Actual Developments of Navi-Robot, a Navigator Able to Block itself in the Correct Position during Orthopaedic Surgical Procedures

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Abstract: - A self-balancing Navigation system able to turn itself into a robot, reaching the positions required to precisely guide a tool during a surgical procedure is under construction of the prototype. The instrument is, basically, a goniometric device, characterised by the presence of three arms, each bearing six degrees of freedom. Thus the instrument is able to measure the relative position between any of its extremes, two of the arms being only passive (measuring arms) the third being movable both actively and passively (the operating arm). Each arm has basically the configuration of a SCARA Robot, mounted on a vertical slide and counterbalanced by a weight mounted on a second vertical slide, the other extreme being either in the doctor's hands or hooked to the patient.
Each joint of the measuring arms presents an absolute encoder and a brake that allows locking the arm position in any configuration. The joints of the operating arm present a second brake allowing a motor to transmit motion to the joint. Therefore, when both brakes are lose, the arm is passive and can easily be moved, when the first brake is locked, the arm is rigid, while when the second brake is locked, the arms becomes a Robot.
At the extremity of the measuring arms special connectors are present, that allow positioning the arm in a unique way with respect to a clamp nailed into the patient bone, while at the extreme of the operating arm special masks or pointers can be mounted either allowing using a saw or a drill in the proper plane or direction, or to detect bones profiles, leaving in any event to the doctor the real surgical act.
As a consequence, the system allows representing in Enhanced Reality a surgical procedure once initial calibration images or CAT information are acquired, indicating with the operating arm the correct position for surgery. New procedures to bypass or dramatically reduce the need of ionizing equipment are also under study. On the one hand, like most navigation systems, which however leave always to the doctor the burden to find the correct position for any given task, this is able to "navigate" the patient's body. On the other hand, unlike other surgical robots, this does not pretend to be a doctor, but, indeed, a simple surgical assistant. A PCT application on this device was presented and the preliminary exam stated the originality of this instrument.

Key-Words: - Medical Robot - Computer Aided Orthopedic Surgery - Navigators

1 Introduction

The need of reducing surgical teams radiation absorption has induced several firms, operating in the medical sector, to propose navigation systems [1-6] that allow representing in Virtual Reality the position of tools with respect to the patient's body, on the base of initial radiographic images or CAT scanning.
These systems however, particularly suitable for orthopaedic procedures, if on the one hand allow the doctor to visualise the surgical field, even showing on the computer screen the sequence of operations to be performed, on the other hand do not supply any physical support to him, who must, in any event, move the instrument with free hand to reach the target position and orientation. And this may not be a simple task, since it is necessary to manually control all the six degrees of freedom of a body in space.
As a remedy to this situation, more recently [7] the navigators allow positioning masks in the correct position to guide the cuts during prosthesis implant. However also in this case it is the doctor's burden to find the proper position to lock the mask, and, in any event, the system is not flexible, since a special mask is needed for every implant.
Previously surgical robots were proposed which, on the basis of pre-operative planning [8, 9], substitute the doctor performing for instance the cuts needed to install a prosthesis. Now, it is the author's firm belief that a doctor should never be replaced by an equipment. Only the doctor may have the experience and the sensitivity to understand if a given operation, planned before the actual surgery on the

base of medical images, is really to be accomplished, or should be performed in a different way.

2 Problem Formulation

These are the basic considerations that have led to the idea of an instrument able to combine the characteristics of a Navigator with those of a Robot, turning itself from one to the other upon doctor's request. Basically the system derives from a six degrees of freedom encoder based goniometric device, which has been used for years by the research group of the University of Calabria [10]. This device had to be balanced by counterweights suspended to an external structure in order to be moved freely without efforts and without sensibly affecting the measurements. The whole structure was however too cumbersome to be introduced in an operating room, and that was the reason why the idea came up to make it able to self support its weight [11, 12], unloading this latter to the floor.
To this purpose, a lot of different configurations were studied for years, initially using a robotic arm characterized by the presence of a first vertical rotational degree of freedom, followed by three rotational degrees of freedom characterized by three parallel horizontal axes, and by two last hinges, the first perpendicular to the last joint's axis and laying on a vertical plane, and the last having axis perpendicular to the last two links (Fig. 1).

