinematic redundancy of the robot.

The diagram in Fig. 2 visually summarizes the proposed approach. Three variables are fed to the system:

- An emotion, represented by a point x_{PAD} in the Pleasure-Arousal-Dominance (PAD) space.
- The main task, composed by a temporal sequence of hand poses in the world frame, and represented by its position, p_D, and the orientation, R_D.
- The position of the user eyes in the world frame, p_U.

Following, the PAD point is transformed by the function F_{JVG} into a new space, the Jerkiness-Activity-Gaze (JVG) space, where its coordinates are mapped into the *jerkiness*, *activity* and *gaze* dimensions, thus transforming the initial emotional information to kinematic features. A new transformation, F_m, is applied to transform the JVG point and the position of the user eyes, p_u, into a head orientation, R_H, and a robot configuration, q_m, which contain the emotional information. Finally the desired hand poses and the emotional information feed the task priority inverse kinematics block, which outputs the next configuration velocity, that is integrated, sent to the Pepper robot and used to compute the current position and orientation, p_C and R_C, through the direct kinematics, K.

3.2 From PAD to motion features: F_{JVG}

The PAD model [32] is used as the framework to code emotions. In this model Mehrabian describes three traits: Pleasure, P, Arousal, A, and Dominance, D. They are nearly independent and form a three dimensional continuous space such that the domain of each dimension is the interval $[-1,1]$. Points in this space can be linked to different emotions [20]. Several efforts have been made to develop a map between physical features of human gestures and the dimensions of the PAD model [7, 21]. Our work is mainly concerned with the arm and body motions (*pleasure* and *arousal*) and the robot gaze (*dominance*).

In the present approach, points in the *pleasure* and *arousal* dimensions of the PAD model are mapped to body motions similarly as in [30] but using the categorization of *jerkiness*, J, and *activity*, V, inspired by [21]. Finally, by exploiting *gaze* directness, G, *dominance* can also be conveyed.

In [21] it is stated that, from a set of 25 motion features that convey emotions to users, 4 features retain the majority of the emotional information. These 4 features are *activity* (which captures how energetic the motion is), excursion (how is the energy distributed along the motion), extent (the openness of the arms and head) and jerkiness. Results in [21] show that *activity* positively correlates with arousal, as does extent to a lesser degree, hence the choice of *activity* as the carrier of the arousal dimension of the PAD space.

In the literature it is stated that pleasure negatively correlates with *jerkiness* when arousal is high [21, 33]. To capture this our proposed pleasure to jerkiness map is such that the less pleasure, the more *jerkiness* there is.

Gaze is a powerful mean for robots to communicate with humans in different tasks [47]. With respect to *dominance*, several works [1, 13, 25, 27, 37, 42] point out the correlation between a direct (averted) gaze and high (low) dominance in humans. The proposed *dominance-gaze* map captures this information. Considering that the gaze of the robot can be naturally commanded through its joints, it is a straightforward mean available in a humanoid robot to convey dominance, hence its choice to convey the dominance dimension of the PAD space.

With the previous considerations a linear map F_{JVG} is defined between the points $x_{PAD} = (P,A,D) \in [-1,1]^3$ in the PAD space to the points $x_{JVG} = (J,V,G)$ within the normalized domain $[0,1]^3$ in the JVG space as:

$$F_{JVG}: \begin{pmatrix} P \\ A \\ D \end{pmatrix} \rightarrow \begin{pmatrix} J \\ V \\ G \end{pmatrix} = \frac{1}{2} \begin{pmatrix} 1-P \\ 1+A \\ 1+D \end{pmatrix} \tag{2}$$

3.3 From JVG to the emotional configuration: F_m

Activity, $V \in [0,1]$, directly relates to the kinetic energy of the robot. Let $\Theta_m(t) = [\theta_{m_i}(t)] \in \Re^{15}$ be the body configuration vector of the robot at time t. Given a minimum and a maximum expanded configurations, $\Theta_0 = [\theta_{0_i}]$ and $\Theta_{V_0} = [\theta_{V_{0i}}]$, respectively, a linear map between *activity* and the configuration space of the robot is introduced:

$$\theta_{m_i}(t) = (1-V)\,\theta_{0_i} + V\left[\theta_{V_{0i}} + h_i \sin(\omega t + \varphi_i)\right] \tag{3}$$

In (3) $H = [h_i] \in \Re^{15}$, with $h_i > 0$, can be seen as an offset to Θ_{V_0} such that when the robot is in its maximum expanded configuration it oscillates with an angular velocity ω between the configurations $\Theta_{V_0} - H$ and $\Theta_{V_0} + H$.

Differentiating $\theta_{m_i}(t)$, and assuming V, h_i, ω and φ_i as constant, then $\dot{\theta}_{m_i}(t) = \omega\, V\, h_i \cos(\omega t + \varphi_i)$ and the maximum kinetic energy K_{max_i} for joint i can be computed as:

$$K_{max_i} = \max\left(\frac{1}{2}\, I_i\, \dot{\theta}_{m_i}(t)^2\right) = \frac{1}{2}\, I_i\, \omega^2\, V^2\, h_i^2 \tag{4}$$

where I_i is a given positive value that plays the role of the moment of inertia of joint i. From (4) it is straightforward to see that when *activity* is minimum (maximum), $V = 0$ ($V = 1$), the kinetic energy K_{max_i} is minimum (maximum). Fig. 3 visually summarizes the *activity* category selected in this work for the Pepper robot.

