Reactive collision avoidance for safer human-robot interaction

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Abstract- **Related to human-robot interaction, safety is not a simple attribute encompassed by the concept of dependability: it is a central requirement for the risks occurring during the motion of articulated robot manipulators. Both industrial and service robots need strategies for improving safety of people in their workspace. Collision avoidance algorithms are therefore crucial, and reactive techniques are important for unstructured domains. The so-named "skeleton algorithm" is an effective tool for reactive collision avoidance in industrial and service robotics. It needs good sensory information in order to plan the avoidance trajectories before possible collisions. This is achieved simply for self-collision avoidance (where highly dependable sensory data are available), while it needs further attention, related to safety, when noisy and, possibly, delayed exteroceptive sensory data are used, e.g., for people avoidance by heavy robots. Experiments with robots of these two categories are considered.**

I. INTRODUCTION

According to researchers in the field of dependability for computing [1], this integrated concept encompasses attributes like: safety, availability, reliability, integrity and maintainability.

Related to physical Human-Robot Interaction (pHRI), safety becomes more important, since the risk of collisions from moving robots can lead to fatal injuries. It is more than a generic attribute of the wider concept of dependability with the same importance, e.g., than maintainability. It is a novel, crucial optimality and evaluation criterion for a robotic system.

Collisions constitute one of the major source of risk for safety in pHRI. New standards and safety criteria are expected for assessing their relevance [2], since current evaluation criteria seem to be unsatisfactory, and industrial standards do not allow the user to be in the workspace of working manipulators.

While recent promising researches [3] show that a lightweight robot could be safe also in the presence of collisions, a complete scheme for safe human-robot interaction should also consider collision avoidance facilities.

This is important because not every useful robot arm can be kept as lightweight and slow as it is necessary in order to guarantee acceptable levels of injury criteria [2] when a collision happens.

Moreover, it is worth noticing that the use of highly redundant multi-arm robotic manipulators (like humanoids) cannot be faced only via deliberative planning/control schemes.

Reactive collision avoidance is therefore necessary in both robot-robot and human-robot interaction. The first is simpler, because of the high reliability of sensory data. For reactive collision avoidance in human-robot interaction, tracking of important parts of the human body is necessary, while a reactive control system acts on the interacting robot for forcing it to move away from possible collisions.

Sensor dependability and integrated planning/control become central in order to safely interact with the environment. This gives emphasis also on the electronic hardware and software safety procedures, which intelligently monitor, supervise, and control robot operation.

By focusing on the collision avoidance trajectories, variable kinematic configurations may be used to minimize the instantaneous effect of an impact for a redundant robot [4], where changes in the internal kinematic configuration are aimed at minimizing the inertia seen at the end-effector.

A reactive collision-avoidance approach implemented both for advanced lightweight and ordinary industrial manipulators is presented in this paper.

Reactive collision avoidance has been widely addressed in the robotics literature [5][6][7]. In the so-called "skeleton algorithm", first introduced in [8] the central feature is the fast and automatic analytical computation of distances from obstacles and Jacobian matrices for arbitrary structures. The robot structure is not divided in finite elements located in fixed positions, but segments lying on the axes of the mechanical structures of the robot are built, spanning all the manipulator's structure. Jacobian matrices are computed until the control points, which can move all along the structure.

The reactive trajectories are related to the distance of a point on the robot which could possibly collide. The approach does not take into account explicitly the full dynamics of the robot, while this can be faced via modification of the potential fields [9] used for shaping the amplitude of the repelling force

Comparing the results of experiments with advanced and ordinary robots, from the dependability viewpoint, it is clear that the proposed technique is intended to offer an additional tool for safety in pHRI. The approach is suitable for a wide class of robot manipulators, but the risk of harm during reactive motion is more acceptable where dependability for the system is guaranteed by the human compatible safety levels at the possible collision instant, resulting from the lightweight link design, compliant transmissions, post-collision tactics.

Previous analysis of reactive motion is to be extended in order to consider the articulated structure of a robot.

In the following, the reactive algorithm will be recalled, with a discussion related to its possible application to collision avoidance in pHRI.

