Robotica (2005) volume 23, pp. 345–354. © 2005 Cambridge University Press
doi:10.1017/S0263574704000967 Printed in the United Kingdom

A Serial-parallel robotic architecture for surgical tasks

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(Received in Final Form: July 24, 2004)

SUMMARY

In this paper the concept of a serial-parallel macro-milli manipulator is presented for medical applications by investigating the feasibility of combining two different robotic structures into one system. The combination of the two structures can be used as a redundant system in which stiffness, singularity and accuracy can be optimized as related to workspace demands and restrictions that are required for *a priori* selected medical applications. A case study has been experienced at LARM (Laboratory of Robotics and Mechatronics) at the University of Cassino through a new system composed of a commercial Adept COBRA and CaPaMan2bis (Cassino Parallel Manipulator 2bis). The performance of this system is compared with a previous serial-parallel macro-milli robotic system also developed at LARM in Cassino. Experimental tests have been carried out in order to characterize the proposed systems.

KEYWORDS: Surgical tasks; Robotic architecture; Two structures.

1. INTRODUCTION

The use of robots for medical purposes is a practice, which has started only few years ago. However, several researchers have investigated and demonstrated the advantages of robotic systems in surgery, such as Kavoussi et al.[1] and Cameron et al.[2] Thus, some robots for surgery tasks are already available in the market[3–11] and many robots have been already tested in several medical procedures.[12–24] Examples are described in references [14–24] by referring, for example, to endoscopic surgery, hip or knee replacement, pedicle screw fixation and other orthopedic procedures, stereotactic biopsy, craniotomy, ophthalmic surgery and otoneurosurgery.

Nevertheless, those solutions are mainly robots having serial architectures. Robots having this type of architecture suffer with several known drawbacks. In particular, the serial architecture suffers from a relatively low stiffness and accuracy, low nominal payload/weight ratio, and heavy weight.[25] These aspects are critical for medical tasks in which accuracy and safety are a matter of life or death.[26] Therefore, researchers are investigating parallel and hybrid architectures in order to design manipulators having a better performance for a specific surgical task or limited field of tasks.

In this paper, the feasibility of serial-parallel macro-milli manipulators is presented for areas of medical applications by investigating the combination of two different robotic structures into one system in order to obtain the advantage of both architectures, as proposed for example in references [27–31].

2. MAIN REQUIREMENTS FOR ROBOTIC SURGERY

Considering the data in the referenced literature and feedback from surgeons in operating rooms (O.R.), the following requirements and characteristics can be considered essentials for a medical robotic system performing medical tasks: effective control, limited workspace, limited volume occupancy, limited forces, force feedback, immunity against magnetic interference, fail-safe features capability, high accuracy, singularity free task, easy calibration and registration, sterilization ability.

The force applied by the robot during procedures should be fully controlled in order to prevent damages to tissues and to increase accuracy. A force control is particularly needed in procedures where different levels of force should be implied such as bone cutting. In fact, due to the bone structure, different forces have to be applied depending on directions, depth of cut and type of bone cortex and medullar parts. Therefore, the robotic system should have a fast control of the exerted force on the bone due to quick changes in this force.

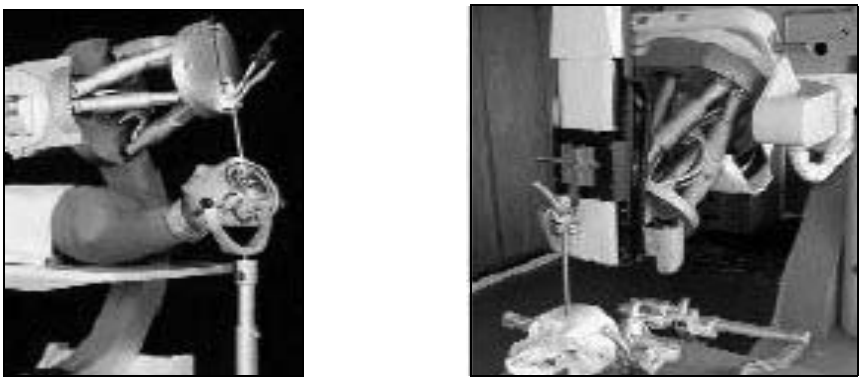
Effective control is required mainly for both force and speed control of the end-effector in real-time. The physician should be allowed to control these two magnitudes in all robot configurations with a user-friendly interface. Moreover, a physician should have the ability to stop or pause the process according to his/her judgment.

The workspace of a robot should be limited to the effective area of the operation in order to prevent accidental damage both to the physician and patient. An optimum design procedure could be implemented in order to optimize the coverage of the end-effector workspace relative to the tasks workspace. In this way, only the needed region within the task workspace would be reachable by the surgery tool.

A limited volume occupancy of the robotic system is needed in order to have enough space for the surgeon and all the surgery tools in the O.R. It is of fundamental importance

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(a) (b)

Fig. 1. Prototypes of robots for medical applications having parallel architecture: (a) a model of an Hexapod robot for neuroendoscopies; (b) "Evolution 1" during a drilling at the skull basis, [4].

to let the surgeon capable of operating in the operation area, although the presence of the robots.

Immunity against magnetic interference of other surgical tools available in the O.R. is also a very important requirement not only for a medical robotic system but also for any system in the O.R.

High accuracy can be guaranteed only if the robotic system can be easily calibrated and registered with respect to the target by using a suitable tracking system that can track the location of the tool relative to the target. Solutions that can be adopted are, for example, the use of intra-operative imaging, real-time measuring devices or vision sensors.