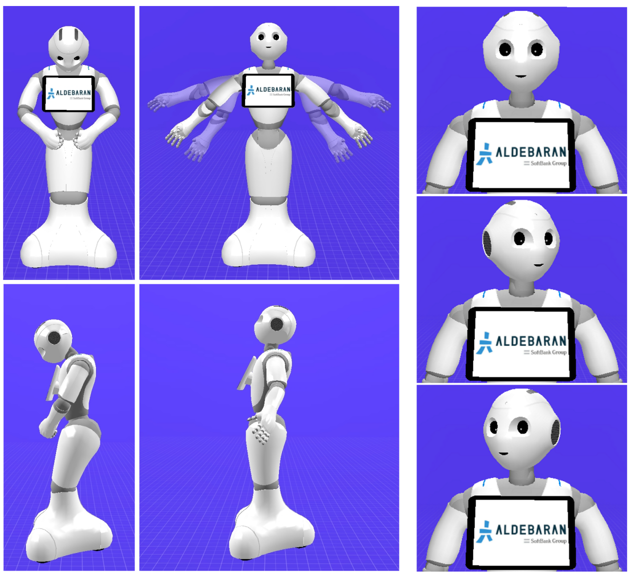


Fig. 3 Left set of four pictures: frontal and lateral views of the Pepper robot in its minimum *activity* (left pictures, $V = 0$), Θ_0; and maximum *activity* (right pictures, $V = 1$): Θ_{V_0}, the non-shaded configuration; $\Theta_{V_0} - H$, the shaded configuration with the lower arms; and $\Theta_{V_0} + H$, the shaded upper configuration with the horizontal arms. Right set of figures: the top figure shows the maximum directed gaze, while the other two show the extreme averted gazes; note that this is a basic example and in a real situation the head motion is added to the base emotional motion, that is, the left figures.

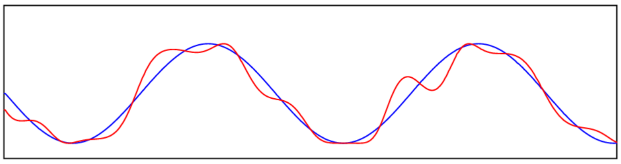


Fig. 4 A joint base motion (blue) and the same motion with the added jerk signal (red)

Jerkiness, $J \in [0,1]$, over a base trajectory can be constructed by adding Fourier series terms in φ_i in (3):

$$\varphi_i(t) = J \sum_{j=1}^{n_J} [a_j \sin(\omega_j t) + b_j \cos(\omega_j t)] \quad (5)$$

In Fig. 4 a joint trajectory can be compared when the *jerkiness* is added using the above expression.

Gaze directness, $G \in [0,1]$, is an influential factor when conveying emotions. The command of the robot *gaze* is done through the head orientation, as the eyes are non-actuated. When the *dominance* is maximum (D = 1) then *gaze* is also maximum (G = 1) and the orientation of the head is faced towards the user. When *dominance* is minimum (D = 0), the gaze is averted (G = 0) and the head follows the motion defined by the *activity* and *jerkiness* motion described before. Fig. 3 shows a direct gaze and two fully averted gazes.

The rotation matrix of the *gaze* orientation, R_H, is computed as the spherical linear interpolation (slerp) between two head rotation matrices: the direct *gaze*, R_G, and the emotional head orientation, R_m. R_G is the rotation matrix of the head orientation when *dominance* is maximum, that is, when the *gaze* is fully directed towards the user.

The head orientation R_m is computed from the direct kinematics of $q_m = [\, x \;\; y \;\; \phi_z \;\; \Theta_m \,]^T$, obtained using (3). Thus, the desired head rotation, R_H, is computed as:

$$R_H = \mathrm{slerp}(R_m, R_G, G)$$

where the computation of R_G is straightforward given the position of the eyes of the user, p_U, and the current position of the robot eyes, p_E. p_E corresponds to the position vector of the head pose, and can be computed from the direct kinematics of the head chain. Then R_G is a rotation matrix computed with the X axis as the unit vector from the robot eyes to the user gazed by the robot, $p_U - p_E$; the Y axis, as the cross product of vector $(0,0,1)^T$ and the computed X axis, and the Z axis completes the orthonormal base. The tracking of the orientation in R_H becomes the task for the second priority level of the inverse kinematic algorithm (Sect. 3.4).

Once q_m and R_H have been obtained F_m can be defined as $F_m(x_{JVG}) = \{q_m, R_H\}$ and fed to the task priority module.

3.4 The Multi-Priority Inverse Kinematic Algorithm

A robot is said to be kinematically redundant when its number of DOF is greater than the number of variables needed to describe a given task. A well known mean to exploit the redundancy is through the Jacobian null space of the robot [15].

Considering the task x of a robot and its direct kinematics $f_x(q)$, the robot configuration q that fulfils

$$x = f_x(q) \quad (6)$$

can be obtained using to the first-order differential kinematics, $\dot{x} = \frac{\partial x}{\partial t}\dot{q} = J\dot{q}$, by resorting to the inverse of the Jacobian, $\dot{q} = J^{-1}\dot{x}$, and integrating.

When the robot is redundant J has more columns than rows and the pseudoinverse, J^+, has to be used. In this situation the number of DOF needed to execute the task is lower than the number of DOF of the robot, and infinite solutions exist that satisfy (6). The general solution can be computed as:

$$\dot{q} = J^+\dot{x} + P\dot{q}_0 = J^+\dot{x} + \left(I - J^+J\right)\dot{q}_0 \quad (7)$$

where P represents the orthogonal projection matrix in the null space of J, and $\dot{q}_0$ is an arbitrary joint-space velocity which allows to obtain different velocities of q that satisfy the desired task. Thus, a secondary task can be executed through $\dot{q}_0$ with lower priority than task x. This concept can be further extended to execute different tasks at distinct levels of priority [14, 17, 31, 41].

In this work the selected algorithm is that of [14] and has been implemented as in [5]. The algorithm has been used to convey emotions through the priority levels two (*dominance*, through *gaze*) and three (*pleasure* and *arousal*, through *jerkiness* and *activity*, respectively) as:

$$\begin{aligned}
\dot{q}_t &= J_t^+ e_t \\
\dot{q}_h &= \dot{q}_t + P_t\, J_h^+ e_h \\
\dot{q} &= \dot{q}_h + \left[P_t - (J_h P_t)^+ (J_h P_t)\right] e_m
\end{aligned} \quad (8)$$

where:

- $e_t = (K_p\,\varepsilon_p \;\; K_o\,\varepsilon_o)^T$ is the error of the main task t with:
  - $\varepsilon_p = p_D - p_C$; p_i, with $i \in \{D, C\}$, is the position of the robot final element of task t; and D and C, the desired and current frames, respectively.
  - $\varepsilon_o = \frac{1}{2}[n_C \times n_D + s_C \times s_D + a_C \times a_D]$, where n_i, s_i, and a_i are the columns of the rotation matrix that rotates the inertial frame into the current and desired frames C and D.
  - K_p and K_o are positive definite matrices.
- e_h is the head orientation error computed as ε_o.
- e_m is the emotional conveyance task error:

$$e_m = k_m\,(q_m^* - q^*)$$

where $q_i^* = [0, 0, 0, \Theta_i]^T$, and $k_m > 0$.