II. THE SKELETON ALGORITHM

The skeleton algorithm, first studied together with the DLR research group for self-collision avoidance of a humanoid manipulator [8], can be considered as an extension of the Virtual End-Effectors approach [10], and is composed of these four steps:

- building a proper model of the robot, namely the skeleton;
- finding the closest points to a possible collision along the skeleton (collision points), both for self-collision or collision with external objects;
- generating repulsion forces (or Cartesian velocities);
- computing avoidance torque (or joint velocities) commands to be summed to the nominal commands for the controller.

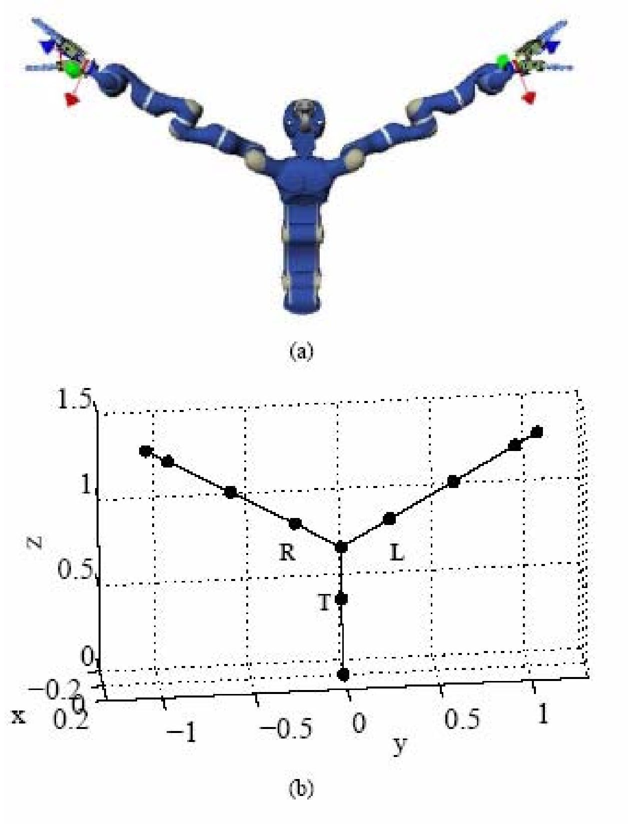

Fig. 1 The DLR “Justin” manipulator (a) with corresponding skeleton (b) for the reactive motion control technique

The problem of analyzing the whole volume of the parts of a manipulator is simplified by considering a *skeleton* of the structure (Fig. 1), and proper volumes surrounding it.

The adopted geometrical model leads to using a very simple and fast computation rule for distance evaluation and modification of the trajectories for each point of the manipulator. Such a skeleton can be composed by considering segments lying on the links of a robot. Kinematics of course affects the composition of such a skeleton. For the DLR Justin manipulator [11] (see Fig. 1 and Section III) it is possible to observe ten segments in which the manipulator is decomposed, where the segment ends located at the Cartesian positions of the joints are computed via simple direct kinematics.

It is always possible to find the two closest points for each pair of segments of the structure (see Fig. 2 (b)). This information can be used in order to avoid a collision between these two points, e.g., by pushing the closest points whenever their distance becomes lower than a threshold.

Spheres centered at the collision points can be constructed as protective volumes. Since the closest point can vary between the two ends of the segment, the resulting protective volume will be a cylinder with two half spheres at both ends (on the assumption of a fixed radius, see Fig. 2 (a)). With varying radiuses, any structure that is a solid of rotation.

With reference to the structure in Fig. 1 (b), the volumes constructed around the torso point *T* and the points *L* and *R* for the left and the right arm, respectively, encompass the two segments from *T* to *L* and *T* to *R* which thus can be discarded, leading to consideration of a total of eight segments, i.e. two for the torso and three for each arm.

For each segment in which the structure is decomposed, the distance to all the other segments is calculated.

Formulas are reported in [8]. A simplification occurs when evaluating distances from the segments to point in the space (e.g., centroid of a face of an interacting person).

The complete coverage of a body depends on the quality of the skelton model and on the precision of the measure of the “nodes” of the skeleton.