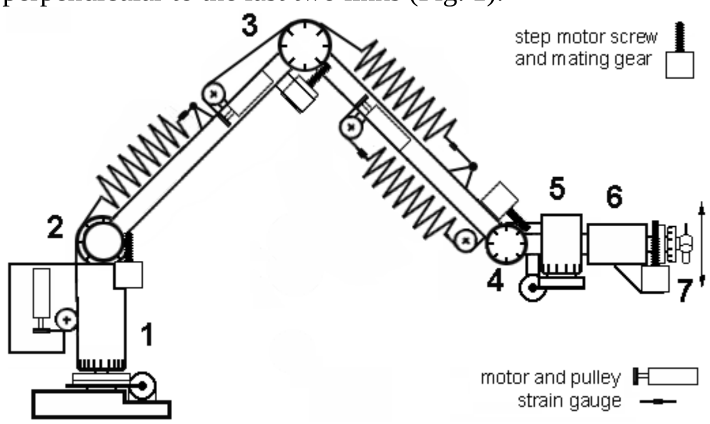

Fig. 1 – Initial Navi-Robot scheme

This configuration however, in order to be self balanced, needed the presence of springs and of two motors, one to control spring tension and one to move the robot. Spring tension had to be changed by actuators, so that the correct torque could be transmitted by every hinge to the structure suspended to it, taking obviously into account the actual configuration assumed by the goniometer. Next, the idea of using only one motor coupled with torsion springs came. Fig. 2 shows the configuration of one of these horizontal axis torque transmitting joints, showing the need for three brakes. A first brake is used to block the joint, a second brake is used to avoid unwanted passive motion of the motor in off condition, the third allows to bypass the torsion spring transmitting power directly in Robot mode.

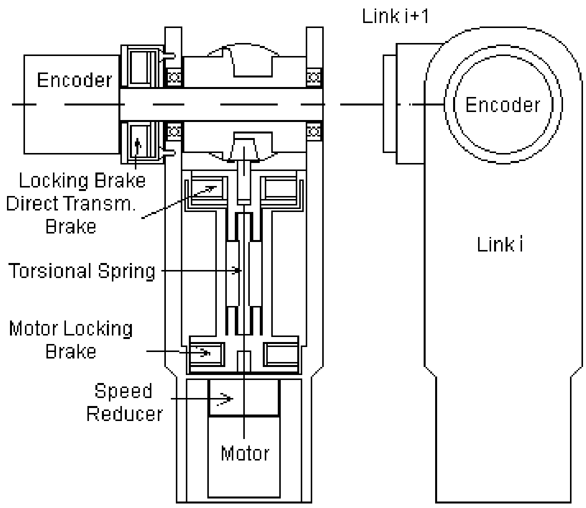

Fig. 2 - Scheme of an horizontal joint transmitting balancing torque

This obviously required a continuous updating of the transmitted torques, as to allow the operator to move the device without feeling the weight of the kinematical chain coupled to the surgical instruments. Not having to apply sensible forces, it was supposed that the error induced into the measurements were also to be reduced. In fact the springs were used exactly to make possible the motion in proximity of each new equilibrium position with minimum effort. However, while simulating the system, it was soon discovered that quite powerful and fast response motors were needed to drive the springs, which would increase the weight and the bulkiness of the robot.
That caused the idea to change completely link configuration as will be described in the following paragraph, since what was important was not the position of the various links, but the idea of being able to easily pass from passive to active mode. And that brought as a consequence also the idea of using three arms, two only passive, placed at the two sides of the operating arm, to allow the central arm to have always clear references with the proximal and distal bones of the joint to undergo surgery, and the central to guide the surgery.
To this purpose, at the extremity of the measuring arms special connectors were to be present, to allow positioning the arm in a unique way with respect to a clamp nailed into the patient bone, while at the extreme of the operating arm special masks or pointers were to be mounted either allowing using a saw or a drill in the proper plane or direction, or to detect bones profiles, leaving in any event to the doctor the real surgical act.
As a consequence, the system also allows representing in Enhanced Reality a surgical procedure once initial calibration images or CAT information are acquired, indicating with the operating arm the correct position for surgery. New procedures to bypass or dramatically reduce the need of ionizing equipment are also under study.

Furthermore, if the doctor judges that the given operation should be modified with respect to what decided during the pre-planning session, he could easily command the robot to move the instrument where he decides, while the system will automatically update all the subsequent operations. Differently from the other operating robots, the actual system never tries to replace the doctor, but it is always on his side, intervening upon request only to stabilise the operations and thus leaving the doctor to be the only responsible of the surgical act. Patent applications cover the device [13].