- J_i is the Jacobian matrix of task $i \in \{t,h\}$.
- J^+ is the pseudoinverse of J.
- $P_t = I - J_t^+ J_t$ is the orthogonal projection operator onto the null space of task t. I is the identity matrix.

A proof of the task prioritization of the proposed approach is shown in Appendix 1, following [14] and [5].

4 Implementation

The algorithm has been implemented in an Ubuntu 14.04, over a Intel Core i5 at 2500 GHz. The code has been written in C++ using the ROS middleware and Rviz has been used for visualization in the development stage. The main purpose of the use of ROS has been to ease a future integration of the software in a higher-level framework. Regarding the execution on the Pepper robot, the generated trajectories have been executed from a Python script loaded to Choreograph, the official software to command the Aldebaran robots.

The pseudoinverse in (8) has been computed using the SVD decomposition. This allows the elimination of the inverse of the singular values in the decomposition when the robot is near singular configurations ($\delta < 0.001$).

The frequency at which the algorithms have been executed during the design phase has been 100 Hz. The samples for the trajectory execution have been fed to the Pepper robot at 4.45 Hz due to the dynamic constraints imposed by its lower level controllers. This gives rise to the necessary question of how much does the sampling frequency affect the intended jerkiness of the robot, and how to properly tune the jerkiness values to obtain the desired jerky effect.

The values of the parameters are shown in Appendix 2.

5 The emotion conveyance study

A study has been conducted to evaluate the conveyance performance of the proposed approach, and to analyse the dependencies between the *jerkiness*, *activity* and *gaze* directness with the dimensions of the PAD model.

The idea behind this study is to understand to what extent chunks of robot motions convey emotions at an unconscious level. To do so, relatively fast responses of the participants have been required, so that their responses capture the perceived emotions rather than what they actually think they perceived. The SAM scale [9] has been used to evaluate the degree of emotion conveyance. It is a visual questionnaire composed of three scales, each one corresponding to a dimension of the PAD space. It eliminates the problems related to verbal measures, and due to its visual nature the participants can write their responses fast and intuitively.

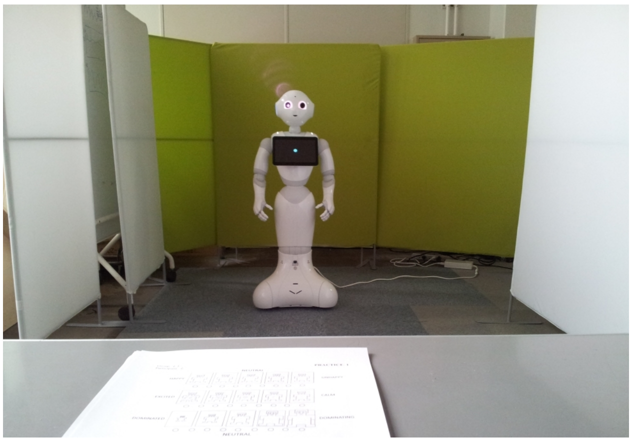


Fig. 5 A participant's point of view during the experiment

5.1 Description

The study has consisted of the execution of twelve trajectories on the Pepper robot and their evaluation using the SAM scale. Each motion had a duration of approximately 5 seconds and following the participants had 7 seconds to do each rating on paper sheets. There have been 30 Japanese participants (26 men and 4 women) divided in groups of 2 and 3 persons, mainly students from the university campus; the average age has been 24.2 with a standard deviation of 3.7 years. The scenario where the experiment took place can be seen in Fig. 5, where Pepper is 3 metres away from the participants.

In all the trajectories Pepper has been doing a salutation movement with the right hand as the main task while the platform was not moving. The salutation movement, consisting of a waving motion of the right hand, constrained the six DOF of the position and orientation of the right wrist. Simultaneously an emotional movement computed from a predefined PAD point has been executed.

The twelve trajectories have been shown in the following sequence:

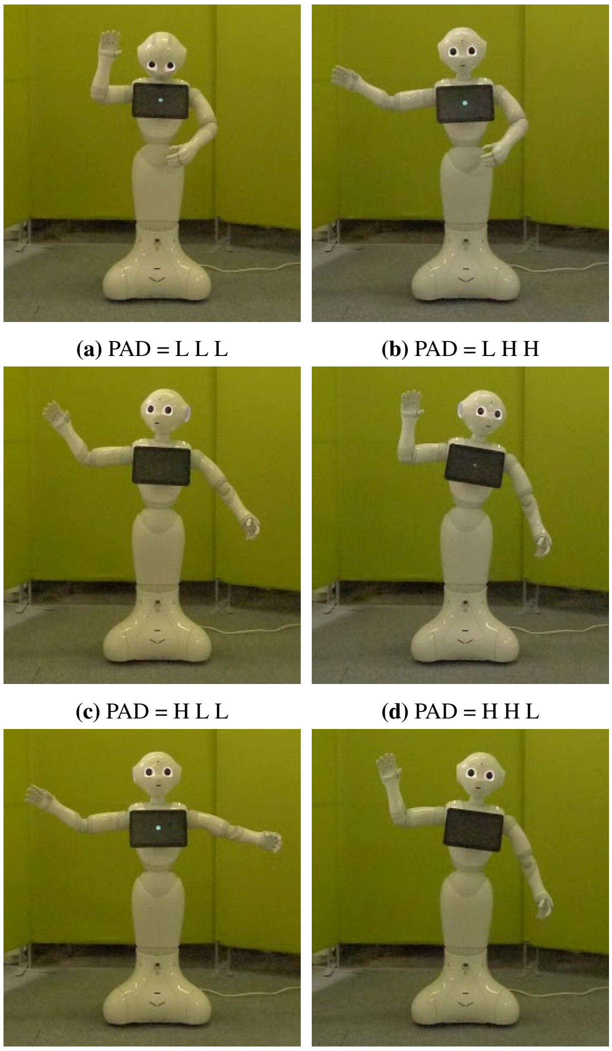
1. A neutral motion where the Pepper robot only waved the right hand and the arm. This motion has not been evaluated.
2. Two random motions. The aim of this pair of motions has been for the participants to practice the SAM scale. Thus, the motions have been evaluated, but not taken into account in the analysis of the data.
3. Eight predefined motions, randomly sorted for each group of participants. Each motion has been generated from a PAD point in which the P, A and D values had one of the two quasi-extreme values in its dimension: a low value $\mathrm{L} = -0.75$, or a high value $\mathrm{H} = 0.75$. The combination of all the values (i.e, low P, low A, low D; low P, low A, high D, etc.) adds up to eight motions. Figs. 6a-6f

