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# BRIGIT, a Robotized Tool Guide for Orthopedic Surgery*

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*Abstract* – **The BRIGIT project (Bone Resection Instrument Guidance by Intelligent Telemanipulator) aims at developing a surgical robot for orthopedic surgery. This robot should be used as a positioner of a guide providing a mechanical support during bone sawing or drilling. The planned position of the guide is obtained after a registration procedure consisting in collecting anatomical landmarks on the surface of the patient's bone. This can be done in a cooperative mode, by grabbing the tool tip, through an appropriate force control, or in a teleoperated mode *via* a master device. In order to facilitate the installation of the robot in the operating theatre and to improve its performance, a procedure based on interval analysis has been developed to optimize the robot placement with respect to the patient, the surgical staff, and the obstacles of the environment.**

*Index Terms – Medical robotics, orthopedics, robot placement, interval analysis.*

## I. Robots in Orthopedic Surgery

One of the main advantage expected in introducing robots in the operating theatre (OT) is to improve the surgeon accuracy. This is of paramount importance especially in orthopedic surgery, *e.g.* for total hip (THR) or total knee (TKR) replacement, where the components of the prosthesis have to be precisely positioned onto the bones [1] to prevent from wear, loosening, and pain, thus avoiding subsequent revision surgery.

The first orthopedic robots used clinically were industrial manipulators equipped with a tool for drilling or milling, such as ROBODOC and CASPAR [2]. During a pre-operative planning procedure using CT images, the surgeon selects the best implant from a data-base and specifies the location of the components. Then, the data are transferred to the robot for intraoperative use. A registration procedure is executed in the OT, involving generally pre-implanted fiducial markers. More recently, an anatomical pinless registration procedure for THR has been proposed for ROBODOC but still using preoperative CT. Then, the robot machines the patient's bone in an autonomous manner, creating an exact implant-specific cavity. Another approach is illustrated by the ACROBOT system [3], where the surgeon guides the robot even during the machining process. The surgeon uses an input handle, incorporating a force sensor, mounted on the tip of the robot. An appropriate force control scheme constrains the tool to remain into a predefined 3D safe region, thus preventing the surgeon from removing too much bone or the tool from colliding forbidden anatomical structures.

A new generation of low-size and lightweight orthopedic robots, generally dedicated to a single type of intervention, has recently appeared. The MARS system (for pedicle screw insertion, and intramedullary nailing for fracture fixation) now developed by Mazor Surgical Technologies, is based on a parallel robot clamped directly near the patient's surgical site, for instance on the spinous process of a vertebra [4]. The robot is used to move a tool guide to the planned location. Then, while the robot is locked, the surgeon executes the machining procedure. A similar femur-mountable device, the ARTHROBOT, was proposed in [5] for THR.

To cover the whole range of solutions intended to improve the orthopedic surgeon's performance, let us mention the effort of several companies to offer "modern" ancillaries based on computer assisted navigation systems (Medacta, OrthoSoft...) together with specific guide positioners providing the necessary degrees of freedom (dof) to reach the desired tool position and orientation (*e.g.* the hand-held operation-robot ITD (Intelligent Tool Drive) [6], Galileo from PI Precision Implants [7], or the GP system [8] from Medacta).

In this paper, we present the BRIGIT system (Bone Resection Instrument Guidance by Intelligent Telemanipulator), which stems from the following analysis: in order to be more acceptable in the OT, the robots should be less cumbersome, easier to install and operate (namely without the use of CT images or with a simplified registration procedure), cheaper than the existing systems. So far, we focused on the second constraint. In the first section we describe the prototype and its performance as well as the registration procedure consisting in collecting anatomical landmarks on the surface of the patient's bone, requiring no preoperative imaging. In the second section, we present the teleoperation control mode that facilitates the surgeon-robot interaction. In the last section, we describe and illustrate the optimal placement procedure.

## II. BRIGIT Description

### A. The BRIGIT system

BRIGIT is a robotic system developed by MedTech SA, a French small engineering company, to assist surgeon during orthopedic interventions such as TKR or osteotomy. The BRIGIT robot is a compact 6-dof robot mounted onto a wheeled trolley, together with its control

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software. A force sensor is mounted between the robot flange and the machining tool. So far, two man-machine interfaces have been integrated: the first is a standard user-friendly graphic interface, the second is a master arm (section III).