3. AVAILABLE MEDICAL ROBOTIC SYSTEMS

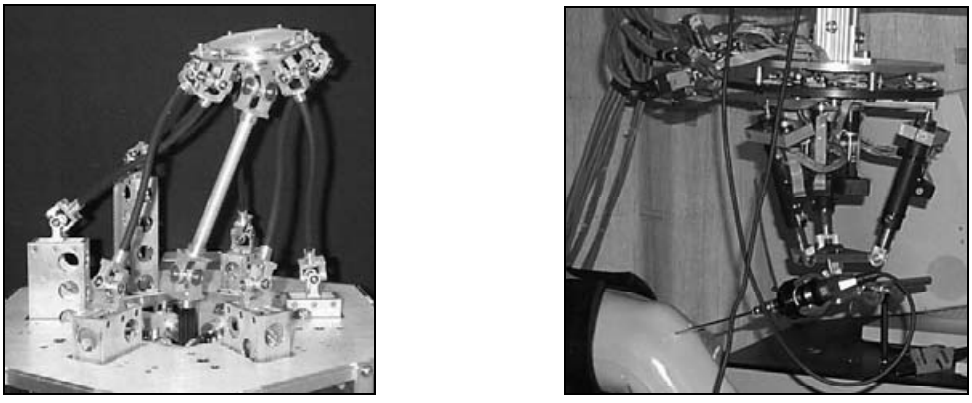
The clear advantages of a robot over the human hand led several researchers to develop robot manipulators for surgical applications. The first known commercial robot for surgery was Robodoc.[3] Since 1990 it has been used for surgery on dogs. Since 1992 it has been used for operating a milling tool in cementless prostheses implant, on humans.

To the authors' knowledge, other robotic systems that are available in the market are: Neuromate[3], CASPAR[4], AESOP[5], ZEUS[5], Da Vinci[6], MKM[7], EndoAssist[8], PathFinder[8], OrthoTrack[8], CyberKnife[9], ParaDex[10] and Laprotek.[11]

CASPAR is used for hip replacement. AESOP is used for camera support. ZEUS and Da Vinci are used for instrument support in endoscopic surgery. EndoAssist and MKM are used as carrier for vision systems and surgical microscopes. CyberKnife is used as carrier for a compact linear accelerator in stereotactic radiosurgery. Neuromate is used for endoscope/catheter guidance. Laprotek is used for the remote operation of several laparoscopic instruments. PathFinder and OrthoTrack are used for precise positioning of surgical instruments in neurosurgery and orthopaedic surgery.

Robotic systems have been already successfully used in the treatment of several diseases. However, the use of robots for medical purposes can be further increased by developing robotic systems that are safer and more user-friendly. Also very useful for surgery tasks is to develop robots having higher accuracy and dynamic response together with lower cost of hardware design, operation and maintenance.

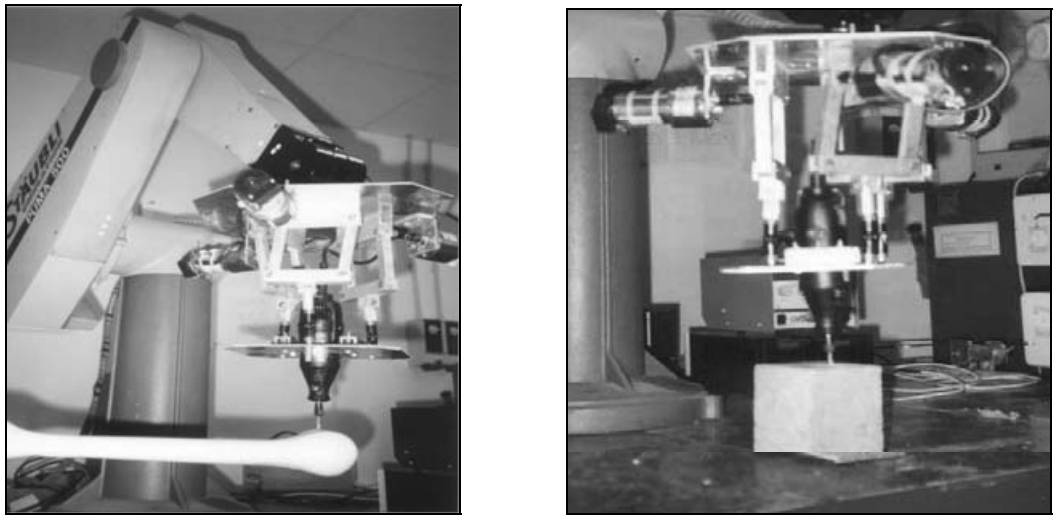
It is worth noting that the available robotic systems for surgery have a serial architecture that is well known to have a lower performance in terms of accuracy, stiffness and payload compared with parallel architectures. Therefore, some research groups are investigating the use of parallel architectures in surgery tasks. Some examples are Evolution 1[4], ParaDex[12] and RSPR3[13], which are shown in Figs. 1 and 2.



(a) (b)

Fig. 2. Prototypes of robots for medical applications having parallel architecture: (a) ParaDex (PARAllel DEXterous), [10]; (b) RSPR3 robot, [13].

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(a) (b)

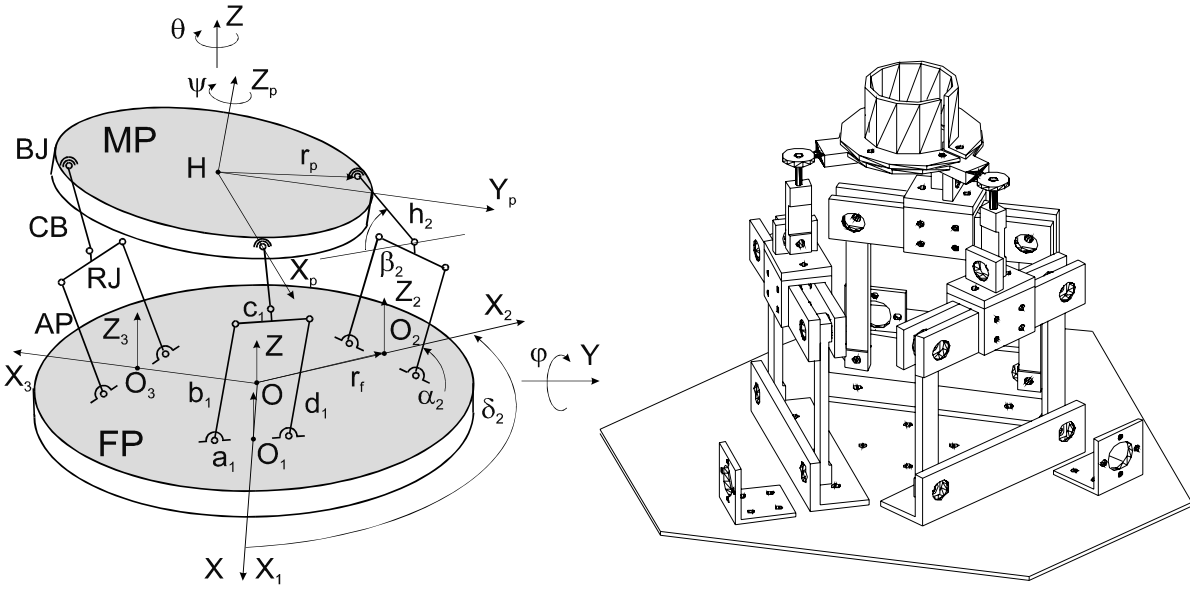
Fig. 3. A serial-parallel macro-milli manipulator at LARM in Cassino (Italy): (a) the overall system composed of an industrial robot Puma 652 and CaPaMan2 prototype; (b) the CaPaMan2 prototype in a drilling operation.