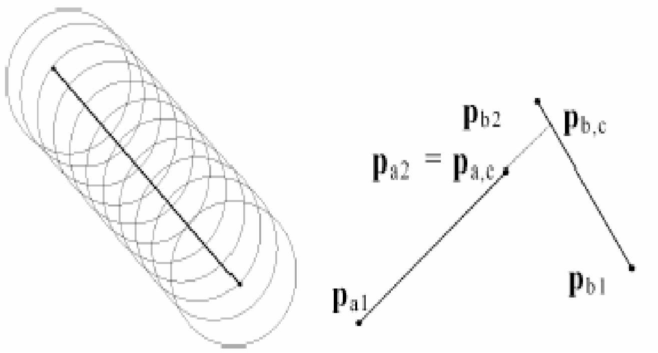

Fig. 2 Protecting spheres on a segment (a) and (b) example of chosen control points ($p_{a,c}$ $p_{b,c}$) via simple distance computation on two segments

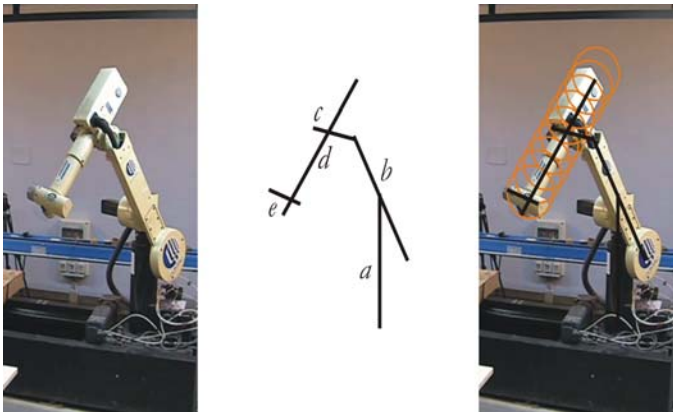

Fig. 3 The skeleton algorithm approach applied to a COMAU Smart 3/S robot manipulator

Potential fields [9] can be used in order to generate the forces which will produce, in this case, the self-collision avoidance motions. Two opposite forces, directed on the line connecting the two closest points which are possibly colliding, can be chosen as the integral of a nonlinear function of the distance, provided that points farther than a threshold are not subject to any repulsion [8].

The amplitude of the forces depends on design choices about the intensity of the repulsion between the arms, which affect the values of possible damping terms.

Inference systems can be helpful in order to dynamically modify the starting and limit distances and the shaping of the potentials. In pHRI, e.g., the tuning of these parameters may depend on the part of the body that is close to the manipulator: more conservative distances and damping actions are to be considered, e.g., for human head avoidance.

In a torque-control implementation, *avoidance torques* can be easily computed in view of the kineto-static duality for robotic systems with holonomic constraints [12], via the transpose of the Jacobian matrices until the collision points, which are actually control points.

In the case of a velocity-level implementation, velocities instead of forces are considered in order to move the possible colliding parts away. With this approach, inverse kinematics is adopted in order to compute the desired joint values for the robot controller, and the inverse of the Jacobian matrix has to be computed, with well-known additional issues.

Please refer to [8] for further details.

III. EXPERIMENTS

A. Experimental setup at DLR RM Institute

A novel humanoid two-arms-hands-torso system, named Justin, has been developed by the Institute of Robotic and Mechatronics (RM) of the German Aerospace Agency (DLR) [10] and has been first shown at the Automatica Fair in Munich in May 2006.

This robotic system (Fig. 1) is composed of a sensorized head, two DLR LWR-III [13] arms and an articulated torso with 3 active and 1 passive DOFs. The total number of DOFs (active and passive) of the robotic system is 18, plus 24 for the hands and 2 for the head. In order to build a skelton for collision avoidance with the "body", the additional 26 DOFs from hands and head are not considered.

The software architecture of Justin is based on the "agile Robot Development" (aRD) developed at DLR, which gives easy access to scalable computing performance and is based on the abstract view of a robotic system as a decentralized "net of calculation blocks and communication links".