The basic ideas behind the development of BRIGIT are the following: i) the robot should be used as a positioner of tool-guides providing a mechanical support during bone sawing or drilling, ii) it should work with the surgeon in a cooperative mode in which an artificial compliance, synthesized from the force sensor data, makes the robot backdrivable (the surgeon can then move the robot by grabbing the tool tip) or in a teleoperated mode through a master arm, iv) it should work without preoperative imaging and navigation system, v) and, obviously, it should comply with the safety rules required in surgical robotics [2] [9].

To illustrate how these specifications have been implemented within the BRIGIT system, we present in the next section the HTO (High Tibial Osteotomy) application [10]. Similar applications are under development for THR and TKR.

### B. *The High Tibial Osteotomy application*

The HTO is a corrective surgical procedure intending to correct the alignment of the tibia and femur, for example in the treatment of arthritic knee. The upper part of the tibia must be resected with a precise angle defined on the radiograph pictures so that the lower limb can be realigned as shown in Fig. 1. One of the major difficulties with HTO is the risk of over- or under-correction leading to non aesthetic and non optimal functional performance, which justifies the robotization of the procedure.

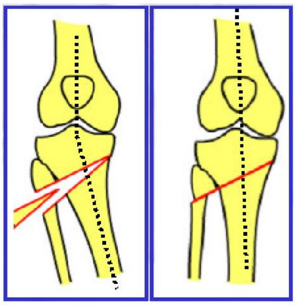

Fig. 1. Tibial osteotomy [11].

The first step of our HTO procedure consists in collecting a series of anatomical landmarks to determine the anatomical axis of the tibia and the level of the upper resection to be done. In order to achieve this, BRIGIT is used in the cooperative mode with a pointing device (Fig 2). Then, the surgeon inputs the desired correction angle as he does in a conventional intervention.

In the second step, the pointing device is replaced by a cutting guide. Adequate position of the guide to realize the resection is derived from geometrical calculations performed from the desired surgical planning parameters and the landmarks (providing equations of the anatomical axes and the resection planes of Fig. 1). Then, the robot positions and locks the guide. In the final step, the surgeon executes himself the cutting process as shown in Fig 3. During both steps, the bone is rigidly attached to the operating table with a specific fixation device.

This approach is intuitive and very easy to operate. It allows an optimal precision of the angle of correction. We have verified through dry bone tests that the geometrical calculations do not depend on the operator. The results are very encouraging since the average error on the correction angle obtained after 20 experiments is better than 0.7°. Moreover, it has been shown that the duration of the operation was shorter and more predictable than with a manual HTO procedure involving conventional ancillaries.

