Design and validation of two embodied mirroring setups for interactive games with autistic children using the NAO humanoid robot

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Abstract— **Socially assistive robots have shown potential benefits in therapy of child and elderly patients with social and cognitive deficits. In particular, for autistic children, humanoid robots could enhance engagement and attention, thanks to their simplified toy-like appearance and the reduced set of possible movements and expressions. The recent focus on autism-related motor impairments has increased the interest on developing new robotic tools aimed at improving not only the social capabilities but also the motor skills of autistic children. To this purpose, we have designed two embodied mirroring setups using the NAO humanoid robot. Two different tracking systems were used and compared: Inertial Measurement Units and the Microsoft Kinect, a marker-less vision based system. Both platforms were able to mirror upper limb basic movements of two healthy subjects. However, despite the lower accuracy, the Kinect-based setup was chosen as the best candidate for embodied mirroring in autism treatment, thanks to the lower intrusiveness and reduced setup time. A prototype of an interactive mirroring game was developed and successfully tested with the Kinect-based platform, paving the way to the development of a versatile and powerful tool for clinical use with autistic children.**

I. INTRODUCTION

Autism Spectrum Disorder (ASD) is a complex neurodevelopmental syndrome, with a global prevalence of 1 in 160 children [1]. ASD symptoms vary in severity and nature; yet, a symptomatic triad is usually present: poor social interaction skills, communication deficit and presence of repetitive behaviours. Treatments tend to focus on the first symptom, trying to develop the social capabilities of patients [2]. However, recent studies demonstrate that not just the social skills are affected in ASD children, but also some motor problems are reported, namely in relation to the praxis of the movement [3]. This also influences the imitative skills. Recent studies have shown that motor, imitation and social skills deficits are related, leading to an increasing interest in the recovery of motor and imitation problems in ASD patients [1]. In this scenario, robots can be useful tools for improving both motor and interaction skills. The advantages of using robots are multi-fold. On one hand, autistic children are very prone to technology, on the other hand, robots have specific features that ASD children appreciate. For example,

they have repetitive actions, represent a stable environment and (especially) humanoid robots have stylized human expressions, easier to be interpreted by an autistic child [2]. Robots have been already used in the treatment of autism as interactive or educational toys, raising positive reactions and increased engagement [4]. It would be important to transform them into "embodied mirrors", recruiting imitation neural circuits and thus using mirroring as a form of motor training [5]. In addition, when compared with virtual reality scenarios, robots induce a stronger effect on spontaneous imitation [6]. Therefore, robots can strongly enhance the impact of motor and imitation training.

To develop embodied mirroring platforms with humanoid robots, three steps are needed: measuring the human movements, mapping the measurements to the robot reference frame and, finally, control the robot motion. For capturing human movements, wearable sensors and marker-less vision based devices are the main options described in literature [7]. Among wearable sensors, Inertial Measurement Units (IMUs) are the most accurate and widely used technology. For tracking human movements, they require to be attached to different body segments and to measure the rotation angles between them. Instead, marker-less vision based devices rely on cameras that are able to reconstruct the 3D position of different body joints [8]. An example of such devices available on the market is the Microsoft Kinect. In its second version, the Kinect detects 2D positions of points and then uses a time-of-flight camera to calculate their depth, based on the difference of phase between an emitted and a reflected modulated signal. In the current work, two embodied mirroring setups were developed, using the two motion capture systems, as described above, and a humanoid NAO robot, which has already been used successfully for rehabilitation and neurorobotic applications [9]. A systematic comparison between the two setups was performed to evaluate the impact of using different sensors/technologies for acquiring body motion in the context of embodied mirroring for rehabilitation, taking into account usability features of the final system. Lastly, a possible protocol for an embodied mirroring game, with the Kinect, was tested, demonstrating its potential as an interactive tool in therapies for ASD children.