B. Experimental setup at PRISMA Lab

The setup in the PRISMA Lab consists of two industrial robots Comau SMART-3 S (see Fig. 1). For the considered application, only one robot manipulator is used. It has a six-revolute-joint anthropomorphic geometry with nonnull shoulder and elbow offsets and non-spherical wrist. Each robot is controlled by the C3G 9000 control unit which has a VME-based architecture with 2 processing boards (Servo CPU and Robot CPU) both based on a Motorola 68020/68882. Upon request, COMAU supplies the proprietary controller unit with a BIT3 bus adapter board, which allows the connection of the VME bus of the C3G 9000 unit to the ISA bus of a standard PC with MS-DOS operating system, so that the PC and C3G controller communicate via the shared memory available in the Robot CPU. In this way the PC can be used to implement control algorithms, and time synchronization is achieved by means of a flag set by he C3G and read by the PC. A closed proprietary C library (PCC3Link produced by Tecnospazio SpA) is available to perform communication tasks.

In the new open controller, named RePLiCS [14], the software running on the PC was completely replaced by a real-time control environment based on RTAI-Linux operating system. RePLiCS allows advanced control schemes to be designed and tested, including force control and visual servoing.

An advanced user interface and a simulation environment have been also developed, which permit fast, safe and reliable prototyping of planning and control algorithms. A noticeable feature of RePLiCS, which is an enhancement of the existing industrial multi-robot controllers, is that it allows not only the time synchronization of the sequence of operations executed by each robot, but also real cooperation between the robots.

In order to recognize the face of a user, a framework for extracting images form video streams has been adopted, based on [15]. The tracking of faces is accomplished through a color and shape-based Particle Filtering and along tracking, exchange of information occurs between the detection and filtering modules. When a face is detected it is tracked along the frames, even if it is partially occluded. In case of totally occlusion, the tracking keeps sampling the same region until the faces reappear or a time-out elapses. A single-user hypothesis has been considered.

A Sony EVI-D31 camera tracks the head motions using a pan-tilt unit. A calibration has been performed in order to obtain a model of the depth, based on a known average size of a face. Of course, this is a source of uncertainty to be assessed in a probabilistic framework, leading to a model of the error, to be related with the size of "safety volumes" wrapping the head. For safety reason, if the tracking of the head is lost, the system is stopped. Better performance is obtained with two cameras (guaranteeing, i.e., triangulation and redundancy).

C. *Case studies*

Experiments have been performed at DLR and PRISMA Lab, in order to test the effectiveness and robustness of the algorithm. In the first case, only self-collision avoidance has been considered for the Justin humanoid manipulator (see Fig. 1), whose "arms" are DLR LWR-III manipulators. Current trajectories have been acquired during manual guidance of the manipulator in torque control, where gravity has been suitably compensated. The manipulator has successfully avoided all collisions, and different potential functions have been tested (see Fig. 3).

The parameters that can be adjusted, according to the approach, are the critical distance where the effect of the repulsion vanishes, which has been set to 30 cm, and damping terms, which can to be added in order to slow down the lightweight robot arms after repulsion forces moved them away, avoiding collisions.

From the repulsion force, the corresponding torques have been computed. Details related to the experiments with the humanoid manipulator are presented in [8].

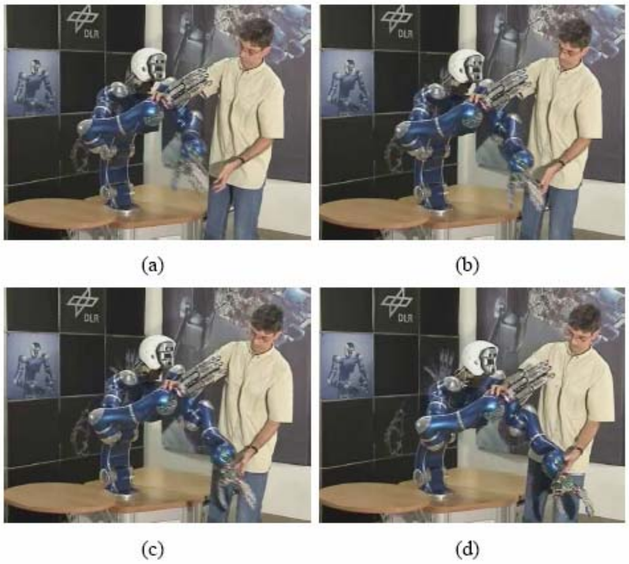

Fig. 4 Self-collision avoidance for the DLR humanoid manipulator based on the skeleton algorithm: reactive motion is summed at the torque level to the commands coming from impedance control

In the experiment in Fig. 4 (please refer to http://www.prisma.unina.it/videos/PRISMAMov_DLR_Justin.wmv), the reaction of the manipulator in real-time for collision avoidance is shown. The user drives the right arm towards the left arm. The system finds the closest point between the segments of the skeleton and, when the distance becomes lower than a fixed threshold, the left forearm moves away along a proper direction, with a speed proportional to the distance and a proper damping in order to stop safely.