show six frames of different motions; note that *jerkiness* cannot be perceived in a photography.

4. Two motions randomly selected from a set of four motions associated to four emotions (*calm*, *sadness*, *happiness*, *fear*; generated from similar PAD values as in [20]). The criteria to select these particular emotions was to use emotions that were characteristic of the PAD space. Mehrabian [32] assigns a representative label to each of the octants of the three dimensional PAD space: the octant corresponding to positive *pleasure*, *arousal* and *dominance* (+P+A+D) is labeled as Exuberant; -P-A-D, as Bored; +P-A+D, as Relaxed; -P+A-D, as Anxious, etc. Each of the four emotions selected for the user study belongs to a different octant: *happiness*, to the Exuberant octant; *sadness*, the Bored; *fear*, the Anxious; and *calm*, the Relaxed. Also, note that *happiness* and *sadness* correspond to opposite octants (+P+A+D and -P-A-D, respectively); and also *fear* and *calm* (-P+A-D and +P-A+D). Thus, the idea behind the choice of the four emotions has been to give the participants a set of qualitatively distinguishable and well known emotions. And even though the granularity of the PAD space can be very fine [20], it was considered that using qualitatively far away emotions was a good starting point to evaluate the emotion conveyance of the proposed approach. The SAM scale has not been used to evaluate these motions. The participants have been asked to select which of the four emotions suited best the shown motion. A ≪Do not know.≫ answer has also been included as a fifth option.

In the animation (Online Resource 1) the full set of shown motions in the user study can be seen: the neutral waving motion, the eight predefined PAD motions, and the four motions corresponding to the four emotions.

Prior to the study each participant has had plenty of time to read the instructions of the experiment and to ask any question to native members of the laboratory. The instructions have been adapted from [28] and later translated into Japanese with the help of Japanese lab members. The experiment took an average of 11 minutes per group of participants.



(a) PAD = L L L **(b)** PAD = L H H

(c) PAD = H L L **(d)** PAD = H H L

(e) PAD = H L H **(f)** PAD = H H H

Fig. 6 The salutation motion with different emotions

A distinction is needed between the PAD values input to the robot to generate an emotional motion and the PAD values of the participant responses, answered in the SAM scales. Thus, from now on, the former will be named PAD and the latter, PAD* (or P*, A* and D*, when its dimensions are expressed separately).

5.2 Results

Two main sets of results have been obtained from the data of the user study. The first set of results accounts for the quality of the emotion conveyance of the proposed approach. The second set of results consists of the dependencies between the features of the physical motions (*jerkiness*, *activity* and *gaze* directness) and the PAD perceived values.

The underlying assumption behind the study is that the users will significantly perceive the PAD dimensions of the shown motions, thus perceiving the corresponding emotions.

Emotion conveyance results

Table 2a shows the results of the emotion selection part of the user study (step 4 in the list in Sect. 5.1), along with the p-values, computed from a binomial distribution, and the 95% confidence intervals of the success rate. The success of the emotional conveyance can be evaluated from its distance above chance, which is 20%. 15 samples have been gathered per emotion.

The results show an emotion is correctly perceived above chance when the Pepper robot is trying to convey *calm*, *happiness* or *sadness*. On the contrary, *fear* is perceived most of the times (80.0%) as *happiness*.

It is also interesting to note that, when wrongly perceived, *sadness* is only perceived as *fear*. Finally, it has to be pointed out that even though *calm* obtained a slightly good score, the participants have been more uncertain about the conveyed emotion (40.0% of ≪Do not know.≫ responses).

Table 2b shows the results of the SAM scale evaluation (step 3 in the list in Sect. 5.1): means, μ; p-values, p; confidence intervals, CI; and the Cohen's d effect sizes, ES. 30 samples have been gathered per measure. The results have been evaluated through statistical significance towards the right bias: for example, if a certain motion tried to convey a high (low) *dominance* of D = H = 0.75 (D = L = -0.75) it has been verified that the mean of the perceived *dominance*, μ_{D^*}, has been positive (negative). The quality can be analysed using the p-value and the effect size. An effect can be interpreted as small if the absolute value of the effect size is less than 0.2; medium, if higher than 0.2 and less than 0.8; and big if it is higher than 0.8. The 95% Confidence Intervals are added for ease of interpretation.

From Table 2b the most straightforward conclusions can be summarized as:

- In two PAD points the three dimensions are well conveyed, in PAD = LLL and PAD = HHH, though the former is far better conveyed, as can be deduced from the p-values.
- Four PAD points are well conveyed in two dimensions: LHH, HLL, HLH, HHL, with mixed results. For example, in HLL the *arousal* and *dominance* are better conveyed than the *pleasure* and *dominance* of HLH.
- Two PAD points, LLH and LHL, are well conveyed in one dimension.