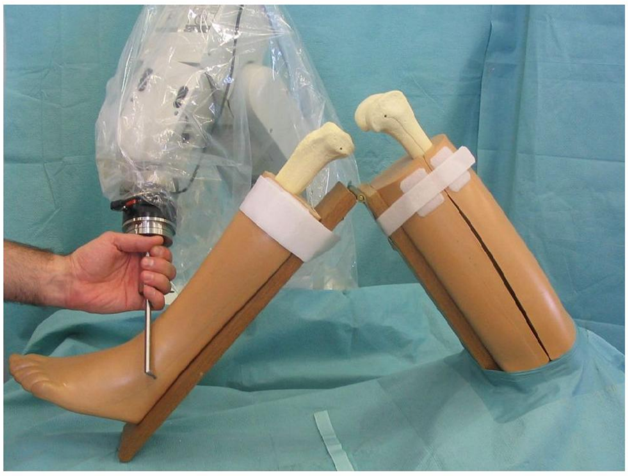

Fig 2. Collecting the anatomical landmarks

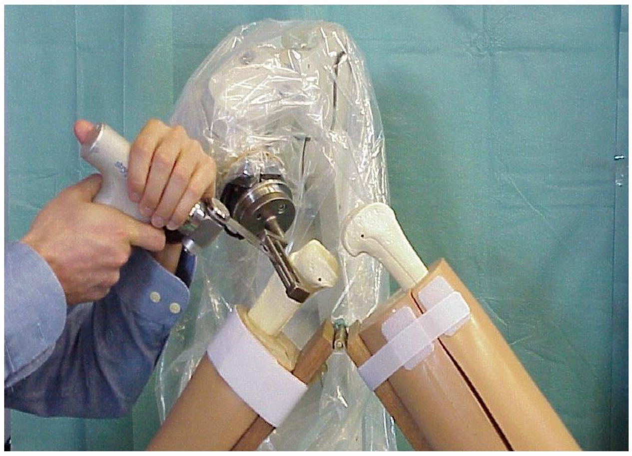

Fig 3. Cutting phase

## III. TELEOPERATION

### A. *Introduction*

One of the main advantages of teleoperation in surgery is to enhance the precision and dexterity of the surgical gesture. This is done through a proper data processing of the master arm prior transmission to the slave arm: tremor can be filtered; the amplitude of motions and interaction forces can be bounded for safety purpose, or scaled for microsurgery. A second advantage is the intrinsic ability of the bilateral configuration of the master-slave system to provide haptic feedback to the surgeon through the master arm, *i.e.* sensations identical to the ones he would have if he were directly holding the tool. This feedback may be synthesized from force sensor data, provided that the sensor is mounted at the very tip of the tool, close to the application point of the interaction forces.

Many such applications concern minimally invasive surgery, in which the surgeon interacts with soft tissues through a master-slave device, or training simulators. As outlined by Esen *et al.* [12], a few work has been done for orthopedic surgery so far. However, we think that haptic feedback could be very useful for the surgeon to feel transitions between bone and soft tissues, and help him to better control cutting or drilling operations. The master-slave architecture described in this section is a preliminary work which will allow us to explore more in details the benefit on the surgeon's performance of the stiffness variation detection.

One basic problem of haptic feedback comes from the delay induced by the communications, which is not much relevant for BRIGIT application since the distance between the master and slave devices is very short (within a few meters). Another problem is the sampling frequency, which is fixed by the robot controller and is generally not high enough. The subsequent limited bandwidth of the closed-loop system implies lessening the gains to prevent instability, to the detriment of the system transparency, *i.e.* the ability of the haptic system to reproduce the sensations as correctly as possible. Several teleoperation structures can be found in the literature [13], handling more or less satisfactorily the trade-off between stability and transparency. These structures have been compared, keeping in mind the hardware and software constraints of BRIGIT.

### B. *Implementation*

We have implemented two structures: a conventional position-force one (the current position of the master is sent to the slave that generates force or torque inputs to the actuators; the force exerted on the environment by the slave is reflected to the master); and a "passive" position-force structure (adding to the previous one some damping parameters). The first one presents good performance in terms of transparency but not good in terms of stability, which is the contrary for the second structure. This choice has been motivated by the simplicity of implementation, and was enough in a first attempt to validate the interest of an haptic feedback for BRIGIT application.

The various equipments available have their own specific and proprietary architectures, and are not configurable by the users. This explains the rather complicated architecture that has been developed (Fig 4). Practically, the client / server architecture requires 2 PC: the server runs under Windows XP and RTX 6.0; the client runs under Windows XP only because the Phantom does not support RTX. The position of the master arm is read and sent to the PC server every 1 ms. The force data are acquired every 0.5 ms and sent to the PC client every 1 ms. The two PC communicate through an Ethernet link with UDP protocol.

Experiments have confirmed existing results indicating that stability highly depends on the tuning of the gain of the force loop. However a satisfying trade-off may be obtained to synthesize a realistic and stable haptic rendering. In the future, more sophisticated structures, based on predictive control with passivity for instance, will be evaluated in order to increase bandwidth while still guaranteeing stability.