3 Problem Solution

Figure 3 presents a schematic representation of a single arm kinematics (basically a SCARA type of configuration), here represented in the active/passive version. As can be observed, it is characterised by a series of joints linked together in such a way that the axes of the first four joints are vertical, the first (1) being prismatic, the following three joints (2, 3 and 4) being hinges. The fifth joint (5), a hinge, has horizontal axis, intersected by the axis of the fourth hinge. The last joint (6) is coaxial to the sixth and seventh link, with its axis intersecting those of the fourth and fifth joints in the same point. Thus this point represents the wrist of the linkage, and behaves as a spherical joint. A cylindrical working space is hence defined. In the same figure the letters are used to designate four possible end effectors of the active arm, a drilling mask (a), two saw cutting masks (b and c) and a pointer (d) for touching the profiles.

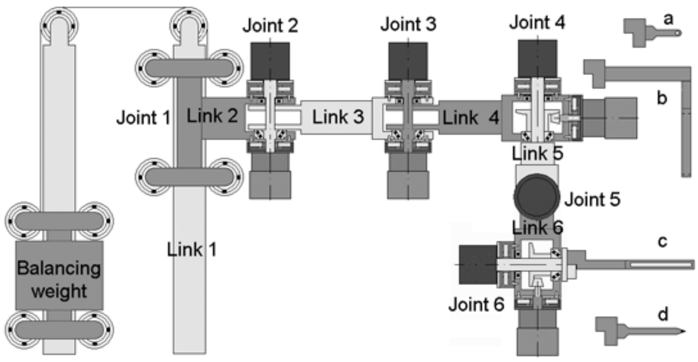

Fig. 3 – Scheme of the active arm of a Navi-Robot

As can be noticed, even without counterbalancing the weight of the sixth and seventh links, which are very light and short, the entire system may be made practically weightless by using a single balancing weight.

Each joint of a measuring arm presents an absolute encoder and a brake positioned immediately below it, allowing to lock the driven link position in any configuration. The joints of the operating arm present also a second brake allowing a motor to transmit motion to the joint, blocking the reducing gear box housing to the link diving link. Therefore, when both brakes are lose, the arm is passive and can easily be moved, when the first brake is locked the arm is rigid, while when the second brake is locked the linkage becomes a Robot. The passive arm differs only in the fact that the motors are missing.

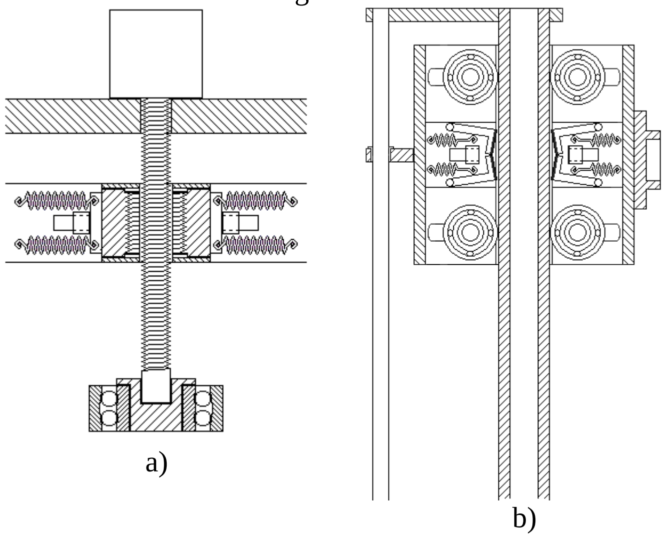

Fig 4 - Scheme of the active and passive vertical blocking systems

As far as the vertical sliding joint is concerned, fig. 4 shows the scheme of the two solutions used for the active (4a) and passive (4b) arms. Optical linear transducers will be used to monitor vertical positions. In the active case, a step motor assisted by an incremental encoder controls the rotational position of a long screw, placed in parallel to the vertical link. The mating female screw is divided in two halves, and moves with the sliding element. When the slider is to be blocked, then solenoids close the female on the long vertical screw, but only after the motor has rotated the screw so that the threads match. In the case of the passive slide the blockage is obtained using a linear L shaped element, very similar in its working principle with the brake used in the rotational joints, as will be explained later.