II. METHODS

A. Description of the setup

A NAO robot from Aldebaran Robotics [10] was used for the embodied mirroring platform. NAO is a humanoid robot with 25 Degrees of Freedom (DOF), and endowed

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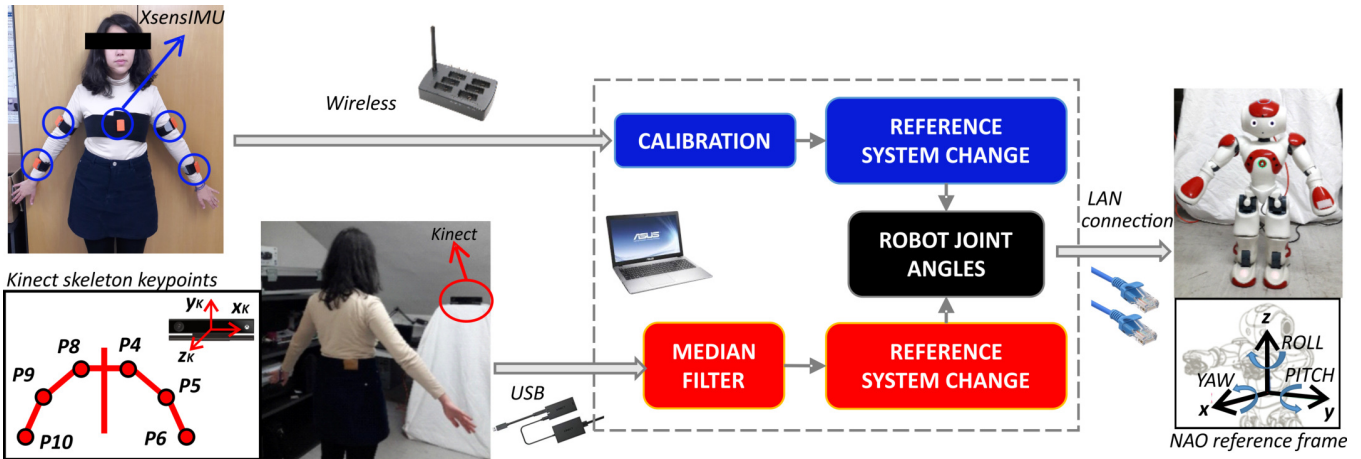
Fig. 1: Block diagram of the embodied mirroring setups based on Inertial Measurement Unit (IMU) (top - blue) and Kinect (bottom - red) tracking systems.

with sensors, LEDs and loudspeakers for interaction with the environment. We focused on movements of the upper limbs and chose to control 3 DOF for each limb: Shoulder Roll, Shoulder Pitch and Elbow Roll. Therefore, the basic allowed movements were: flexion/extension, abduction/adduction, lateral abduction/adduction of the shoulder and flexion/extension of the elbow. To track the subject movements, two systems were compared: one based on IMUs and one using the Microsoft Kinect. The subject was standing in front of NAO during the exercise. For the mirroring action, the subject's joint angles were extracted with the two tracking technologies, and provided as control signals to the NAO robot, see (Fig. 1).

B. Inertial Measurement Units

For the setup based on IMU, five motion tracking sensors from XSens Technologies were used. They were positioned on the upper limbs and chest as shown in Fig. 1. Signals form the sensors were acquired at 45 Hz. During calibration, the subject was standing, while keeping a forward flexion of both shoulders. Sensor orientation was computed with respect to the reference frame of the IMU on the chest ($^{chest}R_s$). Then, the NAO control system reference signals were computed as the angles between limb segments, moved from the chest IMU (*chest*) to the NAO reference frame (*NAO*) (1).

$$^{NAO}R_s = {}^{NAO}R_{chest} \cdot {}^{chest}R_s \qquad (1)$$

Due to higher accuracy than the Kinect, this system was used as the *gold standard* reference for motion tracking signals.