Also hybrid serial-parallel architectures as the one shown in Fig. 3 have been proposed in order to obtain the advantages of parallel and serial architectures. Preliminary successful results that have been obtained by using a serial-parallel robotic system composed of a Puma 562 and CaPaMan2 (Cassino Parallel Manipulator 2) as reported in references [26–34] and shown in Fig. 3. Therefore, enhancements in the design of this serial-parallel robotic system have been studied and a new design has been proposed.

4. A NEW SERIAL-PARALLEL MACRO-MILLI ROBOTIC MANIPULATOR ARM FOR MEDICAL APPLICATIONS

The proposed new robotic system is composed of a commercially available serial robot and a prototype of parallel manipulator having 3 dofs. The serial robot that has been chosen is a SCARA robot Adept Cobra.[35] In fact, this robot has a satisfactory dynamic and accuracy performance. The parallel robot that has been developed for this specific application is named as CaPaMan2bis (Cassino Parallel Manipulator 2bis). It has almost the same kinematic design of CaPaMan2. But several enhancements in the mechanical design have been considered in order to increase the stiffness and accuracy performance, as shown in Figs. 4 and 5.

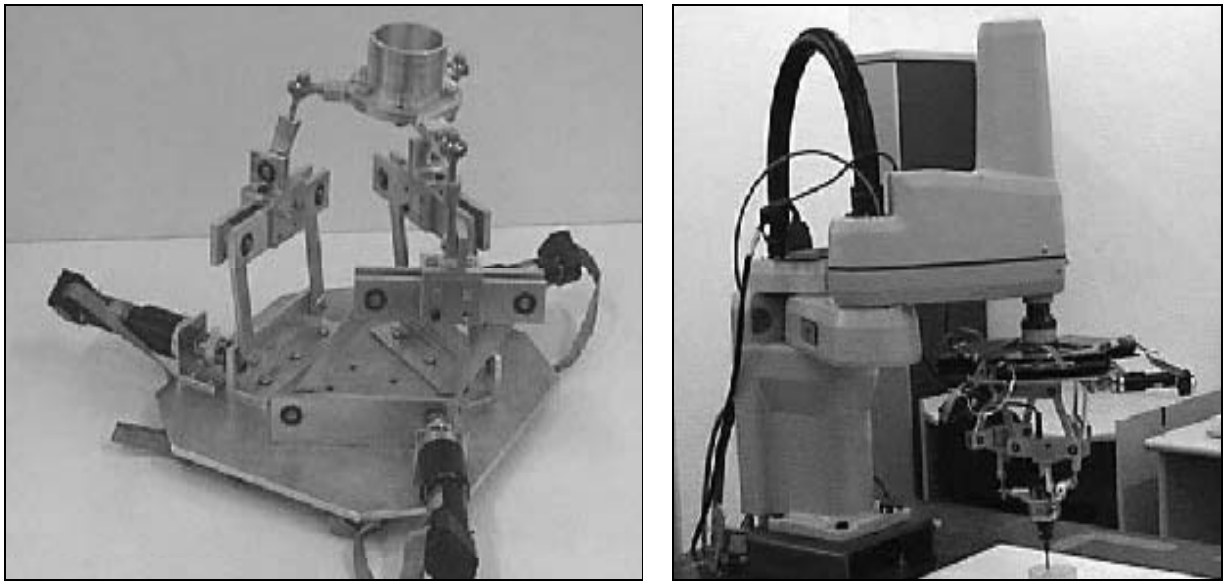
A kinematic scheme of CaPaMan2bis is shown in Fig. 4a), where the fixed platform is FP and the moving platform is MP. MP is connected to FP through three identical leg mechanisms and is driven by the corresponding articulation points. An articulated parallelogram AP, a rotative joint RJ and a connecting bar CB compose each leg mechanism. AP's



(a) (b)

Fig. 4. CaPaMan 2bis prototype: (a) a kinematic model; (b) a 3D CAD model.

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(a) (b)

Fig. 5. A new Serial Parallel Macro-Milli robotic system for surgery tasks: (a) CaPaMan2bis; (b) the overall system (Adept COBRA and CaPaMan2bis).

coupler carries the RJ and CB transmits the motion from AP to MP through RJ; CB is connected to the MP by a spherical joint BJ, which is installed on MP. Each plane, which contains AP, is rotated of $\pi/3$ with respect to the neighbor one.

Design parameters of the k-th leg are identified through: a_k, which is the length of the frame link; b_k, which is the length of the input crank; c_k, which is the length of the coupler link; d_k, which is the length of the follower crank; h_k, which is the length of the connecting bar.