It can also be seen that *arousal* is well conveyed in 7 of the 8 motions, while *dominance* in 5 and *pleasure* in 4. Overall, the interpretation of the results is not obvious and a deeper analysis of the data is necessary to understand the interactions between the intended conveyed emotions and the perceived ones.

Overall perceived values and correlations

The second set of results are presented in Table 3. The main purpose of this analysis is to shed light on the hidden interactions between the JVG variables (Jerkiness, Activity and Gaze) and their perceived PAD* values, not obvious in the previous results. The comparison is done between the JVG motion features and the perceived emotions, PAD*, because this approach allows a more intuitive visualization of the robot motions and eases the interpretation of its effect on the perception of the participant.

Note, from (2) and as explained in Sect. 3.2, that a high *jerkiness*, J = H, corresponds to a low *pleasure*, A = L; a high (low) *activity*, V = H (V = L), corresponds to a high (low) *arousal*, A = H (A = L); and a direct (averted) *gaze*, G = H (G = L), corresponds to a high (low) *dominance*, D = H (D = L).

Table 3a shows the means, μ, standard deviations, σ, and effect sizes, ES, of the PAD* values of the SAM scales rated by the participants; 240 samples per measure have been gathered. In Tables 3b-3e, the Spearman's rank correlation coefficients between the JVG variables and the user PAD responses are presented. Table 3b shows the overall correlation coefficients, and the next six tables present the correlations for certain conditions (i.e. averted *gaze*, $G = L$). Bold values are statistically significant ($p < 0.05$). For the correlations in Tables 3c-3e 120 samples per measure have been gathered.

Table 3 can be summarized as follows:

- There is a statistically significant bias ($p_{D^*} = 0.001$) towards non-*dominance* ($\mu_{D^*} = -0.10$).
- *Activity* correlates positively with *arousal* ($r_{EA^*} = 0.43$).
- *Jerkiness* does not correlate with any value of the SAM scale.
- *Gaze* directness correlates positively with *dominance* ($r_{GD^*} = 0.22$), highly ($r_{GD^*} = 0.48$) when *activity* is low, and almost nothing when *activity* is high ($r_{GD^*} = 0.01$).
- When *activity* is high *gaze* negatively correlates with *arousal* ($r_{GA^*} = -0.23$). Also, when *gaze* is directed the correlation between *activity* and *pleasure*, *arousal* and *dominance* ($r_{EP^*} = 0.64$, $r_{EA^*} = 0.57$, $r_{ED^*} = 0.56$) is more than the double than when *gaze* is averted ($r_{EP^*} = 0.12$, $r_{EA^*} = 0.28$, $r_{ED^*} = 0.28$).

6 Discussion

The results in the previous section point out that *happiness* and *sadness* are correctly recognized; *calm* is slightly well perceived above chance, and *fear* is mostly interpreted as *happiness*.

Also, from the data presented in Table 3 some conclusions can be extracted:

- From the statistically significant bias towards non-*dominance* it can be deduced that Pepper is perceived as low dominant. This seems reasonable as in fact Pepper does not seem by design very dominant and the design can have a significant impact on the user perception of the robot [19]. It also implies that in order to transmit a dominant emotion (with body motion, voice, or any other mean) this bias should be overcome (but it would be easier to transmit low dominant emotions).
- *Activity* effectively carries the *arousal* information.

Table 2 Emotion conveyance results

	Responses (%)					p				
Emotion	C*	F*	H*	S*	⊘	C*	F*	H*	S*	⊘
Calm	**33.3**	6.7	20.0	0	40.0	**0.06**	0.83	0.35	0.96	0.02
Fear	6.7	**13.3**	80.0	0	0	0.83	**0.60**	0	0.96	0.96
Happiness	6.7	0	**73.3**	6.7	13.3	0.83	0.96	**0**	0.83	0.60
Sadness	0	33.3	0	**66.7**	0	0.96	0.06	0.96	**0**	0.96

	Confidence Interval (95%) of the Responses				
Emotion	C*	F*	H*	S*	⊘
Calm	[9.48,57.19]	[0,19.29]	[0,40.24]	[0,0]	[15.21,64.79]
Fear	[0,19.29]	[0,30.54]	[59.76,100.00]	[0,0]	[0,0]
Happiness	[0,19.29]	[0,0]	[50.95,95.71]	[0,19.29]	[0,30.54]
Sadness	[0,0]	[9.48,57.19]	[0,0]	[42.81,90.52]	[0,0]

(a) Results of the emotion selection. 15 samples per emotion have been gathered. Each row corresponds to the results regarding the conveyed emotion of the first column, i.e., users have perceived calm as happiness in a 20.0% of the times (first row and second column in the Responses section); the success rate of each emotion and the corresponding p-value are highlighted in bold. C*, F*, H* and S* correspond to the perceived/selected *calm*, *fear*, *happiness* and *sadness*; ⊘ is the ≪Do not know.≫ answer.

P A D	μ_{P^*}	μ_{A^*}	μ_{D^*}	p_{P^*}	p_{A^*}	p_{D^*}	CI_{P^*}	CI_{A^*}	CI_{D^*}	ES_{P^*}	ES_{A^*}	ES_{D^*}
L L L	**-0.59**	**-0.30**	**-0.52**	0	0	0	[-0.74, -0.44]	[-0.49, -0.13]	[-0.65, -0.38]	-1.4	-0.6	-1.4
L L H	0.13	**-0.14**	-0.11	0.03	0.06	0.12	[0.01, 0.25]	[-0.29, 0.01]	[-0.25, 0.03]	0.4	-0.3	-0.3
L H L	0.27	**0.37**	0.18	0	0	0	[0.10, 0.43]	[0.22, 0.52]	[0.01, 0.36]	0.6	0.9	0.4
L H H	0.24	**0.20**	**0.10**	0	0	0.14	[0.11, 0.38]	[0.07, 0.33]	[-0.03, 0.23]	0.7	0.5	0.3
H L L	-0.53	**-0.30**	**-0.49**	0	0	0	[-0.72, -0.33]	[-0.49, -0.11]	[-0.67, -0.31]	-1.0	-0.6	-1.0
H L H	**0.13**	-0.03	**-0.12**	0.04	0.71	0.06	[0.01, 0.26]	[-0.21, 0.14]	[-0.24, 0]	0.4	-0.1	-0.4
H H L	**0.18**	**0.31**	0.02	0.07	0	0.86	[-0.01, 0.38]	[0.15, 0.47]	[-0.17, 0.20]	0.3	0.7	0
H H H	**0.19**	**0.11**	**0.10**	0.01	0.15	0.14	[0.05, 0.34]	[-0.04, 0.27]	[-0.03, 0.23]	0.5	0.3	0.3

(b) Means of the SAM scale evaluation for each motion. Each row corresponds to the desired conveyed emotion in the PAD scale. 30 samples per emotion have been gathered. Bold means correspond to emotions that have been perceived in the right direction.