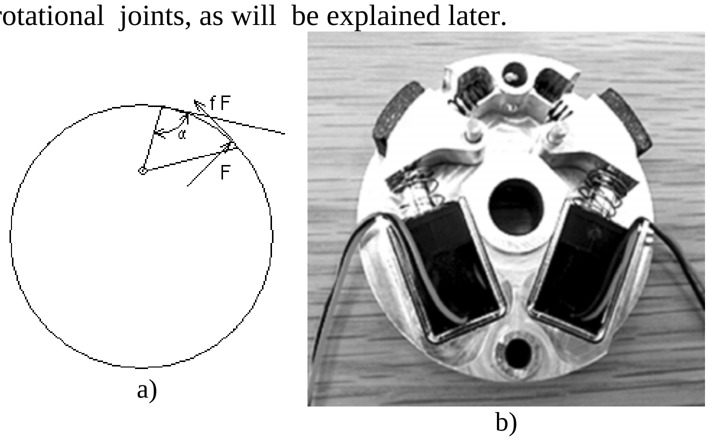

Fig. 5 - Scheme of the forces acting on the shoe of the locking drum brake and its realization

Key element of this project are the brakes, which are actuated by solenoids, and that allow locking and unlocking the various brakes on a simple command. Notice that these brakes need to be strong as entity of torque transmitted, but light in weight. They basically derive from a modified drum brake, and a patent application was also presented

[14]. The basic idea is that if the brake shoe pivot is halfway between the drum surface and centre, and the angle formed between the line joining the pivot to the last contact point of the shoe and the tangent to the drum in this point, is just over 90 degrees (angle α in figure 5a), then very small forces are sufficient to impede rotation in the counter clockwise direction, since in this case friction causes F to increase. By using two shoes positioned anti symmetrically (figure 5b), complete blocking is produced, unless torque is so high as to deform the shoes themselves.

As can be seen, in each hinge, structural and externally applied loads are supported by ball bearings independent from the encoder's one, differently from the configuration of the goniometric device from which the actual instrument derives. Links are made coupling hollow tubes with end connectors, many of which are identical, in order to simplify the construction process.

Under the robot calibration point of view a combination of both Denavit Hartemberg (DH) [15] and Complete and Parametrically Continuous (CPC) [16] model is to be used, in order to keep at a minimum the number of kinematical error parameters, avoiding redundancy [17, 18]. The joints' location selection was operated to reach three main objectives: to allow a direct approach to the region of operation, unlike manipulators having mutually orthogonal joint axes, for which a DH model can be used for calibration; to allow a much simpler inverse kinematical model, and finally to ease the balancing process.

Another key element of this instrument will be the electronic control system. In fact each encoder needs a minimum of five wires, which can grow to eighteen if the output is parallel. In fact there is the absolute need of recording all angles at the same instant of time, and this may favour the use of parallel outputs from each encoder. But each joint has also a step motor (a minimum of four wires) and two couples of solenoids (another four wires). Since there are six linkages on a row, this would cause a minimum of seventy-eight wires (one hundred and fifty six in the worse case) that should pass over the first link, decreasing in number passing from a joint to the following, but probably causing at least a certain rigidity of the entire linkage. Not to speak about the need of connecting at the end all these cables on boards to the controlling computer. To solve this it was decided to use a microprocessor at each joint, all connected to a master microprocessor talking to the PC through an USB2 gate.

