Robotic co-manipulation with 6 DoF admittance control: application to patient positioning in proton-therapy*

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***Abstract*— The paper focuses on controlling by hand a robot carrying a patient lying down on a ”couch top” located at the extremity of the end-effector. The Orion prototype, is a six Degree-of-Freedom (DoF) robotic system. The control of the robot is achieved through a home-made co-manipulated haptic device located under the couch top and operated by a paramedical assistant. This device enables the operator to move the couch top, on which the patient lies down, and within an identified operational safety space. The 6 DoF admittance control algorithm is implemented on this new robotic platform. An experimental validation has been carried out to validate the co-manipulation control of the robot. The adaptable admittance parameters have been tuned on several experiments in order to observe the mass-spring-damper equivalent behaviour and demonstrate the validity of the implemented admittance algorithm.**

I. INTRODUCTION

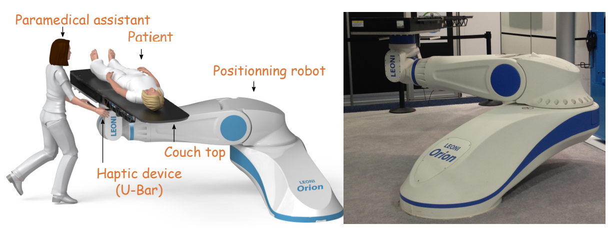

Fig. 1: CAD of the robot with patient and assistant (left), and full scale prototype of Leoni's positioning robot (right)

Physical Human-Robot Interaction (PHRI) is one of the fields supported by the ”France Robots Initiative” plan to position France as a new robotic world leader. Co-manipulated robots (Cobots) are increasingly needed in industry to boost production performance or in clinical application to enhance medical practitioner's gesture accuracy. PHRI is currently a booming topic research field where most of the current works focus on developing:

- Intrinsically safe robots [1]
- Small lightweight robots [2], [3]
- Obstacles avoidance control laws [4], [5] and [6]

In addition, a 2015 national contest dedicated to PHRI has been organized by France and encompasses industrials and research laboratories. PHRI is also a worldwide research topic; several projects (European, ANR, ...) have been funded ([7]–[9]) on these topics.

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II. MEDICAL CONTEXT

The context of this work is radio-therapy medical application. This process aims at cancer treatment by focusing a high-energy beam on an identified tumor in order to damage the cancer cells and stop them from dividing. The application, for which the Leoni robotic system is designed, relates to proton-therapy, a radio-therapy derivative which uses heavy particles (protons) to generate the treatment beam. Proton-therapy aims at providing better treatment accuracy with fewer side effects. Contrary to conventional radio-therapy for which a 6 DoF dose delivering machine can be used (Cyberkniffe for example), in proton-therapy this machine (named Gantry) has only 1 DoF thus the patient positioning device must have at least 5 DoF. The treatment protocol is as follows: the patient lies down on the couch top located at the end-effector of the positioning robot (Fig 1). In order to receive the radio treatment with high accuracy, the patient must be positioned at a specific medical location called the ”isocenter”. The accelerated particles beam is focused on the isocenter, and the patient's tumor shall be positioned at this very location in order to be adequately treated. Figure 2 illustrates the geometrical frames used in the forecoming study.

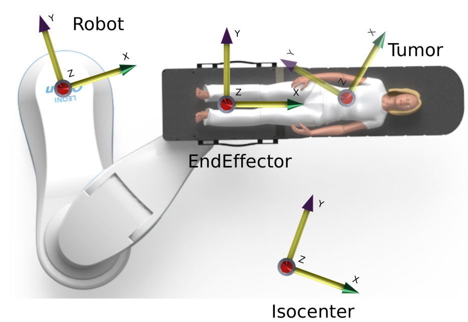


Fig. 2: Robot, end-effector, Tumor and Isocenter Frames

As a complete treatment requires several sessions, the patient has then to be re-positioned for each session on the couch top. The tumor location is only known in relation to a patient-fixed geometric frame and furthermore the patient position on the couch top is not fully accurate. In addition, the robot is moved in relation to its own fixed geometrical frame called the ”Robot” frame (Fig. 2). As a result, to automatically position the tumor at the isocenter with the Leoni robot (also named OrionPT) we need to find the location of the patient tumor in relation to the end-effector frame. Therefore, a manual setup process also known as ”pre-positioning phase” must be performed by the paramedical assistant.