## IV. Optimal Robot Placement

### A. *Introduction*

Placement is a recurrent problem in robotics. It influences the robot performance, and regarding surgical robots, it may have serious outcomes on safety. Very quick procedures should be available to facilitate the robot installation while increasing accuracy and security, and ensuring the feasibility of the task. Practically, when installing a robot, the surgical staff has to deal with several factors: surgical parameters, patient morphology, regulation and environmental constraints, but also robotic constraints which are generally more difficult to handle for a non specialist: the robot should be placed with respect to the patient such that all the anatomical landmarks are reachable without repositioning the robot; all the desired orientations of the guide over the surgical site should be reachable; the singularities of the robot should not affect any desired continuous path of the tool, etc. These constraints justify the need of tools to facilitate the robot placement in the OT.

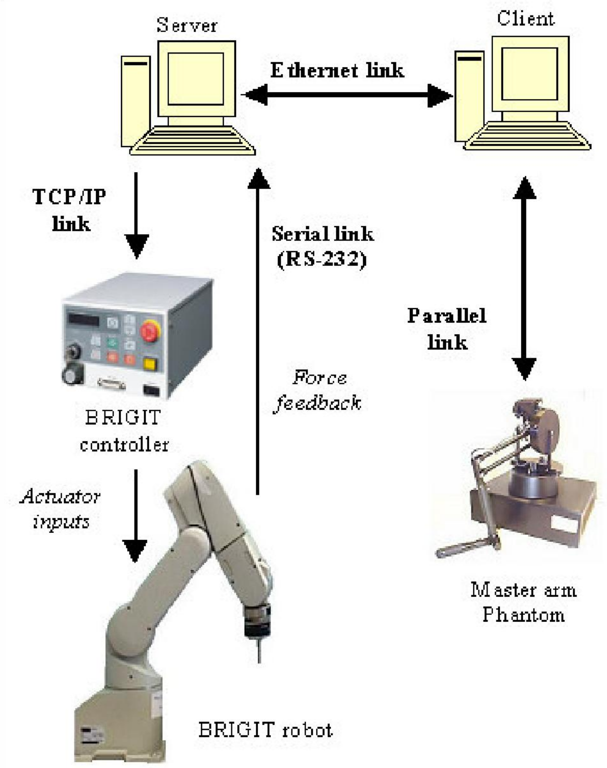


Fig 4. Architecture of the BRIGIT system with haptic feedback

One of the difficulties is that the optimization problem is over-constrained as many constraints are conflicting. Thus some trade-offs have to be found. Several solutions have already been proposed in manufacturing workcells, the goal being there to minimize cycle time of the industrial robots. In [14], the authors present an algorithm based on two heuristic search methods: simulated annealing and genetic algorithm. Pamanes in [15] uses a non-linear search optimization technique to find the best design parameters of a robot and the optimal placement to achieve a predefined task with a maximum dexterity and minimum arm length.

In [16] surgical robotics, the objectives are obviously different, since safety is of higher priority than time. A few works have been reported in the literature so far. In [17], the authors present an integrated planning and simulation software for cardiovascular minimally invasive surgery, based on a semantic description of the intervention, to find the best port placement and robot placement. This is done sequentially after that the surgeon has validated the port placement proposed by their algorithm. Criteria such as reachability from an admissible point and dexterity are maximized. In , similar objectives are pursued with a different approach considering internal landmarks obtained from preoperative images of the patient, rather than external ones. Abdel-Malek in [18] and [19] proposes a numerical method based on maximizing the dexterity at specified target points defined by the surgeon. Engel in [20] presents an algorithm which provides the possibility to preoperatively determine the best relative positioning of robot and patient in craniofacial surgery. A robot manipulator assists the surgeon when drilling or milling the skull bone according to preoperatively planned cut paths. The criteria are feasibility of the path, maximum distance to singularities, no collisions between robot arm segments or between robot and patient and surgical access path. This method is accurate, efficient and safe but time-consuming.

In the following sections, we present an original approach inspired by interval computation in order to optimize the placement of the robot according to the surgical, environmental and robotic constraints [21].

*B. Interval analysis*

Interval analysis is a particular approach of computation on sets initially developed for computers to quantify errors induced by the rational representation of real numbers [22]. In this section we recall some definitions of interval arithmetic.