- *Jerkiness* does not convey anything. One reason might be that when there is *jerkiness* there always is another more energetic motion (*activity*), thus *jerkiness* may not be noticed. Another, as explained in Sect. 4, might be that the interaction between the parameters of the jerky motion and the sample rate of the robot are not properly synchronized. This would indicate that there is a need for a formal definition of *jerkiness*, how humans perceive it, and, specially, how it can be artificially generated and executed on a robot. The miss-conveyance of the jerky motions can also explain why *fear* tends to be perceived as *happiness*. First, it is necessary to consider that both *fear* and *happiness* have high arousal values, but negative and positive values in the pleasure dimension, respectively. The implemented jerky motion may have been interpreted as a non-jerky motion, corresponding to a higher pleasure emotion, that is, *happiness*.
- The positive correlation between *gaze* directness and *dominance* and, more interesting, the fact that it correlates highly with a low *activity*, and barely with a high *activity*, may indicate that when the expanded movement is very energetic (*activity* is high) it drags the user attention, thus influencing all the other correlations. When *activity* is not so noticeable, other features can arise and better convey their emotions.
- The negative correlation between *gaze* and *arousal* when *activity* is high can be explained by noticing that Pepper staring towards the user diminishes the effect of the expanded arms. This can be explained because the more the *gaze* is directed the head moves less, thus the overall kinematic energy of the robot is lower. Also, when *gaze* is directed the correlation between *activity* and *pleasure*, *arousal* and *dominance* is more than the double than when the *gaze* is averted. Thus a direct *gaze* diminishes the impact that *activity* has on the user.
- There seems to be a gross evaluation in the SAM scale using the most relevant motion of the Pepper robot. That is, if *activity* is the most noticeable (energetic) feature of a motion, all values of the SAM scale positively correlate more to *activity*: *activity* seems to drag not only *arousal*, but also *dominance* and *pleasure*. If *activity* is low, then *gaze* is the dragger. This might indicate that the user tends to create a general binary notion of the emotional state of Pepper (happy/sad, good/bad, etc.) and the

Table 3 PAD Means and JVG to PAD* correlations

	μ_i	p_i	CI_{μ_i}	ES_i
P*	0	0.91	[-0.06, 0.07]	0.01
A*	0.03	0.43	[-0.04, 0.09]	0.01
D*	**-0.10**	0	[-0.17, -0.04]	-0.21

(a) Means, μ; p-values, p; confidence intervals, CI; and effect sizes, ES, of the PAD* responses. 240 samples per emotion have been gathered. The index i is the PAD* dimension of the corresponding row, i.e, $\mu_{A^*} = 0.03$; this notation also applies to Tables 3b - 3e.

	r_{Ji}	r_{Vi}	r_{Gi}	$p_{r_{Ji}}$	$p_{r_{Vi}}$	$p_{r_{Gi}}$	$\text{CI}_{r_{Ji}}$	$\text{CI}_{r_{Vi}}$	$\text{CI}_{r_{Gi}}$
P*	-0.02	**0.39**	**0.29**	0.61	0	0	[-0.11,0.15]	[0.28,0.49]	[0.17,0.40]
A*	-0.01	**0.43**	0	0.54	0	0.47	[-0.12,0.14]	[0.32,0.53]	[-0.13,0.13]
D*	0.03	**0.41**	**0.22**	0.69	0	0	[-0.10,0.16]	[0.30,0.51]	[0.10,0.34]

(b) General Correlations. 240 samples per measure have been gathered.

Low Extension (V = L)	r_{Ji}	r_{Gi}	$p_{r_{Ji}}$	$p_{r_{Gi}}$	$\text{CI}_{r_{Ji}}$	$\text{CI}_{r_{Gi}}$
P*	-0.03	**0.66**	0.32	0	[-0.21,0.15]	[0.55,0.75]
A*	-0.05	**0.23**	0.22	0	[-0.23,0.13]	[0.05,0.39]
D*	0	**0.48**	0.48	0	[-0.18,0.18]	[0.33,0.61]

High Extension (V = H)	r_{Ji}	r_{Gi}	$p_{r_{Ji}}$	$p_{r_{Gi}}$	$\text{CI}_{r_{Ji}}$	$\text{CI}_{r_{Gi}}$
P*	0.07	-0.04	0.86	0.72	[-0.11,0.25]	[-0.22,0.14]
A*	0.07	**-0.23**	0.87	0	[-0.11,0.25]	[-0.39,-0.05]
D*	0.09	0.01	0.92	0.43	[-0.09,0.26]	[-0.17,0.19]

(c) Correlations for Low and High Activity. 120 samples per measure have been gathered.

Low Jerkiness (J = L)	r_{Vi}	r_{Gi}	$p_{r_{Vi}}$	$p_{r_{Gi}}$	$\text{CI}_{r_{Vi}}$	$\text{CI}_{r_{Gi}}$
P*	**0.33**	**0.28**	0	0	[0.16,0.48]	[0.11,0.44]
A*	**0.36**	0.03	0	0.33	[0.19,0.51]	[-0.15,0.21]
D*	**0.36**	**0.24**	0	0	[0.19,0.51]	[0.06,0.40]

High Jerkiness (J = H)	r_{Vi}	r_{Gi}	$p_{r_{Vi}}$	$p_{r_{Gi}}$	$\text{CI}_{r_{Vi}}$	$\text{CI}_{r_{Gi}}$
P*	**0.45**	**0.30**	0	0	[0.29,0.58]	[0.13,0.45]
A*	**0.51**	-0.02	0	0.62	[0.36,0.63]	[-0.20,0.16]
D*	**0.47**	**0.20**	0	0	[0.32,0.60]	[0.02,0.37]

(d) Correlations for Low and High Jerkiness. 120 samples per measure have been gathered.