The patient tumor is localized during an imaging technique phase (not presented here) and is physically identified by three ”tumor marks”. Therefore, the calibration perfomed by the paramedical assistant will aim to find the geometric transformation (a transfer matrix) between the patient frame (tumor location) and the ”end-effector” frame. This requires two room-fixed orthogonal lasers (Fig. 3). The intersection of these lasers depicts the isocenter location on which the tumor marks have to be aligned by the paramedical assistant displacement action on the couch top (Fig. 3).When the three markers are colinear with the lasers beams (i.e. isocenter), the patient tumor coordinates can be evaluated with respect to the robot geometrical frame using the robot indirect geometric model.

The pre-positioning procedure is divided in two phases :

- Move the patient/couch top using only translations to approximately position the patient three tumor marks close to the orthogonal lasers cross point (isocenter)
- Rotate (in a plan parallel to the ground) the patient to align the tumor marks with the room lasers (Fig. 3).

This process is executed iteratively until the tumor marks are fully positionned. The next steps of the treatment phase are performed without the need of robot manual control such steps are not described in this article.

The setup process is as follows :

- During a previously performed imaging phase, the tumor is marked with three dots on the patient skin
- The patient is set on the couch top (the three tumor marks are made visible to the paramedical assistant)
- The two room-fixed orthogonal lasers are switched on
- The paramedical assistant moves the robot end-effector (couch top) using the admittance control algorithm in order to align the tumors marks with the room lasers

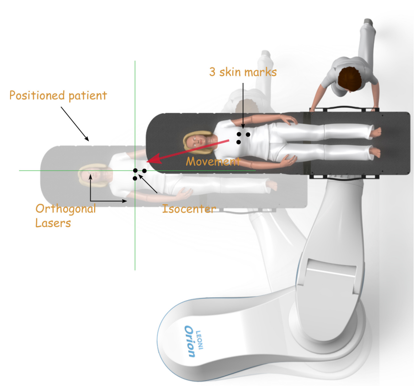


Fig. 3: Patient pre-positionning phase performed by the operator action on the couch top

III. Mechanical Structure

A. Leoni's Robot (OrionPT)

The proton-therapy robot prototype, used for the patient positioning and developed by Leoni Company, is a 6-DoF serial robot composed of 6 rotated joints and can be seen as an hybrid architecture between SCARA and PUMA robot. Figure 4 represents the Leoni robot kinematics with the modified Denavit-Hartenberg parameters.

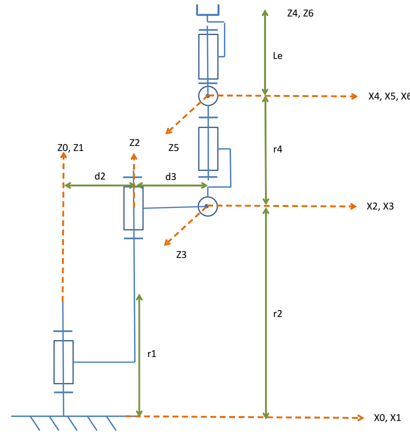


Fig. 4: Kinematics of Leoni's robot

B. Direct-Geometric Model

Table I presents the modified Denavit-Hartenberg parameters [10], [11] of the proton-therapy robot.