The kinematic variables are the input crank angles α_k ($k = 1,2,3$). The size of MP and FP are given by r_p and r_f, respectively, H is the center point of MP, O is the center point of FP, H_k is the center point of the k-th BJ and O_k is the middle point of the frame link a_k, Fig. 4(a). The motion of MP with respect to FP can be described by considering a world frame O-XYZ, which is fixed to FP, and a moving frame H-$X_pY_pZ_p$, which is fixed to MP.

Table I reports the main design parameters of CaPaMan 2bis. Figure 5 shows a built prototype at LARM.

Main design enhancements with respect to CaPaMan 2 can be recognized in the different shape of the movable plate that has been carefully designed to properly lock a commercially available drilling tool. Moreover, spherical joints are used to connect the movable plate to the legs (instead of a rotative joint plus an universal joint). The shape and size of all the links has been redesigned to have higher stiffness. Ball bearings have been installed at the rotative joints in order to reduce friction.

Table I. Main design parameters for CaPaMan2bis.

$a_k = c_k$ [mm]	$b_k = d_k$ [mm]	h_k [mm]	$r_p = r_f$ [mm]	α_k [deg]
100	100	50	65	45 : 135

5. EXPERIMENTAL TESTS

Several experimental tests have been carried out on CaPaMan2bis in order to characterize its operation. In particular, workspace and stiffness performance have been tested since they are critical aspects in robotic surgery. Moreover, experimental tests have been carried out on CaPaMan2 and compared with the results obtained with the new system in order to verify the improvements in the performances that have been obtained with the new design.

Experimental tests for workspace and stiffness performance determination have been carried out by using a simplified version of Milli-CaTraSys (Milli-Cassino Tracking System) that has been designed and built at LARM in Cassino. The Milli-CaTraSys is able to measure position and orientation of robot end-effector through reference points H and F on it, Fig. 6. The position of point H is obtained

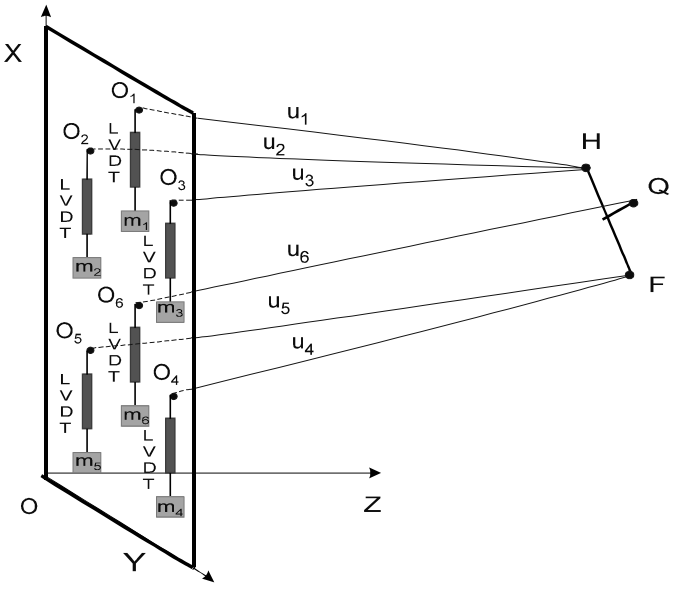


Fig. 6. A scheme of Milli-CaTraSys showing the reference frame, LVDTs and masses m_i applied to the wires $u_i (i = 1, \ldots, 6)$.

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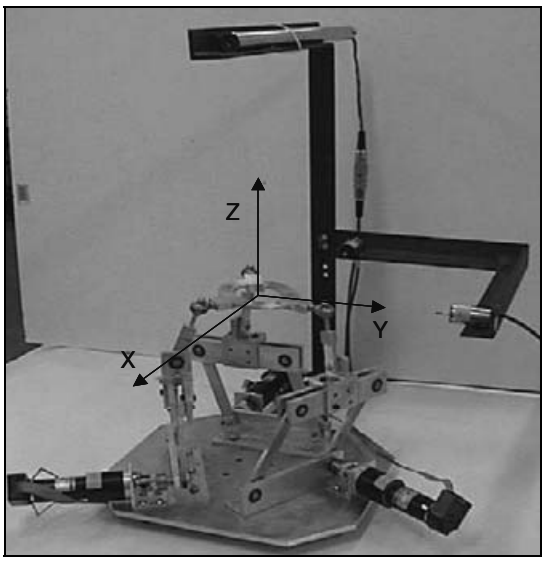


Fig. 7. The Milli-CaTraSys measuring system for measuring displacements of CaPaMan2 bis for workspace determination.

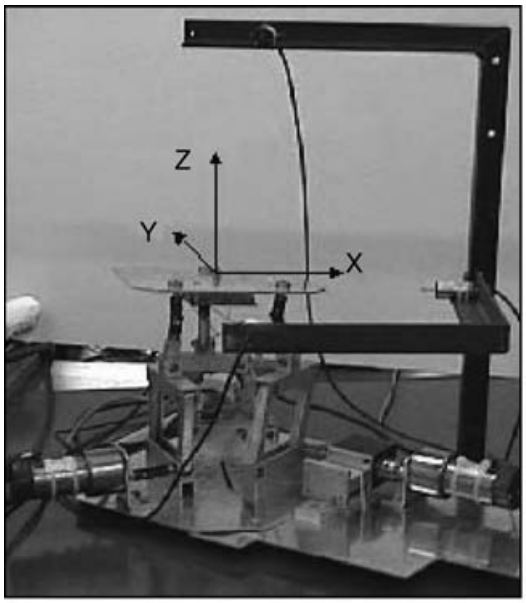


Fig. 9. The Milli-CaTraSys measuring system for measuring displacements of CaPaMan2 for workspace determination.

by means of the trilateration technique. Referring to Fig. 6 the measured distances u_i ($i = 1, \ldots, 6$) are used as radii of arcs from corresponding center points Oi. The position of H on the robot end-effector is defined as the position of the point at which three arcs intersect. It is function of co-ordinates xoi, yoi, zoi of the points Oi, ($i = 1,2,3$), which are the source of the u_i wire lengths. The Milli-CaTraSys can be also used for applying known wrenches on the robot end-effector by attaching known masses on the free ends of the wires u_i. Thus, Milli-CaTraSys can be used also for measuring stiffness performances as mentioned in reference [33].