Averted Gaze (G = L)	r_{Ji}	r_{Vi}	$p_{r_{Ji}}$	$p_{r_{Vi}}$	$\text{CI}_{r_{Ji}}$	$\text{CI}_{r_{Vi}}$
P*	0.02	**0.64**	0.59	0	[-0.16,0.20]	[0.52,0.73]
A*	0.03	**0.57**	0.68	0	[-0.15,0.21]	[0.44,0.68]
D*	0.07	**0.56**	0.86	0	[-0.11,0.25]	[0.42,0.67]

Direct Gaze (G = H)	r_{Ji}	r_{Vi}	$p_{r_{Ji}}$	$p_{r_{Vi}}$	$\text{CI}_{r_{Ji}}$	$\text{CI}_{r_{Vi}}$
P*	0.05	**0.12**	0.78	0.03	[-0.13,0.23]	[-0.06,0.29]
A*	-0.01	**0.28**	0.44	0	[-0.19,0.17]	[0.11,0.44]
D*	0.02	**0.28**	0.61	0	[-0.16,0.20]	[0.11,0.44]

(e) Correlations for averted and direct *gaze*. 120 samples per measure have been gathered.

PAD responses on the SAM scales capture this information.

The results of the user study demonstrate that emotions can be conveyed to the user as secondary tasks using the null space of a humanoid robot. But it is also necessary to point out that the mapping used to transform the emotional information to the kinematic features needs to be improved in order to convey the desired emotions with more accuracy. In this regard, we do not claim that the mapping is unique, nor that the one introduced in this work is the best. Efforts in this direction need to be made.

Another limitation of the proposed approach is a direct consequence of the complexity of the task and the number of DOF of the robot. For a relatively simple humanoid robot and a demanding task the dimensionality of the null space can be too low to convey the desired emotion. It is left for future work to test the proposed approach in other humanoid robots and other tasks. It could also be interesting to create a dynamic mapping, which could increase in complexity (for instance, incorporating more kinematic features) as the number of DOF available in the null space increases, thus providing a higher emotion conveyance accuracy.

The current implementation of the proposed solution also needs the user to be in the field of view of the robot, so that it can gaze him/her to convey dominance. This can be a limitation if the robot needs to stare at a specific location, i.e., an object for visual servoing.

All in all, interesting questions arise from this work:

- To what extent does the main task influence the user perception of the robot emotional state?
- How much is the emotion conveyance influenced by the number of DOF available on the robot?
- How can artificial *jerkiness* be created and properly executed by the robot? How will it be perceived by humans?
- Do more energetic motions better convey emotions? How many emotion dimensions (*pleasure*, *arousal*, etc.) can the robot simultaneously and successfully convey?
- To what extent does the user empathize with only the emotions conveyed by the robot body motions, rather than with motions and voice, for example?

7 Conclusions

A task priority null space approach that conveys emotions to the users as a secondary task has been presented. The approach allows the specification of a desired primary task in the Cartesian space and the use of the remaining DOF to convey a desired emotion to the user through the robot body motions. The emotions are defined as points in the *pleasure-arousal-dominance* space and a transformation from this space to the kinematic features *jerkiness*, *activity*, and *gaze* directness has been introduced. The proposed solution has been implemented in the Pepper robot and is easily extendible to any humanoid robot.

A user study has been conducted along with an analysis of the interactions between the robot emotional kinematic features and the PAD dimensions of the emotions perceived by the user.

To the authors knowledge this is the first work to explore these two aspects of emotion conveyance.

The results indicate that the null space is a promising mean to convey emotions and that the users do perceive emotions on the robot even when it is executing a primary task. *Happiness* and *sadness* can be successfully conveyed. An analysis of the data shows a positive correlation between *activity* and *arousal*, a non-statistically significant perception of *jerkiness*, and a conveyance of *dominance* when *activity* is low and *gaze* is directed towards the user. The study also shows that the Pepper robot is perceived as non dominant.

The contributions of this paper are:

- First use of the null space to convey emotions.
- An approach valid for the Pepper robot and easily extendible to other humanoid robots.
- An analysis of the interactions between motion features of the robot and the emotions conveyed to the user.

Further extensions of the proposed approach aim to close the gap between the current implementation presented in this work and the implementation in real world applications. In this regard, new studies on other robots with more complex main tasks, like manipulation of an object, or carrying a load cooperatively with a user, is a must. The adaptation of the proposed approach to industrial robots can also be an interesting research topic. A more efficient criteria for parameter tuning is desirable, too, and more user studies are necessary to assess the usability and comfortability of the user when he or she is co-working or cohabitating with the robot.

Future work will also include a deeper understanding on the role of *jerkiness* and a more complex map between the PAD space and the kinematic features, which could be addressed using a learning approach. Future studies might evaluate the usability of the framework and comparison with users with intellectual disabilities or autism.

Appendix 1

The emotional conveyance algorithm: task priority proof

Following the work in [14] and [5], a proof of the task prioritization of the proposed solution is shown below, that is, that the execution of the lower priority tasks does not affect the execution of the higher priority tasks.

The next identities will be used:

$$AA^+A = A \tag{9}$$

where A^+ is the pseudoinverse of A.