TABLE I: Denavit-Hartenberg parameters of the Leoni robot

i	σ	α_i	d_i	θ_i	r_i
1	0	0	0	θ_1	0
2	0	0	d_2	θ_2	r_2
3	0	$\pi/2$	d_3	θ_3	0
4	0	$-\pi/2$	0	θ_4	r_4
5	0	$\pi/2$	0	θ_5	0
6	0	$-\pi/2$	0	θ_6	0

C. Haptic Handle

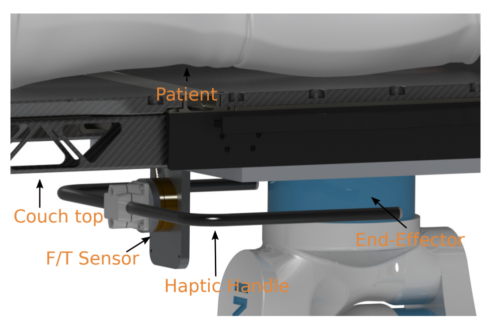


Fig. 5: F/T Sensor and U-shape bar located under the couch top and used in the proof-of-concept

1) Specifications: A dedicated haptic handle using an industrial force/torque sensor has been specifically designed and manufactured for this application. It is used as the input device for the external loop admittance algorithm described afterwards. It is composed of a force/torque sensor and a haptic handle (U-bar) attached to the sensor with an industrial flange (Fig. 5).

NASA[1] and "theergonomicscenter" information helped us to summarize the maximal efforts that will be exerted by the paramedical assistant on the haptic handle on the middle of the U-Bar ("A" point on Fig. 6). The maximal force value is approximately 350 N in front of the paramedical assistant, 65 N on his left and right hand sides and 65 N up and down, so :

$$_A\{\mathcal{T}_{F\to H}\}_\mathcal{R} = \left\{ \begin{array}{c} \overrightarrow{R}_{F\to H} \\ \overrightarrow{M}_{F\to H}(A) \end{array} \right\}_R = \left\{ \begin{array}{cc} 65 & 0 \\ -350 & 0 \\ 65 & 0 \end{array} \right\}_R \quad (1)$$

$$_B\{\mathcal{T}_{F\to H}\}_\mathcal{R} = \left\{ \begin{array}{c} \overrightarrow{R}_{F\to H} \\ \overrightarrow{M}_{F\to H}(A) + \overrightarrow{BA} \wedge \overrightarrow{R}_{F\to H} \end{array} \right\}_R \quad (2)$$

According to the scheme (Fig. 6) equation 2, the resulting force and torque (N and N.m) on the sensor is :

$$_B\{\mathcal{T}_{F\to H}\}_\mathcal{R} = \left\{ \begin{array}{cc} 65 & 45 \\ -350 & 12 \\ 65 & 17 \end{array} \right\}_R \quad (3)$$

The choice of the force/torque sensor used with the haptic handle has been made considering the previously calculated maximal force exerted.

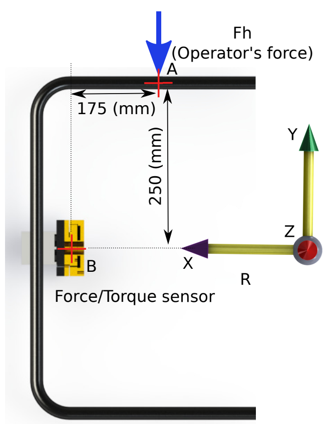


Fig. 6: Human force exerted on Haptic Handle (top view)

In addition the U-Bar has been designed with the following specifications :

- Two lateral parts spaced by 500mm to facilitate the grasp of the haptic handle from any side
- Sufficient length to have two hands side by side : greater than 300mm
- As small as possible to preserve the couch top transparent to the beam

IV. Admittance Control

A. Algorithm

As we discussed previously, the paramedical assistant needs a non-constrained manual robot control in order to

[1]http://msis.jsc.nasa.gov/sections/section04.htm

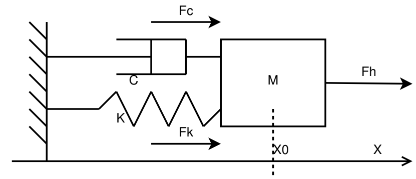


Fig. 7: Kelvin-Voigt Mass-Spring-Damper Representation

position the three tumors marks at the isocenter defined by the two lasers. Several researches have been carried out on admittance control ([12], [13], [14], [15]), there are all based on the impedance control algorithm developed by Hogan [16] in 1985 and provide a compliant behaviour in the cartesian space. The expected robot motion is equivalent to the displacement of a mass-spring-damper system with a force input (Fig. 7). The operator (i.e paramedical assistant) exerts a force F_h on the robot corresponding to the input for the control algorithm (Fig. 6). The kinematics of the robot (i.e couch top) will be similar to the movement of a mass on the equivalent mass-spring-damper system depicted in Figure 7. Figure 7 is a 1 DoF system, but our control algorithm is implemented on six independant equivalent mass-spring-damper systems on its 6 DoF.