A set $[x]$, a real interval, non-empty, closed and bounded subset of real numbers $R$, is defined by:

$$[x] \equiv \left[x^-, x^+\right] \equiv \left\{x \in \mathbb{R} \mid x^- \leq x \leq x^+\right\} \qquad (1)$$

Operations on numbers and Booleans are extended to sets as follows:

$$X \Diamond Y \equiv \{x \Diamond y \mid x \in X, y \in Y\} \text{ with } \Diamond \in \{+,-,*,/\} \quad (2)$$

For example:

$$\left[\underline{x},\overline{x}\right]+\left[\underline{y},\overline{y}\right]=\left[\underline{x}+\underline{y},\overline{x}+\overline{y}\right] \qquad (3)$$

$$\left[\underline{x},\overline{x}\right]*\left[\underline{y},\overline{y}\right]=\left[\min(\underline{x}\underline{y},\underline{x}\overline{y}+\overline{x}\underline{y},\overline{x}\overline{y}),\max(\underline{x}\underline{y},\underline{x}\overline{y}+\overline{x}\underline{y},\overline{x}\overline{y})\right] \quad (4)$$

Given a set $[x]$ and a function on real $F: R^n \rightarrow R^m$, its natural extension to intervals can be obtained by replacing the real variables by their interval counterparts: $[F]: IR^n \rightarrow IR^m$. $[F]$ is an inclusion function (Fig 5) of $F$ if:

$$\forall [x] \in IR^n, F([x]) \subset [F]([x]) \qquad (5)$$

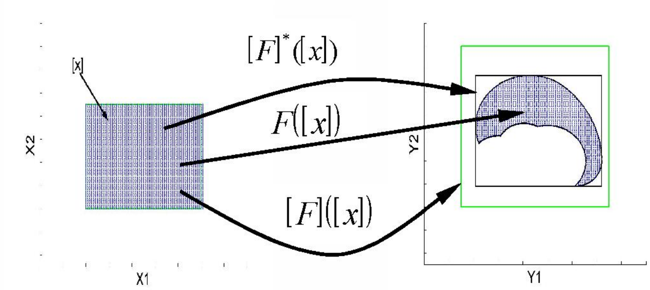


Fig 5. Inclusion function

$[F]$ is one of the various inclusion functions and $[F]^*$ is the minimal inclusion function.

*C. Simulation and results*

In this paper, we present simulation results for a 4-dof spatial manipulator (1 translation and 3 rotations).

The objective is to find the best robot placement providing the required dexterity, avoiding singularities and such that the robot workspace includes the target region predefined by the surgeon. The simulator works as follows: first, the surgical staff places the table in the OT and the patient on the table.

The surgeon selects anatomical landmarks on the tibia that the robot will have to reach during the operation. Then, the simulator computes the corresponding "target spaces" which associate a landmark with a tolerance: a target space is then defined as a set. The next step is to search an inner approximation of the reachable workspace which guarantees the accessibility constraint and respects some given criteria (phases A, B, C in Figure 6).

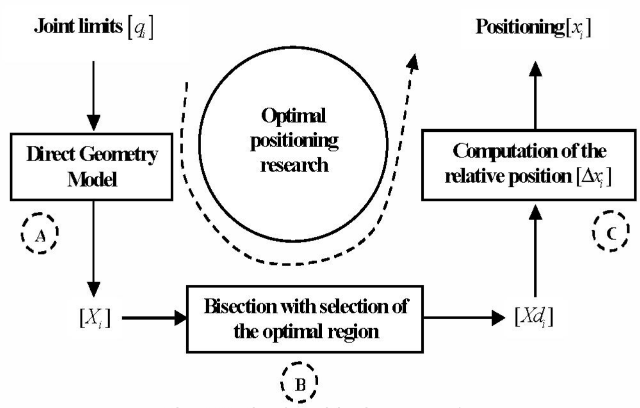


Fig 6. Optimal positioning research

An outer approximation of the workspace (Fig 5 and Fig 6) is computed from the extension to the interval counterpart of the direct geometric model (DGM) (phase A) expressing the Cartesian coordinates of the end-effector as a function of the joint variables:

$$\left[q_j\right]=\left\{q_{j\min}\le q_j\le q_{j\max}\right\} \tag{6}$$

$$\left[X_i\right]=[f]\left(\left[q_j\right]\right) \tag{7}$$

The box obtained will be used as the initial box for the bisection phase (phase B). During this phase, this box will be cut out as several little boxes which are fully included in the workspace [23]. The resulting list is then analyzed to keep only boxes which respect the given criteria (accessibilty, manipulability, …) seen in Fig 7.