Given an idempotent matrix B, that is, $B = B^2$; and Hermitian, $B = B^*$ in general, with B^* the conjugate of B, and $B = B^T$ in particular for this work, then

$$B(AB)^+ = (AB)^+ \tag{10}$$

Given a matrix C, then $D = I - C^+C$ is the orthogonal projector onto the kernel of C, thus idempotent and Hermitian. So, in light of (10):

$$(AD)^+ = D(AD)^+ \tag{11}$$

Given a task x_i of the robot defined as a function of its configuration q:

$$x_i = f_i(q)$$

differentiating and applying the chain rule,

$$\dot{x}_i = \frac{\partial x_i}{\partial t} = \frac{\partial f_i(q)}{\partial t} = \frac{\partial f_i(q)}{\partial q}\frac{\partial q}{\partial t} = J_i\,\dot{q}$$

a mapping between the velocity of task i and the joint velocities is obtained.

Similarly, the differential mapping of the main task t, as defined in Sect.3.4, becomes $\dot{x}_t = J_t\,\dot{q}$. The joint velocities $\dot{q}$ as defined in this work in (8) are:

$$\dot{q} = J_t^+ e_t + P_t\,J_h^+ e_h + \left[P_t - (J_h P_t)^+ (J_h P_t)\right] e_m \quad (12)$$

thus substituting (12) them in $x_t = J_t\,\dot{q}$ it is obtained:

$$\dot{x}_t = J_t\,\left\{J_t^+ e_t + P_t\,J_h^+ e_h + \left[P_t - (J_h P_t)^+ (J_h P_t)\right] e_m\right\}$$

Using (11) in $(J_h P_t)^+$ and rearranging terms the expression can be transformed to

$$\dot{x}_t = J_t\,J_t^+ e_t + J_t\,P_t\,\left\{J_h^+ e_h + \left[I - (J_h P_t)^+ (J_h P_t)\right] e_m\right\}$$

and now using (9) in $J_t\,P_t$ as:

$$J_t\,P_t = J_t\left(I - J_t^+ J_t\right) = J_t - J_t J_t^+ J_t = J_t - J_t = 0$$

becomes $\dot{x}_t = J_t\,J_t^+ e_t$. This expression shows that the emotional tasks h and m do not affect the execution of the main task t.

Similarly for the task h corresponding to the *gaze*:

$$\dot{x}_h = J_h\,\left\{J_t^+ e_t + P_t\,J_h^+ e_h + \left[P_t - (J_h P_t)^+ (J_h P_t)\right] e_m\right\} =$$
$$= J_h\,J_t^+ e_t + J_h\,P_t\,J_h^+ e_h + J_h\,\left[P_t - (J_h P_t)^+ (J_h P_t)\right] e_m$$

which using (10) and (9)

$$J_h\left[P_t - (J_h P_t)^+ (J_h P_t)\right] = J_h\left[P_t - P_t (J_h P_t)^+ (J_h P_t)\right] =$$
$$= J_h P_t - (J_h P_t)(J_h P_t)^+ (J_h P_t) = J_h P_t - J_h P_t = 0$$

becomes $\dot{x}_h = J_h\,J_t^+ e_t + J_h\,P_t\,J_h^+ e_h$. In this expression it can be seen that the second priority task h is only affected by the higher priority task t.

Appendix 2

Implementation values

The angular velocity ω in (3) has been set to $\omega = 2.79$ rad/s. One term has been used in (5) with $n_J = 1$, $a_1 = b_1 = 0.25$ rad and $\omega_1 = 12.57$ rad/s.

Following the convention of Sect.2 the values Θ_{0_i}, $\Theta_{E_{0i}}$ and h_i implemented in (3) can be seen in Table 4.

Table 4 Implemented values in radians

Joint i	Θ_{0_i}	$\Theta_{E_{0i}}$	h_i
Knee Pitch	0.50	0	0
Hip Pitch	0.50	-0.05	0
Hip Roll	0	0	0
Head Yaw	0	0	0
Head Pitch	0.64	-0.30	0
Right Shoulder Pitch	0.90	1.57	0
Right Shoulder Roll	-0.30	-0.85	0.45
Right Elbow Yaw	0	1.50	0.70
Right Elbow Roll	1.10	0.10	0.30
Right Wrist Yaw	1.00	1.15	-0.20
Left Shoulder Pitch	0.90	1.57	0
Left Shoulder Roll	0.30	0.85	0.45
Left Elbow Yaw	0	-1.50	-0.70
Left Elbow Roll	-1.10	-0.10	-0.30
Left Wrist Yaw	-1.00	-1.15	0.20

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Josep-Arnau Claret is a Ph.D. student at the Technical University of Catalonia (UPC) in Barcelona, in the Institute of Industrial and Control Engineering. He received his Masters Degree in Automatic Control and Robotics from the UPC. His current research interests are teleoperation, human robot interaction, robot kinematics and dynamics, mobile manipulators and UAVs.

Gentiane Venture is a French Roboticist who has been working in academia in Tokyo, Japan for more than 10 years. After graduating from Ecole Centrale de Nantes and obtaining a Ph.D. from University of Nantes in 2000 and 2003 respectively, she worked at the French Nuclear Agency and at the University of Tokyo. She started in 2009 with Tokyo University of Agriculture and Technology where she has established the GVlab, an international research group working on human science and robotics. Her research tries to encompass human motion dynamics and non-verbal communication into complex intelligent robot behavior design to achieve personalized human machine interaction. The work of her group is highly interdisciplinary by collaborat-

ing with therapists, sociologists, psychologists, physiologists, philosophers, ergonomists, bio-mechanists, designers worldwide

Luis Basañez received the Ph.D. degree in Electrical Engineering from the Technical University of Catalonia (UPC), Barcelona, Spain, in 1975. From 1986 to 2014 he was a full professor of System Engineering and Automatic Control at the UPC where nowadays he is an Emeritus Professor. From 1976 to 1987 he has been vicedirector of the Institute of Cybernetics (UPC) and from 1987 to 1990, director of this institute. From 1999 to 2003 he has been deputy director of the Institute of Industrial and Control Engineering (IOC) of the UPC. He served as a member of the Executive Committee of the International Federation of Robotics (IFR) from 1987 to 1992, and now he is the Spanish delegate at the IFR. In 2005 he was appointed a fellow of International Federation of Automatic Control (IFAC) and from this year until 2011 he has been member of the IFAC Council. His present research interest includes teleoperation, multirobot systems coordination, task planning, sensor integration and active perception.