This control method developped by Hogan provides a position or velocity control output regarding a force as input with a dynamic relation as follows :

$$F_h(s) = Z(s)sX(s) \quad (4)$$

The leoni robot is controled using joints velocities as input, therefore, our implemented algorithm will compute velocity regarding to the paramedical force input.

There is a dynamic relation between controlled position/velocity and force/torque input (eq. 5 to 8).

In our case the robot is controlled with a velocity input, V is a six-dimension vector: from the second Newton's law we can write (cf. Fig 7) :

$$-F_c - F_k + F_h = M\ddot{X} \quad (5)$$

Assuming the robot initial position is X_0 :

$$-C\dot{X} - K(X - X_0) + F_h = M\ddot{X} \quad (6)$$

$$F_h = K(X - X_0) + C\dot{X} + M\ddot{X} \quad (7)$$

The parameters are (Fig. 7) :

- X : Cartesian position of the mass
- $\dot{X}$: Cartesian velocity of the mass
- $\ddot{X}$: Cartesian acceleration of the end-effector
- M : Mass
- K : Stiffness
- C : Damping

The following equation aims to find the transfer function between the paramedical input (force exerted on the robot) and the robot cartesian velocity. Assume $\dot{X} = V$, we can write the transfer function in the Laplace domain :

$$F_h(s) = \frac{K}{s}V + MsV + CV \tag{8}$$

The velocity output is given by:

$$V = \frac{1}{C + Ms}(F_h - K(X - X_0)) \tag{9}$$

B. Software Architecture

The global admittance control loop is depicted in Figure 8. The input force used in the admittance algorithm is F_h the paramedical assistant force. the velocity command V_c is computed using the equation 9. Then, the internal computation loop containing the geometric model of the Leoni robot is used to compute the joints velocities injected to the robot (eq. 10). Note that an internal servoing loop is included in this control scheme (Fig. 8) which aims at providing an accurate joints velocities servoing. This loop will not be described in this paper.

Based on a common co-manipulation implementation introduced by [17], [18], the software architecture is divided into two loops (Fig. 8). The first one is implemented in a VxWorks real-time operating system and aims at providing a low-level control of the robot. An inverse kinematic model is included in order to calculate the joint velocity with respect to a cartesian velocity as input. The external loop where the co-manipulation algorithm is implemented and executed in an external linux-based computer (i.e non real-time) and is in charge of the high-level control. The object-oriented Ruby script language was used to implement the co-manipulation algorithm.

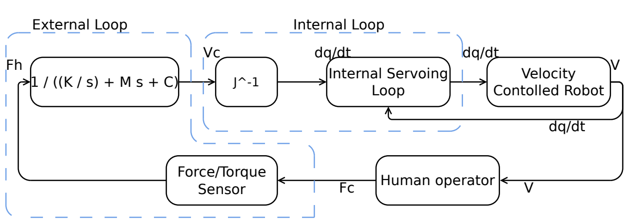


Fig. 8: block diagram of the implemented admittance control loop

The control loop depicted in eq. 10 will be used. The velocity controlled robot input is a joint velocity $\dot{Q}$. As it was previously mentionned, the implemented admittance control algorithm provides cartesian velocity with respect to the force as input. The joint velocity robot input is computed using the inverse Jacobian J^{-1} of the Leoni robot as follows.

We assume V_c (Fig. 8 equivalent to V in eq. 10) is the cartesian control velocity, so :

$$\dot{Q} = J^{-1}V_c = \frac{J^{-1}F_h}{\frac{K}{s} + Ms + C} \tag{10}$$

C. Implementation

In order to implement the previously detailed control algorithm we need to transpose it from continous to discrete form.