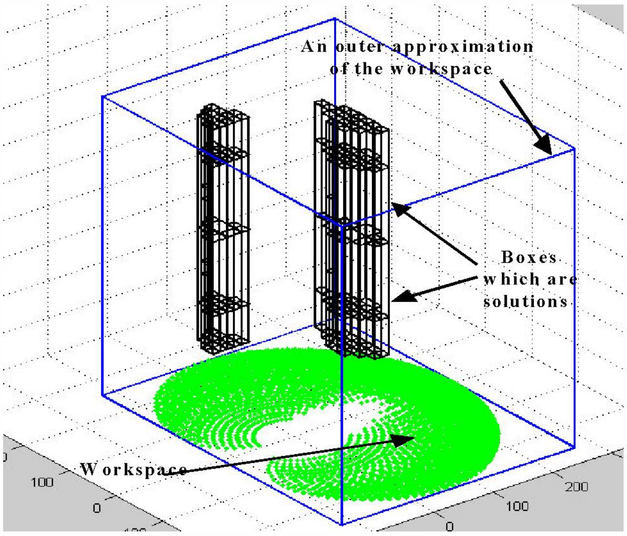


Fig 7. Bisection

The robot positioning phase may start (phase C). Given the relative position $\Delta x_i$ between the robot base and the box solutions, the robot placement ($x_s$, $y_s$, $z_s$) is computed so that the solution regions include the anatomical target region centered in ($x_t$,$y_t$,$z_t$) (Fig 8).

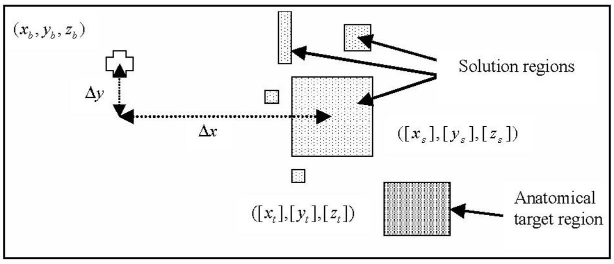


Fig 8. Placement computation

$$\begin{aligned} x_s &= x_t - \Delta x \\ y_s &= y_t - \Delta y \\ z_s &= z_t - \Delta z \end{aligned} \tag{8}$$

The resulting placement solutions are boxes centered in ($x_s$,$y_s$,$z_s$) that represent the set of positions from which the robot can reach all points in the target region.
This processing is repeated twice on the robot workspace for both right and left elbow joint configurations (Fig 9 a and b) which allow reaching respectively the proximal (near the knee) and distal (near the ankle) parts of the tibia. The two non-connected base placement areas of Fig 9 a) are due to the collision between the robot base and the operation table. The final solution is the intersection between boxes solutions for left elbow configuration and boxes solutions for right elbow configuration (Fig 10).