Notice that the right arm is pushed by the same force, but the user is keeping the right wrist, compensating this force. The presence of torque sensors allows the simultaneous computation of proper torques for the manipulators, to cope with the force given by the human user and the forces generated with the skeleton algorithm.

The extension to the avoidance of the user needs exteroception in order to locate the head and the hand. When contact is present, of course the detection of that contact via force/torque sensing can help the sensor fusion architecture to locate the hands.

In the experiments at DLR, "manual guidance" in impedance control is replaceable by other motion control techniques: the reactive contribution from the skeleton approach can be summed at the torque level.

Fig. 5 Attraction from the hand and repulsion from the head in the skeleton algorithm implementation at PRISMA Lab.

In the human-robot interaction experiments held at PRISMA Lab, a cooperative task has been implemented within a project aimed at introducing pHRI techniques for small industrial environments.

Again, the navigation algorithm considers "safety volumes" wrapping people and objects present in the scene, and the planned manipulator trajectories do not intersect these volumes. If this happens, the system activates a reactive mechanism which modifies the manipulator trajectory generating the appropriate motor commands.

The cited face detection system has been used for finding and tracking of a human interacting with the industrial robot (see Fig. 5 and Fig. 6). Besides the cited issues related to calibration, in this case, safety is jeopardized by delays for communication and data filtering between visual system and robot controller.

For this reason, the repelling function acting on the robot has wider range of action and higher intensity in the proximity of the robot. Since one “collision point” is the human head, the critical distance where the effect of the repulsion vanishes completely has been set to 1 m.

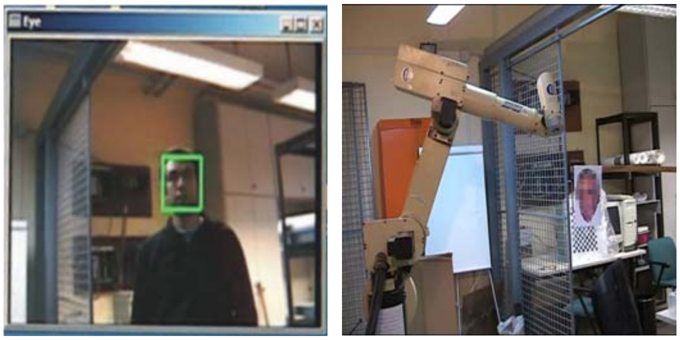

Fig. 6 Face detection has been used for the estimation of head position, which becomes the center of a safety volume pushing the manipulator away

In order to complete a cooperative task, at the same time, an attractive potential towards objects to be picked and the human hand has been considered. The localization and tracking of the head is simpler, due to colored gloves used in the experiments, while simple tools for cooperative work can be tracked based on CAD models.

A critical aspect related to the skeleton algorithm is its possible use for human head avoidance. If a safe robot is used, the additional safety can be enough. With respect to situations where collision-free operation is more important, a quantitative analysis is to be faced in the next future, in order to appreciate the maximum errors in sensors and communication that can be accepted while still avoiding collisions.

Avoidance motion has been successfully tested with dummy users (poles holding pictures of human faces, in order to safely tune the parameters for head avoidance) and persons. In these two cases, possible communication problems result in an emergency stop of the robot.

The implementation is at the velocity level, and the pseudoinverse of the Jacobian matrix has been computed in real time for the inverse kinematics, with classical solutions to cope with singularities.

IV. DISCUSSION

A reactive technique for collision avoidance, where repulsion forces can be shaped arbitrarily and the Jacobian matrices for computation of the corresponding joint motions/torques is a useful tool for completing a human/robot dependable interaction scheme.