C. Kinect

With the Microsoft Kinect, the 3D coordinates of 8 upper-limb keypoints were obtained at a frequency of 30 Hz. The signals were filtered with a median filter (5-sample window), for noise reduction. Then, two rotations were applied, one around the y-axis and one around the x-axis, to align the Kinect coordinate frame to the NAO reference frame. In the new reference frame, the shoulder joint movements were

given by the angle between the arm and the z-axis (lateral abduction/adduction) and y-axis (abduction/adduction); the elbow flexion/extension was calculated from the angle between the arm and the forearm. The vectors representing the arms ($\mathbf{P_{4-5}}$ and $\mathbf{P_{8-9}}$) and forearms ($\mathbf{P_{5-7}}$ and $\mathbf{P_{9-10}}$) were obtained from the 3D coordinates. Then, the angle between two vectors was given by 2. The resulting angles (Table I) were used as control signals for the robot.

$$angle = \arccos\left(\frac{\mathbf{a} \cdot \mathbf{b}}{\|\mathbf{a}\| \, \|\mathbf{b}\|} \right) \qquad (2)$$

TABLE I: Shoulder and Elbow angles calculation with a Kinect

Angles	a	b
Right Shoulder Lateral Abduction/Adduction	$\mathbf{P_{8-9}}$	$-\mathbf{z}$
Right Shoulder Abduction/Adduction	$\mathbf{P_{8-9}}$	$-\mathbf{y}$
Right Elbow Flexion/Extension	$\mathbf{P_{8-9}}$	$\mathbf{P_{9-10}}$
Left Shoulder Lateral Abduction/Adduction	$\mathbf{P_{4-5}}$	$-\mathbf{z}$
Left Shoulder Abduction/Adduction	$\mathbf{P_{4-5}}$	$\mathbf{y}$
Left Elbow Flexion/Extension	$\mathbf{P_{4-5}}$	$\mathbf{P_{5-6}}$

D. Comparison between two tracking systems

The basic test protocol included five acquisitions of three reference movements between a starting and a target angular position: lateral abduction/adduction (from 0 to -π/2 rad) and abduction/adduction (from π/2 to -π/3 rad) of the shoulders, flexion/extension (from 0 to π/2 rad) of the elbows. These movements were chosen to test different joints and planes, and repeated three times for each acquisition. For comparison purposes, the protocol was used with two healthy subjects (an adult and a 11-year-old child) being tracked by the IMU and the Kinect at the same time. Due to different sampling frequencies, the Kinect signal was re-sampled and aligned to the IMU signal, based on the maximum value of the their correlation. Then, the Root Mean Square Error (RMSE) between the two signals was calculated. The adult and the child's legal guardians gave their informed consent prior to

the acquisitions. Finally, with the aim of using the platform for clinical applications, also other features were taken into account, including intrusiveness, cost and flexibility.

E. Kinect-based embodied mirroring game

Thanks to the flexibility of the Kinect-based system, an example of a turn-taking imitation game was designed and implemented with the NAO, including four phases: (i) NAO demonstrating a reference movement and asking a first subject to repeat it; (ii) the first subject doing the movement while the NAO is mirroring him; (iii) NAO asking a second person to repeat the movement; (iv) the second subject doing the reference movement while NAO is mirroring him.

The imitation game was tested during the same reference movements as in Section II.D. with the same subjects, in view of clinical applications with a therapist and a child. For each movement, the angles of the most significant joint were plotted along the whole acquisition time.

III. RESULTS

The developed embodied mirroring platforms were able to successfully mimic basic movements of the upper limbs of healthy subjects. The two motion tracking systems exhibited different advantages and disadvantages in terms of accuracy and flexibility. The Kinect-based setup was chosen as the best candidate for clinical applications with autistic children, and used in the first prototype of an interactive mirroring game.

A. Validation of the IMU-based setup

The IMU-based system requires estimating the rotation matrices between each sensor and the NAO coordinate frame. We verified that the correlation between NAO control signals extracted from IMU data during two acquisitions with different sensor positioning was close to 1 (0.87 shoulder abduction/adduction, 0.92 for elbow flexion/extension), for all movements. This demonstrates the method's robustness to IMU wrong placement and trunk movements during exercise.