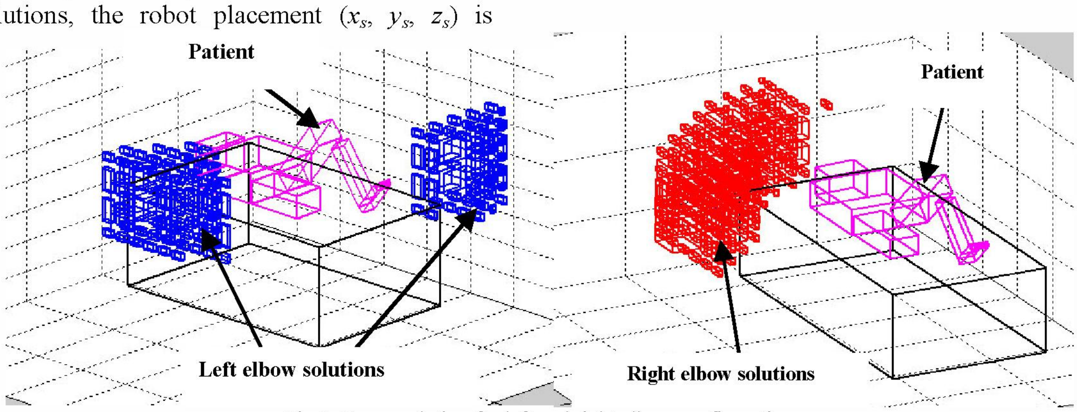


Fig 9. Boxes solution for left and right elbow configuration

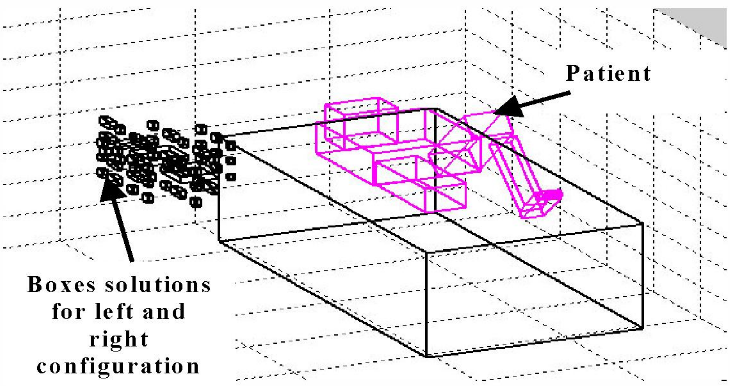


Fig 10. Intersection of solutions

The set of solutions will contain the position where the robot can be placed in order that its end-effector reaches all points situated in the target region including the points predefined by surgeon. In, Fig 11, the robot base is placed to work in the best configuration, its workspace including the two regions of interest for this application.

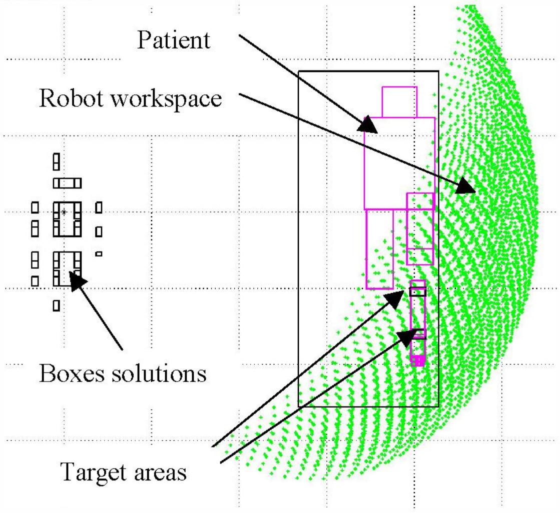


Fig 11. View of robot positioning for operation

Once the optimal region has been computed, and before starting the surgical procedure, a registration step is achieved. A robot path is computed to drive the pointing device on the center of the selected box in the robot workspace. Then, the height of the table and the location of the robot base with respect to the table are manually adjusted until the pointing device coincides with the knee anatomical landmark.

## V. Conclusion

We have presented the BRIGIT system, a robot for orthopedic surgery and its user interfaces. In the design process, emphasis has been put to facilitate the use of the system in the OT. To this end, an intuitive registration procedure, based on anatomical landmarks selection rather than preoperative images, has been validated. The robot is used as a tool guide positioner, the surgeon remaining in the loop to drive the machining tool. We have also validated the use of a master arm to teleoperate BRIGIT, the interest of which being the force-reflecting capabilities to provide the surgeon with haptic sensations. Finally, we have presented a method based on interval analysis for computing optimal placement of the robot in the OT. Criteria such as reachability, joint limit avoidance, and dexterity have been considered. Other criteria, such as avoidance singularity or surgeon comfort should be considered as well. The method has been validated on a 4-dof Scara-like robot. It should be implemented in the BRIGIT application in the next future and experimented in a real environment.

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