Nevertheless, better results depend on sensor dependability for locating the position of human being with respect to the robot. Experiments performed for self-collision avoidance of a manipulator correspond to an ideal case where positions of the possibly colliding bodies are known almost exactly. Moreover, software and communication dependability are to be guaranteed.

Experiments at PRISMA Lab show how effective the technique can be also with traditional robots, but a trade-off with performance is needed (e.g., slowing down the maximum repulsion motions), since the intrinsic nature of heavy industrial manipulators gives less robustness with respect to consequences of sudden motions in case of malfunctioning (which has to be related with probabilistic aspects).

As an example, consider the evaluation of Head Injury Criterion for industrial and service robots in [3] [16].

Software issues can be relevant as well as mechanical aspects, but the simple software implementation for the skeleton algorithm does not pose additional software dependability problems.

It is worth noticing that the real key point is the quality of sensing. Encoders and resolvers which measure joint displacements give always a good estimate of the position of all the parts of a manipulator. This means that the “control part” of the approach, which is strongly affected by the computation of Jacobian matrices, can be effective and robust.

After planning the trajectories, the dependability of the computation of the Jacobian until the control point (and the corresponding planned torques or velocities) may be affected by a wrong evaluation of the closest point to a collision. Sensor fusion algorithms are therefore to be considered together with a model of their accuracy.

If the vision system considered for the experiments at PRISMA Lab is adopted, dependable estimation of the head position must cope with issues related to: vision hardware speed and synchronization, camera calibration, model of the face detection, maximum allowable errors and delays in the considered probabilistic framework. These issues are under investigation for a more quantitative evaluation of the safety in the proposed approach.

In order for a robot to be perceived as safe, cognitive aspects as the appearance can play an important role. However, a friendly appearance can result in a “faked” dependability. For such reason, the use of a lightweight manipulator has to be encouraged: despite the importance of “active” control, it is not possible to understand all the possible movement and reaction of a user. This becomes more relevant for manipulators designed for special users, like impaired persons. For such reason, a reactive approach, even robust, has to be accompanied by an architecture where also the possible post-collision phase is managed in order to reduce the exposure of a user to a crash.

Despite the robustness of the control, skilled users interacting with the industrial manipulators used for experiment were never fully confident while the robot moved towards the goal point and reconfigured itself in order to comply with the planned repulsion strategy.

Anticipation of robot movement by the user is a good feature for improving safety. The repelling force can be identified as a virtual spring from the user, who can anticipate the forthcoming motion of the robot, provided that she/he has an idea of the type of “bouncing” implemented on the robot (e.g., nonlinear spring with damping).

Dependability of a complete system for human-robot cooperation is dominated by the safety issues. Related to the control of “active” safety, planning/control with reactive techniques must take into account both objective physical metrics and cognitive aspects.

In an effective selection of papers related to human friendly robotics [17], dependability of reactive mobile robots has been considered, especially related to navigation, while, for manipulators, the emphasis has been given to the intrinsic safety and post-collision identification and reaction. This can be related to the usual applications of manipulators in industrial environments where standards hold [2] that forbid physical HRI.

The proposed approach aims at suggesting reactive features for a safer pHRI, to be connected to kinematic and dynamic aspects of manipulator control.

V. CONCLUSION

Safety for physical interaction with robots can benefit of reactive control techniques, since unstructured domains cannot be faced only via deliberative schemes. A reactive system for collision-avoidance has been presented. Reactive control gives emphasis on sensory data. This is necessary for unstructured domains, but it shifts the attention to the dependability of many components like sensors and software procedures.

The algorithm is robust, modular and with the possibility of adapting different shapes of the repelling functions (also on-line and based on cognitive evaluation) [8].

However, this research needs further attention, related to dependability analysis: for risk assessment, not only sensors, but also communication and the application domain strongly affect possible dangers for interacting people. Possible fault detection and dependability assessment of sensors become central before reasonable acceptance of such a reactive approach in everyday industrial and service environment.

Reactive techniques can be a good tool for improving safety but also without deeper quantitative estimation of inertias and computation time, the use of an intrinsically safer manipulator like the DLR LWR-III is encouraged, also for “cognitive” reasons, related to its friendly appearance and comfort of users.