A simplified Milli-CaTraSys has been built by using only 3 wires and 3 LVDT sensors as shown in the set-ups of Figs. 7, 9, 11 and 13. In particular, the set-up of Figs. 7 and 9 have been used for measuring the workspace of CaPaMan2bis and CaPaMan2, respectively.

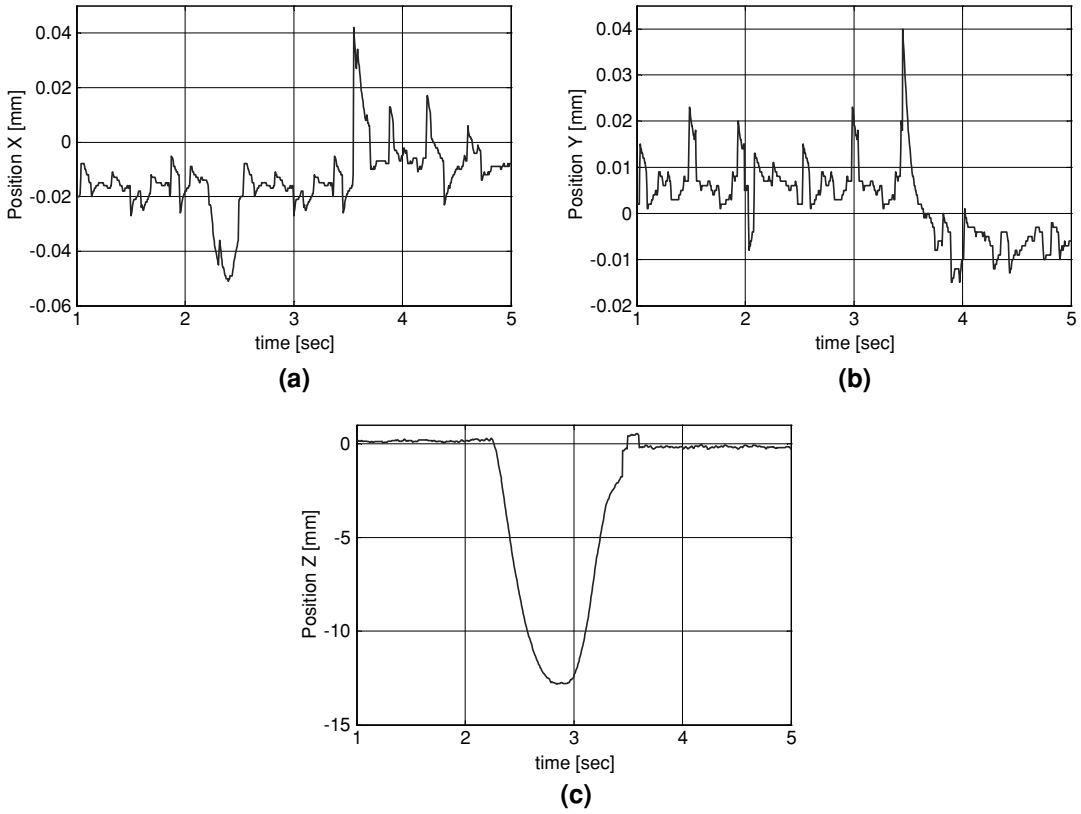


Fig. 8. Displacements of CaPaMan2bis for a motion of all the legs from 90 to 130 and back to 90 deg. for workspace determination: (a) displacement in X direction; (b) displacement in Y direction; (c) displacement in Z direction.

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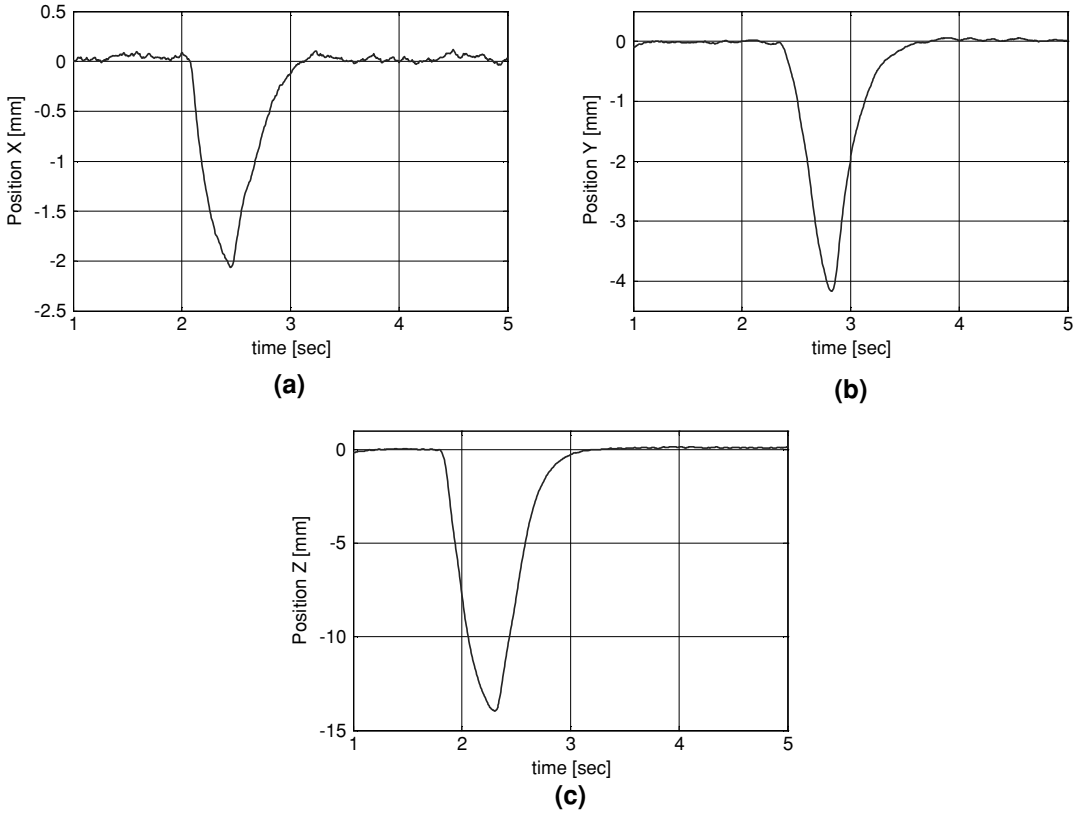


Fig. 10. Displacements of CaPaMan2 during a motion of all the legs from 90 to 130 and back to 90 deg. for workspace determination: (a) displacement in X direction; (b) displacement in Y direction; (c) displacement in Z direction.