B. Comparison between two tracking systems

We took the IMU tracking system as the baseline, *gold standard*, due to its higher accuracy and lower angular errors with respect to the Kinect. Figure 2 and Table II show that the Kinect-based platform was able to mirror the subject movements with acceptable errors, compared to IMU [11]. Moreover, the cross-correlation between the Kinect and IMU signals was above 0.85 for all tested movements. In view of clinical applications with ASD children, other features of the setup were evaluated. The Kinect-based system was less intrusive, did not need any setup/calibration time and allowed recording more people at the same time, without increasing the costs. As a result, the Kinect system was chosen as the best candidate for our purposes.

C. Testing of the embodied mirroring game

Exploiting the capability of the Kinect-based setup to track more than one person simultaneously without increasing costs, computational load and system transparency, a first prototype of the interactive mirroring game was tested.
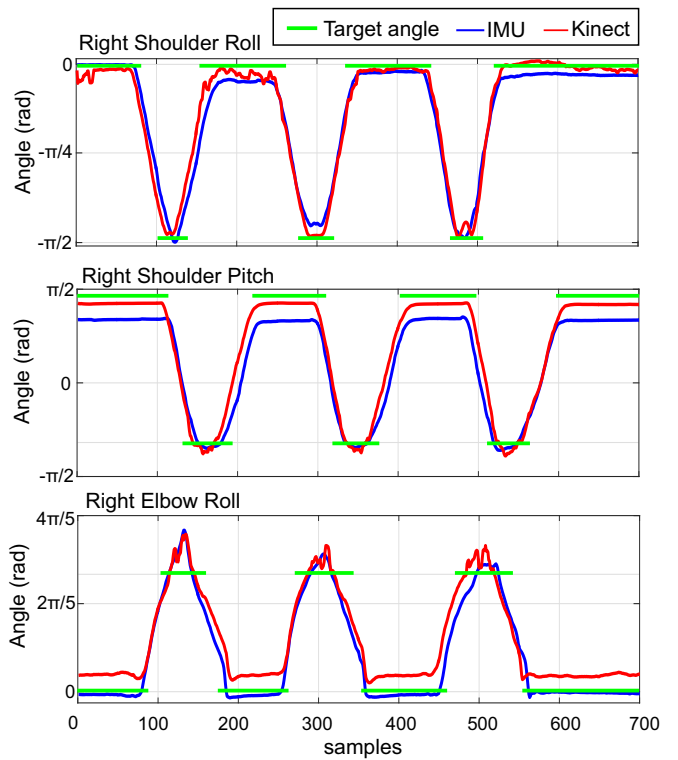

Fig. 2: Comparison between NAO control signals obtained with the two tracking systems during one example acquisition with the 3 movements of the adult left upper limb, to reach constant target angles (green lines).

TABLE II: RMSE and cross-correlation between IMU and Kinect-based control signals for the adult and the child. Values are reported as mean±SD (Standard Deviation).

Movements	RMSE (rad)		Cross-Correlation	
	Adult	Child	Adult	Child
Lateral Abduction/ Adduction shoulder	0.23±0.12	0.41±0.19	0.94±0.06	0.85±0.19
Abduction/ Adduction shoulder	0.35±0.07	0.41±0.04	0.96±0.03	0.96±0.02
Flexion Extension elbow	0.31±0.10	0.30±0.19	0.94±0.04	0.91±0.13

During the session, two subjects were successfully mirrored by the NAO robot, while executing upper limb movements, which were first shown by the robot (Fig. 3). The NAO robot mediated the interaction, leading the turn-taking phases.

