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Fall Detection and Management in Biped Humanoid Robots

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Abstract— **The appropriate management of fall situations – i.e. fast instability detection, avoidance of unintentional falls, falling without damaging the body, fast recovering of the standing position after a fall - is an essential ability of biped humanoid robots. This issue is especially important for humanoid robots carrying out demanding movements such as walking in irregular surfaces, running or practicing a given sport (e.g. soccer). In a former contribution we have addressed the design of low-damage fall sequences, which can be activated/triggered by the robot in case of a detected unintentional fall or an intentional fall (common situation in robot soccer). In this article we tackle the detection of instability and the avoidance of falls in biped humanoids, as well as the integration of all components in a single framework. In this framework a fall can be avoided or a falling sequence can be triggered depending on the detected instability's degree. The proposed fall detection and fall avoidance subsystems are validated in real world-experiments with biped humanoid robots.**

I. Introduction

BIPED humanoid robots carrying out demanding movements such as walking in irregular surfaces, running or practicing a given sport are prone to fall down, due to their inherent instability. In view of the current development of humanoid robotics, it seems necessary to developed strategies for the management of falls situations, instead of limiting the kind of movements that biped humanoid robots perform.

To illustrate these ideas, let us analyze the humanoid soccer robotics case. In soccer, as in many other sports that allow contact among players, it is usual that players fall down, as consequence of fouls, collisions with other players or objects, or extreme body actions, such as fast movements or ball kicks from unstable body positions. In addition, soccer players can intentionally fall down to block the ball trajectory (defense player) or to gain control of the ball (goalkeeper). Therefore, we can affirm that in soccer, as in many other sports, one of the essential ability of good players, humans or humanoids, is the appropriate management of fall situations – i.e. fast instability detection, avoidance of unintentional falls, falling without damaging the body, and fast recovering of the standing position after a fall.

Given that one of the main goals of humanoid robotics is to allow robots to behave and move as humans do, the correct management of fall situations in humanoid robots is a very relevant matter. However, to the best of our knowledge this issue has not been addressed properly yet, although some interesting work have been developed in the last years related to the detection of unstable situations [1]-[6], and the design of low-damage fall sequences [7]-[10].

The study of human falls (medical studies, biomechanics, martial arts, human dynamics simulation) provides some insights on how fall are managed by humans [10]: (i) human musculoskeletal systems has the capacity of absorbing the energy of impacts, thus reducing the damage of falls, (ii) when detecting falls, humans make extensive uses of fall-managing strategies to avoid the fall or to reduce the fall damage, and in some cases use limbs to shift the fall impact to less important organs or bones, and (iii) as done in martial arts, if the person can predict a fall, then he/she can take control of the fall and change it into a fluid movement that helps to dissipate energy and/or quickly recover the desired behavior.

Thus, fall management in biped humanoid robots should be tackle from an integrated point of view, considering the following elements:

(i) Robot design. Robot bodies should passively help as much as possible to avoid fall damage. Passive techniques include padding and the use of protections.

(ii) Instability Detection. Falls need to be detected as soon as possible to have sufficient time to manage them.

(iii) Fall Avoidance. After instability detection, a fall can be avoided by feedback control or by reflexes. A reflex corresponds to a pre-calculated sequence of motions that requires the abortion of the current activity (e.g., walking). If in a given situation both mechanisms can be used to avoid a fall, feedback control should be preferred because it does not interrupt the current task.

(iv) Fall management. In case a fall cannot be avoided or in case of an intentional fall, a falling sequence can be triggered with the purpose of reducing the body- damage, or even for fast recovering of the standing position after a fall.

In a former contribution we have addressed the design of low-damage fall sequences [10], which can be activated/triggered by the robot in case of a detected unintentional fall or an intentional fall. In this article we tackle the detection of instability and the avoidance of falls in biped humanoids, as well as the integration of all components in a single framework. In this framework a fall can be avoided or a falling sequence can be triggered

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depending on the detected instability's degree.