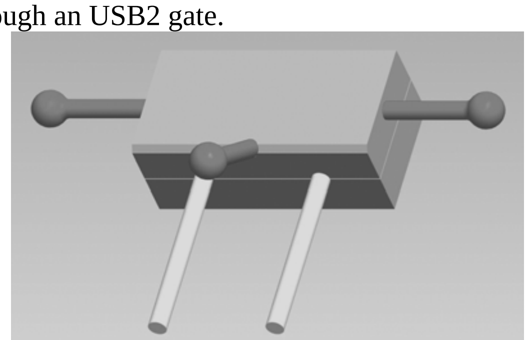

Fig. 6 - Clamp bearing three spheres for position reference

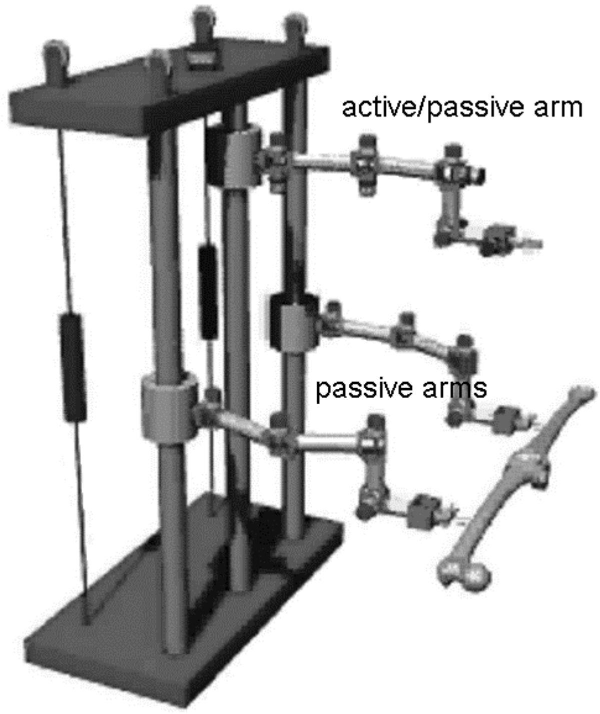

Fig. 7 - Actual CAD representation of Navi-Robot.

Passing to the foreseen software to be used in conjunction with this equipment, one way will certainly be to use it in conjunction with CAT scanning results, to compute and consequently represent in real time the position of the tool with respect to the patient's bony structure. In this, as in the following case, it will be necessary first to position two clamps, as the one shown in Fig. 6, each connected to the patient's bony structure by two pins, and characterized by the presence of three radio opaque spheres positioned in such a way that they can be observed as being separate from both a sagittal and a frontal point of view, before performing the scanning. Moreover the clamps will have to present a specially machined surface provided with keys, so that the measuring device will have only one way of being connected to the clamp. Thus if through the CAT the position of the bone will be known with respect to the spheres, then, knowing the geometry of the clamp, also the bone position will be known with respect to the Navi-Robot, which will hence be able to guide the doctor in locating the position determined as best to be used during the pre-planning section. This is indeed an almost ideal method, since it allows to study beforehand the situation, still being able to modify the approach intra-operatively. However it will also require a long preparation time, which is not always available. Moreover, the patient will have to be exposed to ionized rays, as will be in the second case.

An alternative way will be to acquire two fluoroscopic images, approximately a frontal and a sagittal view, once the clamps are again installed. Then, without moving the patient, the two passive arms of Navi-Robot should be connected in their unique way to the clamps. Then, identifying the six spheres on both pictures as well as the bones profiles, and eventually correcting for distortion,

knowing the spheres positions from Navi-Robot measurements, the points of observation of the two pictures will be determined [19] in the Robot frame of reference, that will hence supply an approximate 3D representation of the operating field, and the surgical procedure will be performable.
A third alternative, not needing any X ray information, will be the following, at the moment relative to a knee arthroplasty. First, as usual, the clamps will be installed, and immediately connected to Navi-Robot. Next the doctor will move the patient leg determining the hip centre of rotation, together with some useful information about the actual knee status (Lachman test, etc.). Next, keeping the foot fixed on the table, the foot central position will also be determined. Meanwhile, since the distance from clamp and bone is known with a good approximation from the pins length, counting the number of turns needed to pass from the first cortical bone to the second (being the thread length known in advance), and evaluating the amount of pin exiting from the clamp, then the position of the bone diaphyses will be known. Thus, knowing hip and foot centres, varus and valgus angles will be computed. Then the robot arm will advance so that the doctor may position a pointer on it, touching the external knee surface (in passive mode). At this point the doctor has all information needed to start the surgery. Once the skin is cut and the bone uncovered, condylar and glenoidal processes should again be described with the pointer, and Navi-Robot will show the doctor which cuts should be performed and way. Upon acceptance from the doctor, or request of change, the instrument will guide in Robot mode the sequence of cuts to be performed, also testing the results at the end.

4 Conclusion

Clearly at the moment no experimental results are available, but simulations performed with Functional Virtual Prototyping software, have allowed investigating on the static and dynamic stability of this system.
The design process is very advanced, and the first joint complete with rotational locking brakes was built and tested, demonstrating the validity of the concept. However still another version will be built and tested to find the best solution, since we need absolute reliability. Then, the entire prototype should be completed in a short time, thanks to our numerical milling machine. Consequently, the first prototype and experimental data are foreseen to be ready by october of this year, even if the electronic control system may not be ready by that time.

References:

[1] N. Suhm, L.P. Nolte, P. Ragazzoni, P. Messmer, M.E. Mueller “Computer Assisted Arthroscopically Controlled Removal of an Intraarticular screw: A Case Report” *5th International Symposium on CAOS* (Computer Assisted Orthopaedic Surgery) February 17- 19/2000 Davos (CH) – pag. 77.

[2] U. Berlemann, F. Langlotz, U. Langlotz, L.P. Nolte, “Computer-assisted orthopaedic surgery (CAOS): From pedicle screw insertion to further applications” *ORTHOPADE* 26 (5): 463-469 May 1997.