Because of the low latency time computation (∼20ms) we can assume :

$$\ddot{X} = \frac{V_{k-1} - V_k}{\Delta_T} \tag{11}$$

In setting :

- V_k : Computed cartesian velocity
- V_{k-1} : Previously computed cartesian velocity
- Δ_T : Computation sampling time
- X_k : Current robot cartesian position
- X_0 : Initial robot cartesian position
- F_{hk} : Current paramedical assistant force input

So, equation 6 can be written in a discrete form :

$$-CV_k - K(X_k - X_0) + F_{hk} = M\frac{V_k - V_{k-1}}{\Delta_T} \tag{12}$$

so,

$$V_k = \frac{MV_{k-1} - K\Delta_T(X_k - X_0) + \Delta_T F_{hk}}{C\Delta_T + M} \tag{13}$$

The computed cartesian velocity obtained in equation 13 will be converted into joints velocities using the robot inverse Jacobian of the robot (eq. 10) then injected into the six actuators.

The proposed control approach was implemented on the 6-DoF system but the following experimental results shows a 3 DoF (translation) system.

V. Experiments

The experiment were carried out using the Leoni patient positioning robot associated with the haptic handle. In order to validate the admittance control algorithm, it was firstly decided to set the damping parameters to non-null values and the stiffness and mass diagonal cartesian matrices to 0 to provide a free-space motion capability needed for the medical application then to use a so called stiffness control (on axis Z) which will be used in an incoming work dealing with obstacles avoidance.

A. Damping Control

For the so called *Damping Control* [19], the velocity output will be proportional to the paramedical assistant's force F_h. Damping control is a common implementation [20], [12], [21] in order to obtain a free-space (non-constrained) motion capability with a force amplification.

As mentionned, the patient positionning movement is divided into translations and rotations. The following experiments cover the translation part of the pre-positioning phase, that's why we use only the three translations.

The control algorithm was only applied onto 3 DoF (translations) and an untrained operator exerted random forces on the haptic U-bar in order to move the robot in free-space. No specific information was given to the operator for this test as the main goal was to observe the relation between the computed velocities and the input forces. The robot must follow the operator, therefore the computed cartesian velocities must be collinear to the input forces.

TABLE II: Values of the diagonal cartesian damping matrix

x	y	z	Rx	Ry	Rz
500 $N.s.m^{-1}$	800 $N.s.m^{-1}$	3000 $N.s.m^{-1}$	0	0	0

The admittance parameters used are summarized in table II. In order to demonstrate the capability for this control algorithm to works with different parameters we set three different damping values on the three controlled cartesian axes.

The cartesian velocities and forces on axis X, Y and Z are given on figure 9. The cartesian velocity is proportional to the force input, and we observe a prominent time delay of about $300ms$ induced by a force signal processing. In fact, to reduce vibrations, a Butterworth filter (order 3 and cut-off 1 Hz) has been implemented. This validates the admittance algorithm principle, however an improvement has to be considered in order to reduce the time delay for a better transparency.

B. Adding Stiffness control

We tested here the stiffness part of the admittance algorithm which will be used for collision avoidance (not detailed in this paper), we added a non-null spring value on axis Z and observe the response both for a step and for a random input from an untrained operator. The damping (i.e "C") and stiffness (i.e "K") values are given in the table III.

TABLE III: Values of the diagonal cartesian damping and stiffness matrix

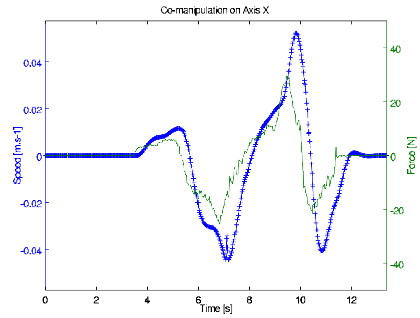
Parameter	x	y	z
C	500 $N.s.m^{-1}$	500 $N.s.m^{-1}$	500 $N.s.m^{-1}$
K	0 $N.m^{-1}$	0 $N.m^{-1}$	400 $N.m^{-1}$

The robot behaves as a spring plus damper system and reaches its stable position at 0.075 m as expected considering the force input (30 N) and the Z-Axis set stiffness $400N.m^{-1}$ (Fig. 10a).
The system tends to recover its initial position similarly to a spring-damper system behaviour without excitation force (Fig. 10b).