We focus on managing instabilities produced by external disturbances such as external forces produced by collisions with other robots or objects, foot slippage or irregular surfaces (e.g., steps), instead of on the gait stabilization problem that usually deals with instabilities produced by the gait itself (e.g., oscillations).

This article is structured as follows. In section II some related work is analyzed. Section III describes the humanoid robot used in our experiments. In Section IV and V the proposed fall detection and fall avoidance subsystems are described and validated in real world-experiments. Finally, in section VI some conclusions of this work are given.

II. Related Work

A. Fall Detection while Walking

Instability detection produced by disturbances such as external forces (e.g., collisions), foot slippage or irregular surfaces have been addressed only in the last few years (e.g., [2][5][6]).

In [5] a dynamical instability indicator for walking situations, which compares the sensor measurements with a sensor model, is built. The sensor model depends of the gait speed, and it corresponds to the low-frequency coefficients of the sensor measurements in simulated walking situations. The trunk attitude and its derivative in the lateral and sagittal planes are used as sensor measurements. The system is evaluated in simulations and using a real robot.

In [6] two techniques for the detection of falls when the humanoids are walking steadily are proposed. Sensor data is composed by the linear acceleration measurements in x, y and z, the angular velocities in x and y, the ZMP´s x and y values, and the reference center of gravity trajectories in x and y, corrected by feedback control. In the first method, the degree of deviation from a normal state, defined as the statistical average of sensor data obtained from stable walking training-samples, is measured. Falls in some cases cannot be detected because of the difficulty to set appropriate thresholds. This drawback is fixed by the use of discriminant analysis to reduce the dimension of the sensor data to one dimension, previously to the measurement of the degree of deviation from the normal state.

In [2] instability detection is addressed as a pattern classification problem. The feature vector is composed by measurements from four force sensors, inertial measurements of the robot's trunk (attitude and its derivative in the lateral and sagittal planes), inertial measurements of the robot's feet (attitude and its derivative in the lateral and sagittal planes), and phase information. The feature vector components are normalized, and its dimension is reduced using PCA. In both cases the parameters are estimated using training data. A GMM and a HMM classifier are used for classification. Better results are obtained by the use of the GMM.

In the here-proposed work, offline models of the sensor measurements, as in [2][5][6], are not used. Instead, direct comparisons between smoothed attitude measurements and joint angles (lateral plane), and comparisons between attitude measurements and on-line models (sagittal plane) are employed. Main reasons for this decision are the need of fast instability detections, and non-dependency of gait parameters (gait models and gait speed).

B. Fall Avoidance and Management

Fall avoidance using simple mechanisms has been addressed. For instance, in [5] two type of reflexes are proposed: in case of a small instability the robot just slow down, while in case of a large instability the robot stops and lower its center of mass. In [2] reflex steps are used to avoid the fall, and crouching mechanisms are employed when a fall is unavoidable.

In the case that falls cannot be avoided, it is necessary to have mechanisms that allow to reduce the fall damage. Martial arts have addressed the issue of controlled falling with low body-damage long time ago. Falling techniques (e.g. *ukemi*[1]) produce a sequence of movements that vary the geometry of the human body in order to lower the force of the impacts, and spread the kinetic energy transfer through a wider contact area, a longer lapse of time, and limb movements. Moreover, some of these techniques are designed to allow the fighter to move away from the attacker and prepare himself to continue the combat by quickly recovering an upright stance. Some works of Japanese researchers have designed robot fall sequences based on *ukemi* motions [8][9][6]. Fujiwara analyzed falling situations from a standing position, and reduced the robot body damage by contracting and expanding the body length [8][9]. In [6] this approach is extended to the case of robot falling while walking. Basically, a Linear Inverted Pendulum Mode is used to generate a motion of the robot center of gravity, and to produce the *ukemi*-like motions.

In [10] a more formal approach to fall management is proposed, and a methodology for the design of low-damage fall sequences that takes into account joint's injuries and the protection of valuable robot parts, is proposed. This approach is used in this paper. In [10] is proposed a falling strategy that modifies the robot's falling direction in order to avoid hitting a person or object placed in the robot vicinity.