[3] D. Schmucki, R. Schwyn, J. Wirth, P. Messmer, S. Koller, P. Regazzoni “Robotics, Navigations, and a new passive holding device – A combination for the future?” *3rd Annual Meeting of CAOS – International – Proceedings* – Marbella (Spain) June 18-21 2003 p.328.

[4] K. Bouazza-Marouf, I. Browbank, J.R. Hewit, “Robot-assisted invasive orthopaedic surgery” *Mechatronics*, Volume: 6, Issue: 4, June, 1996, pp. 381- 397

[5] K. Bouazza-Marouf, I. Browbank, J.R. Hewit, “Robotic-assisted internal fixation of femoral fractures” *Proc. IMechE part H – Engng Med.* 209 (H1), 51-58 (1995)

[6] P.Y. Zambelli, S.T. Dewarrat, C.H. Bregand, G.A. Marti, C.H. Baur, P.F. Leyvraz “Electro mechanical arm – An alternative to the classical opto-tracking system” *3rd Annual Meeting of CAOS – International – Proceedings* – Marbella (Spain) June 18-21 2003 p.412

[7] N. Confalonieri, “The Role of Computer Assisted Surgery for Hip and Knee”, *Ist PRO.MI National Congress*, Monza, nov. 12-13, 2004

[8] A. Leardini, L. Rapagnà, A. Ensini, F. Catani, A. Cappello, “Computer-assisted preoperative planning of a novel design of total ankle replacement” *Computer Methods and Programs in Biomedicine*, Volume: 67, Issue: 3, March, 2002, pp. 231 – 243

[9] G. Voss, A. Bisler, U. Bockholt, W.K. Muller-Wittig, A. Schaffer, “ICAPS an integrative computer-assisted planning system for pedicle screw insertion” *Stud Health Technol Inform* 2001;81:561-3

[10] G. Gatti, G. Fragomeni, e G.A. Danieli, "Theoretical Study and Design of a six Degrees of Freedom Measuring Device for Biomechanical Applications", *6th Biennial Conference on Engineering Systems Design and Analysis*, Istanbul, Turkey, july 8-11 2002, # ESDA2002/BIO-015

[11] G.A. Danieli, G. Fragomeni, G. Gatti, S. Savio and S. Vitelli "Theoretical analysis of a new self balancing twelve d.o.f. goniometer for Virtual Reality representation of the surgical theatre" *11th World Congress in Mechanism and Machine Science*, April 1-4, 2004, Tianjin, China, paper #Rd56

[12] G.A. Danieli, G. Fragomeni, G. Gatti, D. Moschella and D. Mundo “Introducing Navi – Robot, a novel instrument for surgical procedures” *International Congress on Computational Biomechanics*, Zaragozza, Sept. 23-26, 2003, Vol. 1, 125-129

[13] G.A. Danieli, G. Fragomeni, G. Gatti e D. Mundo "Navigator – Robot for Surgical Procedures",

PCT/IT03/00322 del 27/05/2003, WO 03/4469/3 of December the 4th 2003, EP03730474.8

[14] G.A. Danieli, "Ulteriori Affinamenti del Navigatore - Robot per interventi di protesica ortopedica", Patent Application No. CS2004A00010, deposited 09/08/2004

[15] J. Denavit and R. S. Hartenberg, “A kinematic notation for lower-pair mechanism based on matrices”, ASME *J. Appl. Mechan.*, pp.215-221, June 1955

[16] H. Zhuang, Z. S. Roth, H. Fumio, “A complete and Parametrically Continuous Kinematic Model for Robot Manipulators”. *IEEE Transactions on Robotics and Automation* 8(4), 451-463, 1991.

[17] H. Zhuang, K. Wang, Z. S. Roth, “Error-modelbased robot calibration using a modified CPC model”. *Robotics Computer-Integr*. *Mfg* 10(4), 287-299, 1993.

[18] J. Caenen and J. Angue, “Identification of geometric and non geometric parameters of robots”, *Proceedings of the 1990 IEEE International conference on robotics and automation*, pp. 1032-1037.

[19] G.A. Danieli, G. Fragomeni and G. Perrozziello, “An iterative solution to establish a correspondence between points image and real coordinates in space for application to real time V. R. representation of surgical procedures”, *6th Biennial Conference on Engineering Systems Design and Analysis*, Istambul, Turkey, july 8-11 2002, paper ESDA2002/BIO-016