The displacements of the center of movable plate of CaPaMan2bis and CaPaMan2 have been measured for several different cases. Figure 8 shows the displacements of CaPaMan2bis during a motion of the legs from 90 to 130 and back to 90 deg. In this case, the motion of the end-effector is mainly in Z direction while very small motions in X and Y directions occur due to manufacturing errors. The maximum displacement in Z direction for CaPaMan2bis is of 12.8 mm as shown in Fig. 8(c). The maximum undesired displacement in X and Y directions are 0.04 mm as shown in Figs. 8(a) and (b), respectively. The maximum displacement in Z direction for CaPaMan2 is of 13.9 mm as shown in Fig. 10(c). The maximum undesired displacement in X and Y directions are 2.1 and 4.2 mm as shown in Figs. 10(a) and (b), respectively. Thus, CaPaMan2bis has a little bit smaller displacement in Z direction but a better accuracy due to the lower undesired motions in X and Y directions.

Experimental tests have been carried on CaPaMan2bis and CaPaMan2 in order to measure their compliant displacements by using the set-ups of Milli-CaTraSys shown in Figs. 11 and 13, respectively. Figure 12 shows the compliant displacements occurring to CaPaMan2bis when all the legs are in the 90 deg. configurations and a mass of 0.1 Kg is applied on the first wire. This wire has the same direction of the X-axis in the unloaded configuration. The maximum compliant displacement Δx is of 0.3 mm while the compliant displacements Δy and Δz can be considered as negligible. Figure 14 shows the compliant displacements occurring to CaPaMan2 for the same case of the previous experiment.

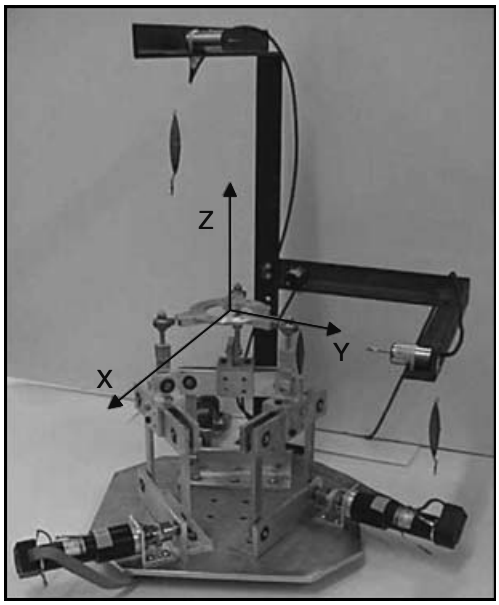


Fig. 11. The Milli-CaTraSys measuring system for measuring compliant displacements of CaPaMan2bis.

The maximum compliant displacement Δx is of 0.5 mm while the compliant displacements Δy and Δz can be considered as negligible. The comparison of Figs. 12 and 14 shows an improvement of stiffness performance of 40% for CaPaMan2bis.

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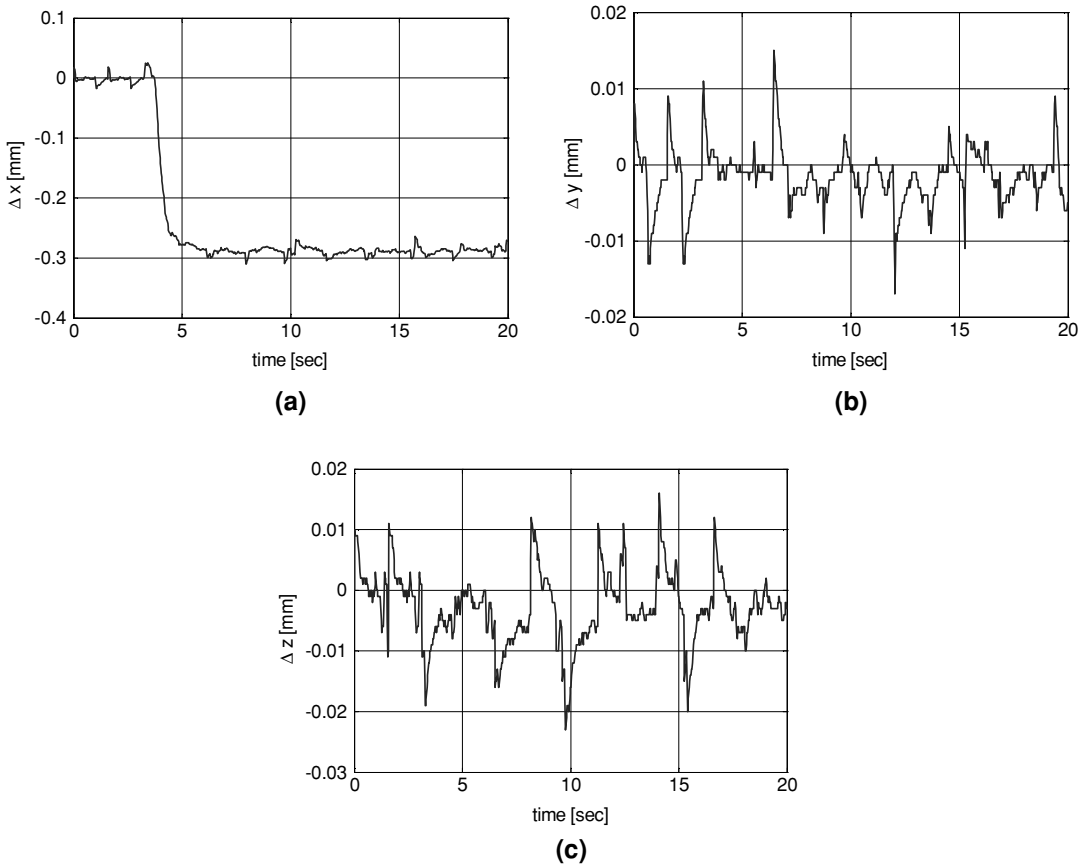


Fig. 12. Measured compliant displacements for a wrench equal to m1 = 0.1 Kg, m2 = 0 Kg; m3 = 0 Kg when CaPaMan2bis is in its vertical configuration: (a) Δx; (b) Δy; (c) Δz.