Finally, it is worth to mention that in some works very small or not fully humanoid robots are used in the experiments (e.g., [2][6]). As in [5][8][9], in this work a full humanoid robot, 52 centimeters high, is used.

III. Robot Description

In this research our UCH H1 biped humanoid robot was employed. The robot height is 526 mm, it weights 3.04kg, and it has 22 DOF controlled by Dynamixel RX-28 servomotors. The high-level control of the robot run on a PICO820-Z530 PC card (Intel Atom 1.6GHz processor)

[1] Breakfalls used in judo and other Japanese martial arts to avoid injury when being thrown. In some contexts the term *ukemi* is also used as "practice of falling" or "falling safely".

[11], and the motor and sensors are controlled by a custom controller (32 bit DSP TMS320F28335 150 MHz). As attitude sensors we use the IDG-300 dual-axis gyroscope (full-scale range +/- 500 °/s), and the ADXL330 3-axis accelerometer (measurement range +/- 3g). The gyroscopes are read every 140 Hz, while the accelerometers at 550 Hz.

IV. Fall Detection And Avoidance

A. VAT - Virtual Attitude Sensor

The robot's truunk attitude (ϕ) and its derivative ($\dot{\phi}$) are computed in the lateral and sagittal planes by combining the accelerometer and gyroscope measurements using a standard linear Kalman filter. The output of the Kalman filter is considered as a single virtual attitude sensor (VAT).

The state vector $x \in \Re^2$ corresponds to the robot attitude and the gyroscope bias *b*, $x = [\ \phi \ \ b\ ]^T$. According with the standard Kalman procedure the updated state vector $x_k^- \in \Re^2$ and the estimation error covariance matrix $P_k^- \in \Re^{2x2}$ are given by:

$$\begin{aligned} x_k^- &= A x_{k-1} + B u_{k-1} \\ P_k^- &= A P_{k-1} A^T + S_w \end{aligned} \tag{1}$$

with

$$A = \begin{pmatrix} 1 & -\Delta t \\ 0 & 1 \end{pmatrix}; B = \begin{pmatrix} \Delta t \\ 0 \end{pmatrix}, \tag{2}$$

and u_k the gyroscope angular rate measurement in time step *k*, Δt the reading period, and S_w the error covariance matrix of the model. Then, the Kalman gain is then computed as:

$$K_k = P_k^- C^T (C P_k^- C^T + S_v)^{-1} \tag{3}$$

and the attitute estimation and its covariance matrix are computed as:

$$\begin{aligned} x_k &= x_k^- + K_k (z_k - C x_k^-) \\ P_k &= (I - K_k C) P_k^- \end{aligned} \tag{4}$$

with z_k a smothed measurement of the accelerometer, S_v the error covariance matrix of the observations, and

$$C = [\ 1 \quad 0\ ], \tag{5}$$

Finally, the attitude derivative is given by

$$\dot{\phi}_k = u_k - b_k . \tag{6}$$

The covariance matrices are obtained by sensor characterization.

B. Fall Detection while Standing Still

Fall detection from a standing position seems to be a trivial problem, but that should be incorporated in the integral fall management strategy. For instance, in robot soccer it is very frequent that a player will be collided by other players. Similar situations can arise in other contexts where large interaction between humanoids or with humans will be allowed.

In the lateral and sagittal planes instabilities are measured independently, by thresholding the trunk's attitude and trunk's attitude derivative computed by the VAT. Thus, robot instability will be detected if one of the following conditions is satisfied:

$$\begin{aligned} \|\phi_p\| &> att_{s,p} \\ \|\dot{\phi}_p\| &> att\_d_{s,p} \end{aligned} \tag{7}$$

with $\phi_p / \dot{\phi}_p$ the trunk's attitude/attitude derivative in the *p* plane (lateral or sagittal), and $att_{s,p} / att\_d_{s,p}$ the corresponding threshold values. The subscript *s* stands for standing position.