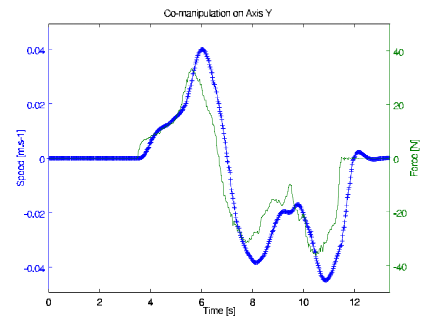
VI. Conclusion

An admittance algorithm was implemented on a dedicated patient positioning robotic system. Two sets of experiments were carried out to validate the implemented algorithm. The results for axis Z are depicted on Fig 10 and demonstrate the validity of the admittance algorithm. A time delay has been identified, which reduces the co-manipulation transparency.

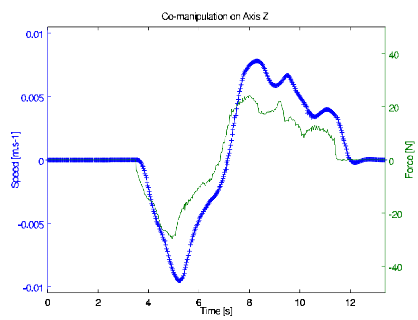
With the validation of this proof of concept, we showed that Leoni patient positioning robot could be co-manipulated; the future work will focus on relocating the force/torque sensor between the couch top and the end-effector to improve the interaction between the robot and the paramedical assistant. Hence, it will allow the paramedical assistant to grab the U-bar and move the couch top from anywhere around the couch top. Moreover, several haptic tests will be carried out to quantify the transparency of the co-manipualtion.



(a) Axis X using C = 200 $N.s.m^{-1}$.



(b) Axis Y using C = 800 $N.s.m^{-1}$.



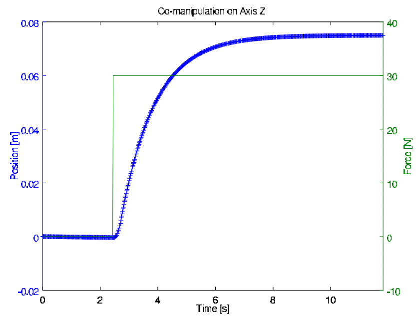
(c) Axis Z using C = 3000 $N.s.m^{-1}$.

Fig. 9: Experiments results for 3 DoF damping control

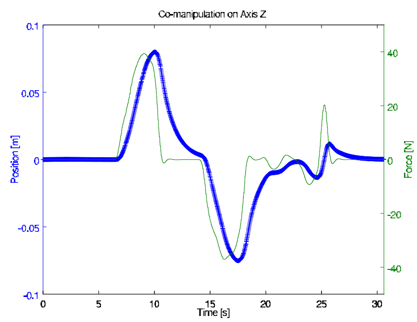
References

[1] S. Haddadin, A. Albu-Schäffer, and G. Hirzinger, “Safe physical Human-Robot interaction: Measurements, analysis and new insights,” in *Robotics Research*, ser. Springer Tracts in Advanced Robotics 66, Springer Berlin Heidelberg, Jan. 2011, pp. 395–407.

[2] R. Bischoff, J. Kurth, G. Schreiber, R. Koeppe, A. Albu-Schäffer, A. Beyer, O. Eiberger, S. Haddadin, A. Stemmer, G. Grunwald, and G. Hirzinger, “The KUKA-DLR lightweight robot arm - a new reference platform for robotics research and manufacturing,” in *Robotics (ISR), 2010 41st International Symposium*



(a) Response to a step input (30 N) using K = 400 $N.m^{-1}$.



(b) Response to an arbitrary input using K = 400 $N.m^{-1}$.