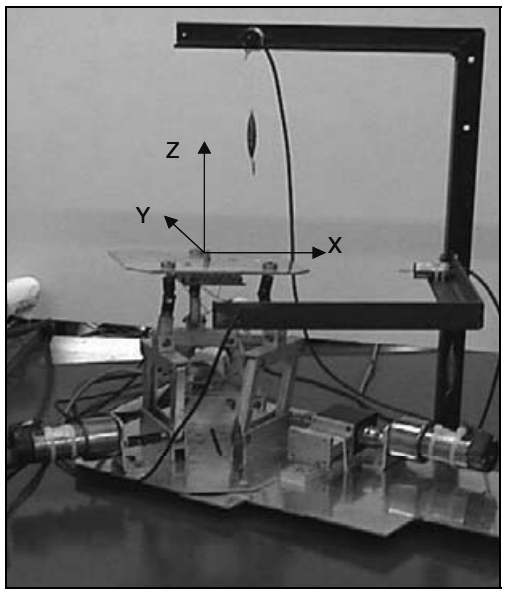


Fig. 13. The Milli-CaTraSys measuring system for measuring compliant displacements of CaPaMan2.

Experimental tests have been carried out also by using a JR3 six axis force/torque sensor installed on the wrist of the serial robot as shown in Fig. 15. Thus, the forces and torques acting on the fixed plate of the parallel manipulator and on the serial robot wrist can be measured during the operation. This setup has been used for experimental tests consisting of drilling objects made of wood, teflon and wax. Also a drilling test on a sheep bone has been successfully performed.

The drilling task has been performed through the following phases:

- locate properly the parallel manipulator by using only the serial robot motion;
- register the position of the wrist of the serial manipulator relative to the target (after this phase the serial robot is fixed and its compliance can be compensated);
- move the parallel manipulator from its home position to drilling position;
- perform the drilling operation by a drilling tool installed on the movable plate of the parallel manipulator;
- move the parallel manipulator back to its home position;
- relocate the overall system to its home position by using the serial robot motion.

The results obtained for different objects differ only for the drilling phase. Thus, the results of Figs. 16 and 17 only refer to the drilling phase. In the drilling phase with an object of wood the maximum measured forces and torques have been evaluated about 7.0 N and about 0.4 Nm, as shown in Fig. 16(c) and (d), respectively. Similarly, in the drilling phase with an object of teflon the maximum measured forces and torques have been evaluated about 5.0 N and about

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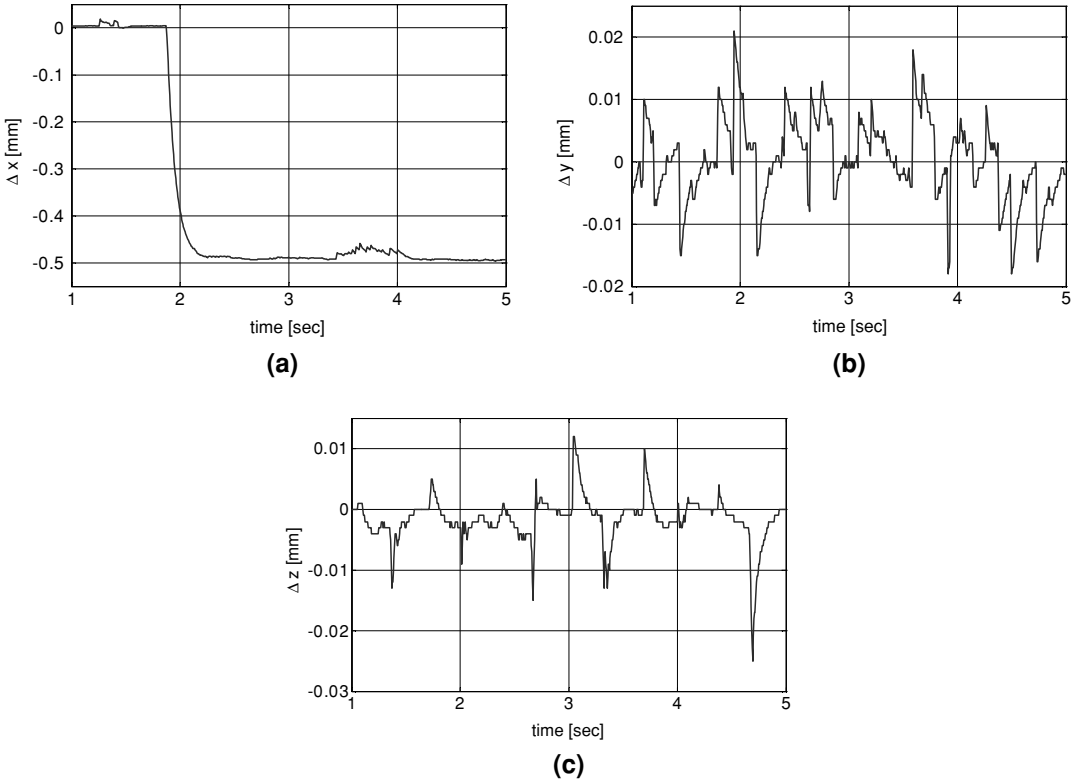


Fig. 14. Measured compliant displacements for a wrench equal to m1 = 0.1 Kg, m2 = 0 Kg; m3 = 0 Kg when CaPaMan2 is in its vertical configuration: (a) Δx; (b) Δy; (c) Δz.