C. Fall Detection while Walking

In the lateral plane instability is detected by comparing trunk's attitude measurements in the lateral plane and the roll angles of the ankles. We empirically observed that while the robot is walking, the roll angle of each ankle is correlated with the trunk's attitude in the lateral plane, and that the composed angle of the ankle (θ_{ankle}), computed as the scaled sum of both roll angles, is very similar in frequency and amplitude to the attitude in the lateral plane (ϕ_x), existing just a delay between both signals. For instance, in the example shown in fig. 1, the correlation index between $\phi_x(t)$ and $\theta_{ankle}(t)$ is 0.9125.

The composed angle of the ankle is defined as

$$\theta_{ankle}(t) = \alpha \left(\theta_{ankle,l}(t-1) + \theta_{ankle,r}(t-1) \right) \tag{8}$$

with α a scaling factor.

Thus, the robot instability in the lateral plane can be detected if the smoothed difference between the attitude in the lateral plane and the composed angle of the ankle is larger than a given threshold $att_{w,x}$, or if the attitude derivative in the lateral plane is larger than a threshold $att\_d_{w,x}$:

$$\begin{aligned} \| f_{smooth} \ (\phi_x - \theta_{ankle} \ )\| &> att_{w,x} \\ \|\dot{\phi}_x\| &> att\_d_{w,x} \end{aligned} \tag{9}$$

with f_{smooth} a simple smoothing, i.e. low-pass, function.

In the sagittal plane the attitude angle and its derivative change continuously, depending on the gait smoothness and speed. Therefore fixed threshold values cannot be used to detect instabilities, the number of false detections is too high. We were also not able to find some relationship between these sensor measurements and joint angles. Considering that one of our goals was not using offline models of the sensor measurements, and therefore to be gait independent, we decide to build on-line models of the attitude and the attitude derivative in the sagittal plane. Both variables are modeled as Gaussian functions, and instability is detected as the distance of the current measurements and the on-line models.