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REFERENCES

[1] A. Avizienis, J.-C. Laprie, B. Randell, and C. Landwehr, “Basic concepts and taxonomy of dependable and secure computing”, *IEEE Transactions on Dependable and Secure Computing*, vol. 1, pp. 11–33, 2004.

[2] R. Alami, A. Albu-Schäffer, A. Bicchi, R. Bischoff, R. Chatila, A. De Luca, A. De Santis, G. Giralt, G. Hirzinger, V. Lippiello, R. Mattone, S. Sen, B. Siciliano, G. Tonietti, L. Villani “Safe and dependablephysical human-robot interaction in anthropic domains: state of the art and challenges”, *Workshop on Physical Human-Robot Interaction, 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Beijing, PRC, 2006.

[3] A. De Luca, A. Albu-Schäffer, S. Haddadin, G. Hirzinger, “Collision detection and safe reaction with the DLR-III lightweight manipulator arm”, *2006 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Beijing, PRC, 2006.

[4] I.D. Walker, “Impact configurations and measures for kinematically redundant and multiple armed robot systems”, *IEEE Transactions on Robotics and Automation*, vol. 10, pp. 670–683, 1994.

[5] O. Brock, O. Khatib, “Elastic strips: a framework for motion generation in human environments”, *International Journal of Robotics Research*, vol. 21, pp. 1031–1052, 2002.

[6] F. Seto, K. Kosuge and Y. Hirata, “Real-time self-collision avoidance system for robots using RoBE”, *2003 IEEE-RAS International Conference on Humanoid Robots*, München, D, 2003.

[7] J. Kuffner, K. Nishiwaki, S. Kagami, Y. Kuniyoshi, M. Inaba, H. Inoue, “`Self-collision detection and prevention for humanoid robots”, *2002 IEEE International Conference on Robotics and Automation*, Washington, DC, 2002.

[8] A. De Santis, A. Albu-Schäffer, C. Ott, B. Siciliano, G. Hirzinger, “The skeleton algorithm for real-time collision avoidance of a humanoid manipulator interacting with humans”, submitted to *2007 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, Zurich, CH, 2007.

[9] O. Khatib, “Real-time obstacle avoidance for robot manipulators and mobile robots”, *International Journal of Robotics Research*, vol. 5(1), pp. 90–98, 1986.

[10] A. De Santis, P. Pierro, B. Siciliano, “The virtual end-effectors approach for human-robot interaction”, *10th International Symposium on Advances in Robot Kinematics*, Ljubljana, SLO, 2006.

[11] C. Ott, O. Eiberger, W. Friedl, B. Bäuml, U. Hillenbrand, C. Borst, A. Albu-Schäffer, B. Brunner, H. Hirschmüller, S. Kiehlöfer, R. Konietschke, M. Suppa, T. Wimböck, F. Zacharias, G. Hirzinger, “A humanoid two-arm system for dexterous manipulation”, *2006 IEEE-RAS International Conference on Humanoid Robots*, Genova, I, 2006.

[12] L. Sciavicco, B. Siciliano, *Modelling and Control of Robot Manipulators*, (2nd Ed.), Springer-Verlag, London, UK, 2000.

[13] G. Hirzinger, A. Albu-Schäffer, M. Hahnle, I. Schäfer, N. Sporer, “On a new generation of torque controlled light-weight robots”, *2001 IEEE International Conference of Robotics and Automation*, Seoul, K, 2001.

[14] F. Caccavale, V. Lippiello, B. Siciliano, L. Villani, “RePLiCS: An environment for open real-time control of a dual-arm industrial robotic cell based on RTAI-Linux”, *2005 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Edmonton, CND, Aug. 2005.

[15] P. Viola, M. Jones “Robust real-time face detection”, *International Journal of Computer Vision*, vol. 57(2), pp. 137–154, 2004.

[16] M. Zinn, O.Khatib and B. Roth, “Human-robot physical interaction: Design for safety and performance”, Lecture by O. Khatib at the *IEEE-RAS/IFRR International School of Robotics Science on “Robot Design”*, Tokyo 2005.

[17] “Safely among us”, *IEEE-Robotics and Automation Magazine*, Special issue on Dependability of Human-friendly robots, June 2004.