Fig. 10: Experiments results for damping+stiffness control on axis Z

on and 2010 6th German Conference on Robotics (ROBOTIK), Jun. 2010, pp. 1–8.

[3] A. Albu-Schäffer, S. Haddadin, C. Ott, A. Stemmer, T. Wimbock, and G. Hirzinger, "The DLR lightweight robot : Design and control concepts for robots in human environments," *Industrial robot*, vol. 34, no. 5, pp. 376–385, 2007.

[4] A. De Luca and F. Flacco, "Integrated control for pHRI: collision avoidance, detection, reaction and collaboration," in *2012 4th IEEE RAS EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob)*, Jun. 2012, pp. 288–295.

[5] S. Haddadin, A. Albu-Schäffer, A. De Luca, and G. Hirzinger, "Collision detection and reaction: A contribution to safe physical Human-Robot interaction," in *IEEE/RSJ International Conference on Intelligent Robots and Systems, 2008. IROS 2008*, Sep. 2008, pp. 3356–3363.

[6] A. De Santis, A. Albu-Schäffer, C. Ott, B. Siciliano, and G. Hirzinger, "The skeleton algorithm for self-collision avoidance of a humanoid manipulator," in *2007 IEEE/ASME international conference on Advanced intelligent mechatronics*, Sep. 2007, pp. 1–6.

[7] *Project ICARO (Industrial cooperative assistant robotics) — ANR - agence nationale de la recherche*, http://www.agence-nationale-recherche.fr/?Project=ANR-10-CORD-0025, 2010.

[8] *SAPHARI - safe and autonomous physical Human-Aware robot interaction - home*, http://www.saphari.eu/, 2011.

[9] *Phriends*, http://www.phriends.eu/, 2008.

[10] J. Denavit and R. Hartenberg, "A kinematic notation for lower-pair mechanisms based on matrices.," *Trans. of the ASME. Journal of Applied Mechanics*, vol. 22, pp. 215–221, 1955.

[11] W. Khalil and E. Dombre, *Modeling, Identification and Control of Robots*, 3rd. Bristol, PA, USA: Taylor & Francis, Inc., 2002.

[12] P. Labrecque and C. Gosselin, "Robotic force amplification with free space motion capability," in *2014 IEEE International Conference on Robotics and Automation (ICRA)*, May 2014, pp. 134–140.

[13] X. Lamy, "Conception d'une interface de pilotage d'un cobot," PhD thesis, Paris 6, Jan. 2011.

[14] V. Duchaine, "Commande des robots destinés à intéragir physiquement avec l'humain," PhD thesis, Laval, Laval, 2010.

[15] J. Dumora, "Contribution à l′interaction physique homme-robot : Application à la comanipulation d′objets de grandes dimensions," PhD thesis, CEA List, 2014.

[16] N. Hogan, "Impedance control: An approach to manipulation: Part I—Theory," *Journal of Dynamic Systems, Measurement, and Control*, vol. 107, no. 1, pp. 1–7, Mar. 1985.

[17] H. Kazerooni, "Extender: A case study for human-robot interaction via transfer of power and information signals," in *, 2nd IEEE International Workshop on Robot and Human Communication, 1993. Proceedings*, Nov. 1993, pp. 10–20.

[18] B. Cagneau, G. Morel, D. Bellot, N. Zemiti, and G. d'Agostino, "A passive force amplifier," in *IEEE International Conference on Robotics and Automation, 2008. ICRA 2008*, May 2008, pp. 2079–2084.

[19] D. E. Whitney, "Force feedback control of manipulator fine motions," *J. Dyn. Sys., Meas., Control 99(2), 91-97*, Jun. 1977.

[20] P. Kazanzides, "Force sensing and control for a surgical robot," Nice, May 1992.

[21] H. Kim, L. M. Miller, Z. Li, J. R. Roldan, and J. Rosen, "Admittance control of an upper limb exoskeleton–reduction of energy exchange," *Annual International Conference of the IEEE Engineering in Medicine and Biology Society.*, vol. 2012, pp. 6467–6470, 2012, PMID: 23367410.