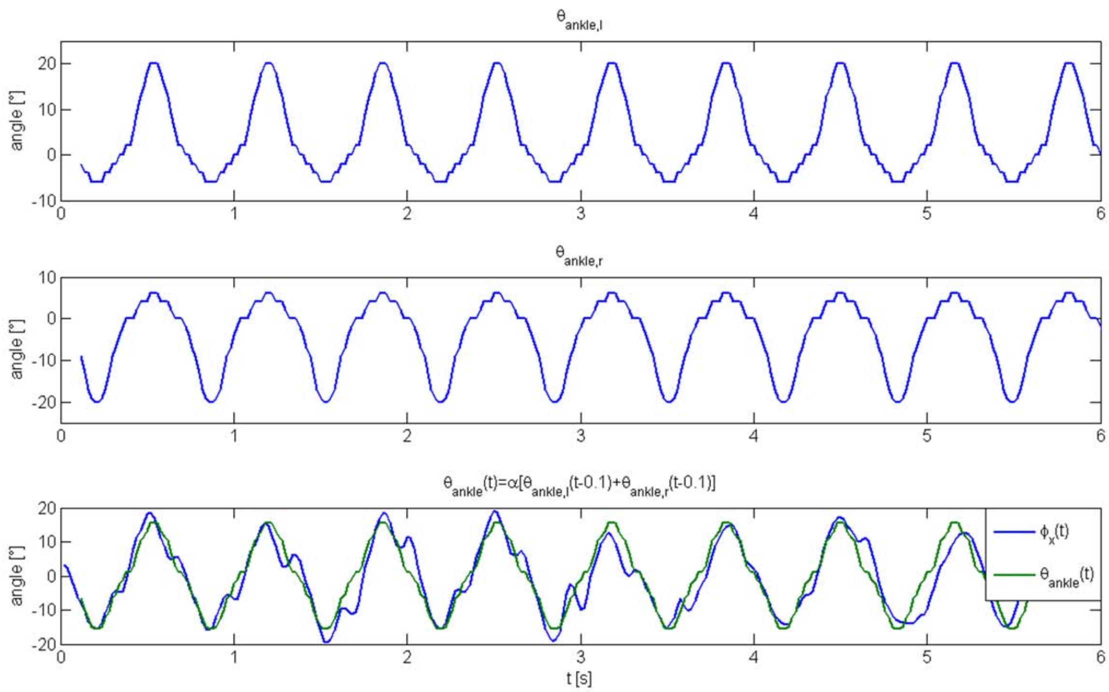

Fig. 1. First/second rows: Left/right roll angle of the ankle $\theta_{ankle,l}(t)\,/\,\theta_{ankle,r}(t)$. Third row: Composed roll angle of the ankle $\theta_{ankle}(t)=\alpha\left(\theta_{ankle,l}(t-1)+\theta_{ankle,r}(t-1)\right)$ (in green), and attitude angle (in blue). The correlation between these two signals is 0.9125.

Thus, robot instability is detected if one of the following conditions is satisfied:

$$\begin{aligned} \left\|\phi_y-\overline{\phi_y}\right\| &> k_1\sigma_{\phi,y} \\ \left\|\dot{\phi}_y-\overline{\dot{\phi}_y}\right\| &> k_2\sigma_{\dot{\phi},y} \end{aligned} \qquad (10)$$

with k_1 and k_2 scaling parameters.

D. Fall Avoidance and Management

When a low instability is detected in the sagittal plane, feedback control of the tilt angles of the ankles is employed. In case of a larger instability detected in the sagittal plane while standing, the center of mass of the robot is lowered until stability is achieved. If the same situation is detected while walking, the robot stops walking, and at the same time it lowers its center of mass. Stop walking in the single support phase, means completing the step, and lowering the center of mass in the double support phase. When instability is detected in the lateral plane, same fall avoidance mechanisms are employed, except that in this case feedback control is not used.

In case of detecting large instabilities that cannot be compensated by feedback control or special reflex movements (stopping or lowering de center of mass) a falling sequence is triggered. We use the low-damage falling sequences that we have designed with the methodology proposed in [10]. These sequences correspond to preprogrammed series of movements that reduce the damage in the robot's joints produced by the fall impacts, and protect valuable robot parts (e.g., the head). The sequences have been already validated in simulations and in the UCH H1 humanoid robot (see falling sequences description and validation in [10]):

- *FrontLow*: Frontal fall sequence where the robot folds its legs in order to lower its center of mass before the impact.
- *FrontTurn*: Frontal fall sequence where the robot turn its body before touching the ground. This complex action allows the spreading of the kinetic transfer through a longer lapse of time and several contact points.
- *BackLow*: Back fall sequence where the robot separates and folds its legs in order to lower its center of mass before the impact.
- *LateralLow*: Lateral fall where the robot folds its legs in order to lower its center of mass before the impact. Depending on the situation the robot can fall towards its left or right side. Both sequences are symmetric.

When a large instability is detected in the sagittal plane, the *FrontLow* or *BackLow* falling sequences are triggered, depending on the falling direction. The *FrontTurn* is scarcely employed because of the synchronization requirements, which until now have been only achieved in simulation environments (see example in fig. 4). When instability is detected in the lateral plane, the *LateralLow* fall sequence is used to fall towards the left or the right side.

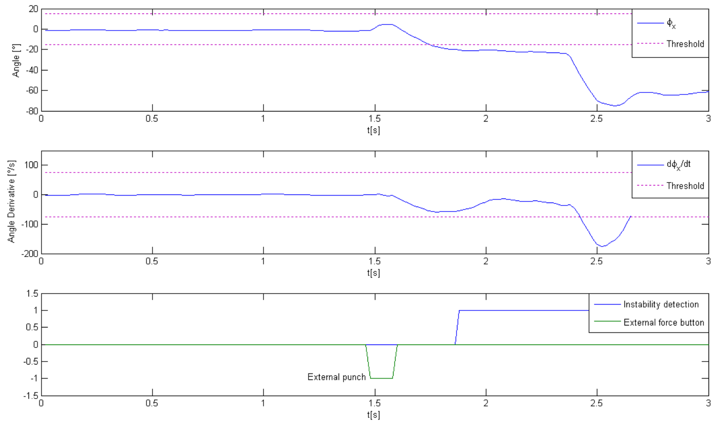

Fig. 2. Fall detection in the lateral plane while standing still (see main text for details).