IV. DISCUSSION AND CONCLUSIONS

We developed and tested an embodied mirroring setup for therapy sessions with ASD children, to improve motor and social skills. Over the last decades, robotic applications have been developed for patients with motor, social and cognitive impairments, in order to facilitate their participation and engagement during therapy [12][13]. Assistive robots have been used as coaches, teachers or assistants in daily life [14]. Several studies have focused on the appearance and features that a robotic setup should have, to facilitate the interaction with patients. Particularly for ASD children,
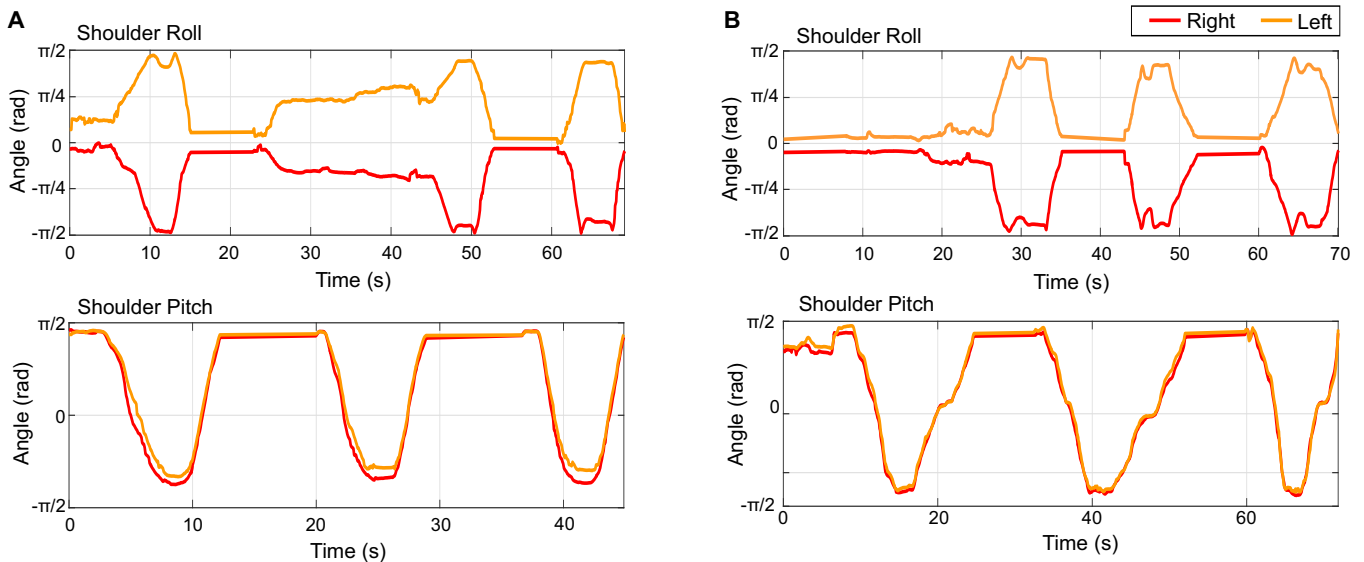
Fig. 3: Example NAO control signals in the interactive mirroring game with the two subjects, during execution of shoulder lateral abduction/adduction (top panels) and abduction/adduction (bottom panels) by the adult (A) and child (B).

humanoid, child-sized and stylized robots are recommended, and non-intrusiveness and ease of setup are key [2].

The link between social and motor deficits in autism suggest that therapies should be targeted at the improvement of both skills [3]. The platform we developed is suitable for embodied mirroring games with ASD children for several reasons: (i) the NAO robot's features perfectly match the above-cited requirements, and (ii) the Kinect tracking system successfully allowed to mirror the subject movements properly. With respect to the more accurate IMUs, the Kinect-based system has a much smaller setup time, avoiding sensor placing and calibration time, and is non intrusive. The proposed protocol for interactive games also suggests that the embodied mirroring setup has a strong potential for improving patient's social skills, and mediating the interaction between two people. Future work includes the design of a feedback system, exploring NAO interactive elements, to guide the execution of movements and increase motivation and engagement. In order to focus also on cognitive skills, the movements will be contextualized within a semantic framework/narrative. The final setup should be versatile and easy to use by therapists/clinicians. Systematic tests with patients will be needed to improve and eventually use the setup as therapeutic tool together with traditional exercises and games.

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