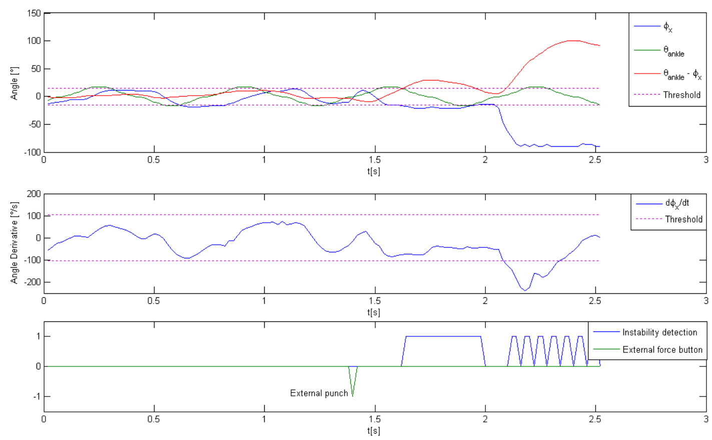

Fig. 3. Fall detection in the lateral plane while walking (see main text for details).

V. EXPERIMENTAL RESULTS

Instability detection in standing and walking situations is carried out using the relationships described in (7), (9) and (10). The parameters were adjusted after several experiments in which the robot was disturbed by external punches and different kind of collisions with various objects and surfaces. The instability-detection time was measured using a switch that was pressed by the collision event, and that was red by the robot controller. In figs. 2 and 3 two exemplar situations are shown.

The proposed approach was validated on a set of 175 experiments in which the robot interacted with real-world objects in 7 different situations (25 tries are conducted for each case). In all of these cases the robot walked 80cm before colliding. Table 1 summarized the obtained results. In terms of instability detection, we observe that the proposed mechanisms are very robust, the detection rate is very high, and the number of false positives very low (just 1 in 175 experiments). Regarding the proposed fall avoidance mechanisms, we observe they are able to avoid falls robustly in just one situation. In other two situations, fall can be avoided in ~30% of the cases.

For a first validation, the complete fall management framework was integrated in a soccer simulation environment (see description in [10]). Figs. 4 and 5 shows two examples of the collision between two robots the simulated environment. In the first situation the red robot hits the back of the blue robot. The red robot avoids the fall, while the blue robot actives the *FrontTurn* falling sequence. In the second situation the blue robot hits the chest of the red robot. The red robot avoids the fall, while the blue robot actives the *BackLow* falling sequence.

Table 1. Experimental results of instability detections and fall avoidance. TP (True Positive) detection rate. FP (False Positive) detection rate. FaP: Falling Probability when no avoidance mechanisms is used. FaAP: Falling Avoidance rate.

Collision Type	**TP**	**FP**	**FaP**	**FaAR**
Frontal collision against a wall	1.00	0.00	1.00	0.00
45° collision against a wall	0.96	0.00	1.00	0.00
Step down	1.00	0.00	0.76	0.08
Step up	0.84	0.00	1.00	0.08
Frontal collision with the legs against a small object.	1.00	0.00	0.64	1.00
Frontal collision against a robot	0.80	0.04	1.00	0.24
Frontal collision against a walking robot	1.00	0.00	0.88	0.36

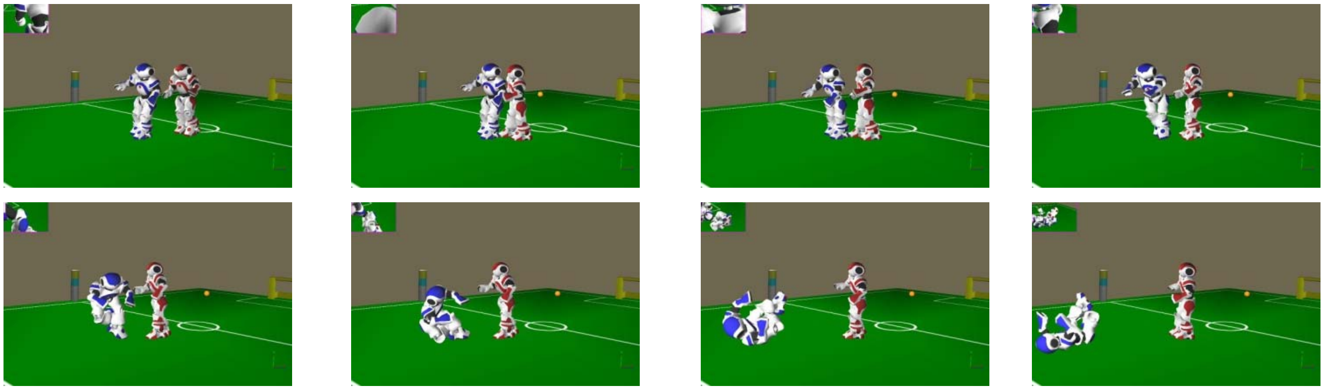

Fig. 4. Collision between two robots in a simulated soccer environment. The red robot hits the back of the blue robot. The red robot avoids the fall, while the blue robot actives the *FrontTurn* falling sequence.

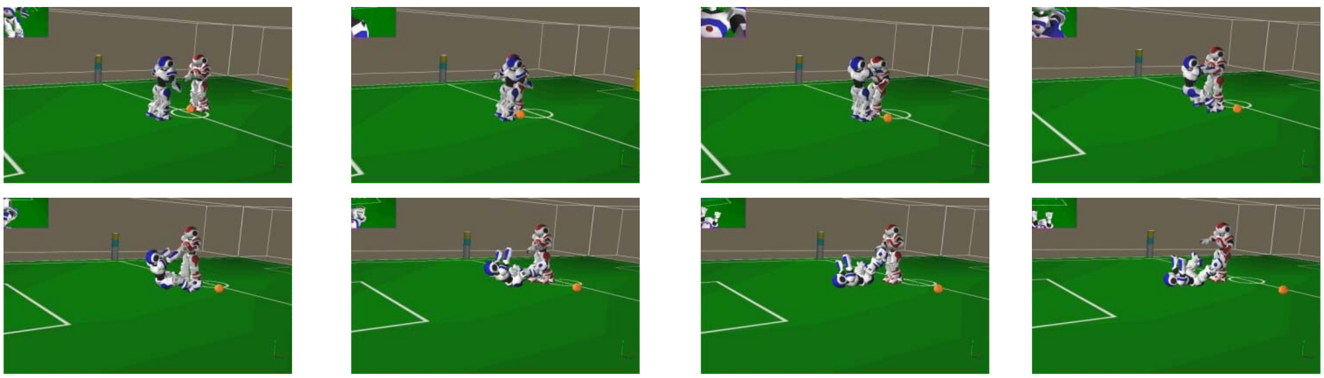

Fig. 5. Collision between two robots in a simulated soccer environment. The blue robot hits the chest of the red robot. The red robot avoids the fall, while the blue robot actives the *BackLow* falling sequence.

VI. CONCLUSION

The appropriate management of fall situations is an essential ability of biped humanoid robots. We have proposed a framework that allows managing fall situations in an integrated fashion. Instability is detected in walking and standing situations using correlations between attitude sensors and joint angles, or using an online model of the sensors. After detection, a fall can be avoided or a falling sequence triggered depending on the detected instability's degree. Instabilities are detected in most of the cases, and falls can be avoided in case of low or middle instability values. The whole framework has been validated in real humanoid robots.

As in the case of offline methods, the proposed approach requires the offline setting of some thresholds. However, this setting is much more simple and faster than adjusting a model. The sensitivity of the threshold values need to be further analyzed, as well as the behavior of the approach with other gaits. The proposed approach is not able to detect disturbances if they are introduced slowly. However, this is not a problem, because such disturbances are not expected in the case of a humanoid interacting with the real world.

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