1.0 Nm. In the drilling phase with an object of wax the maximum measured forces and torques have been evaluated about 2.0 N and less then 0.1 Nm.

Experimental tests have been carried out also by locating the JR3 six axis force/torque sensor beneath the object that has to be drilled. In particular, Fig. 17 shows the forces and torques that have been measured by the six axis force/torque sensor beneath the object for the same experiment of Fig. 16.

It is worth noting that Figs. 17 and 16 show that the forces and torques acting during the drilling of wooden objects are within the operating range of both the serial and parallel robot. Moreover, the comparison of Fig. 16 and 17 can be used in order to define a force feedback. The results of all the experimental tests that have been carried out on the proposed macro-milli robotic system show a satisfactory performance and validate the operation of the proposed robotic system for surgery tasks.

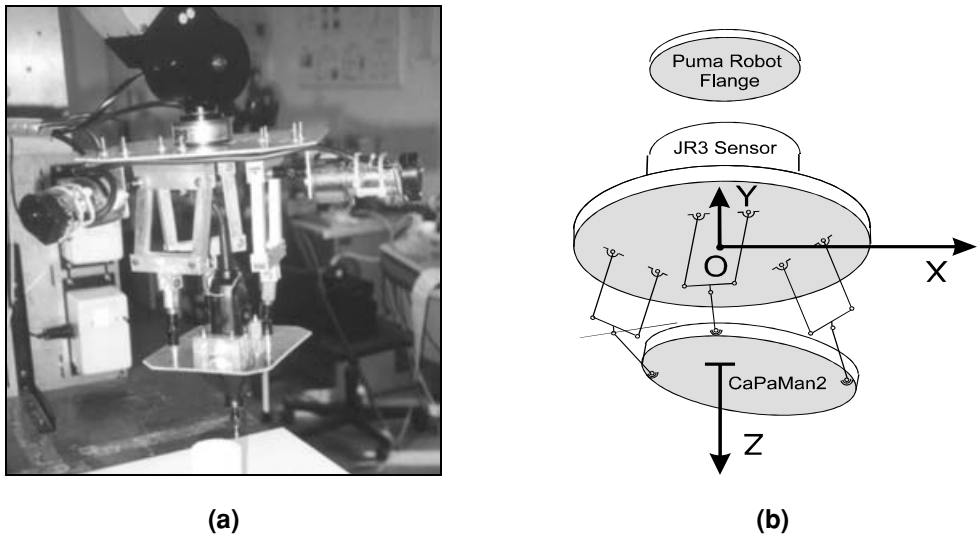


Fig. 15. The JR3 sensor installed between Puma robot and CaPaMan2: (a) the hardware layout; (b) a model for reference frame.

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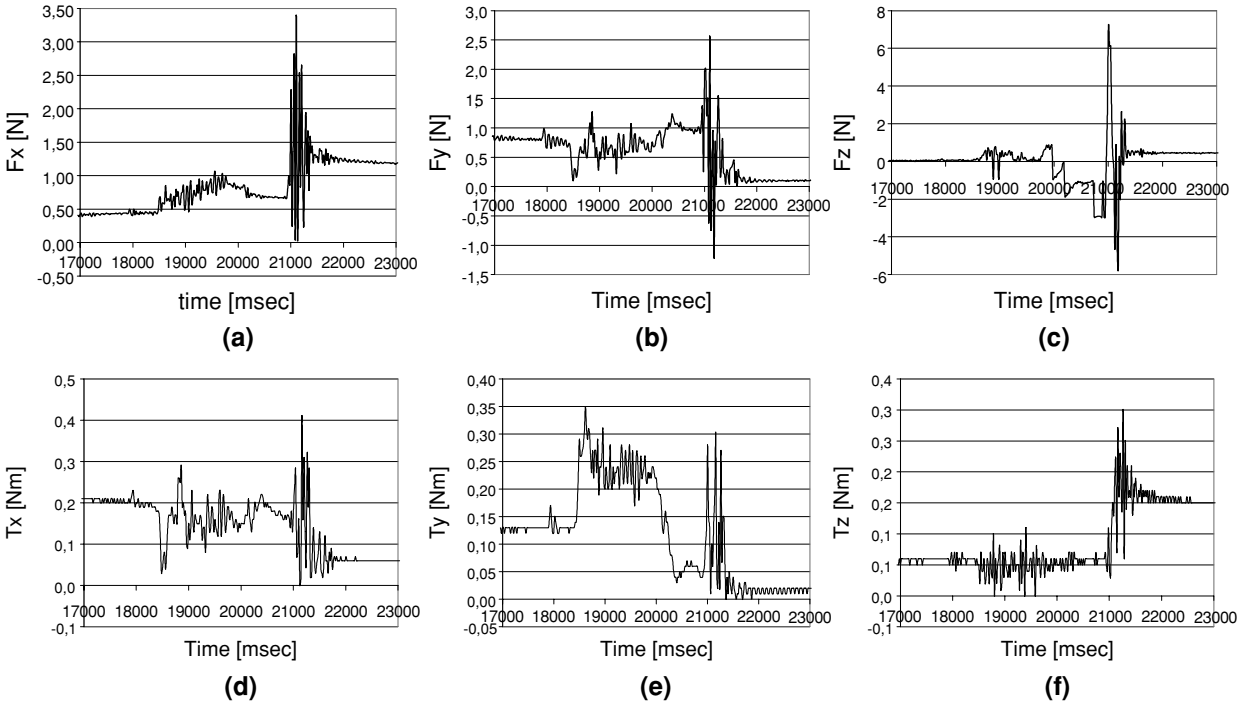


Fig. 16. Forces and torques measured during the drilling phase with a wood object: (a) Fx; (b) Fy; (c) Fz; (d) Tx; (e) Ty; (f) Tz.

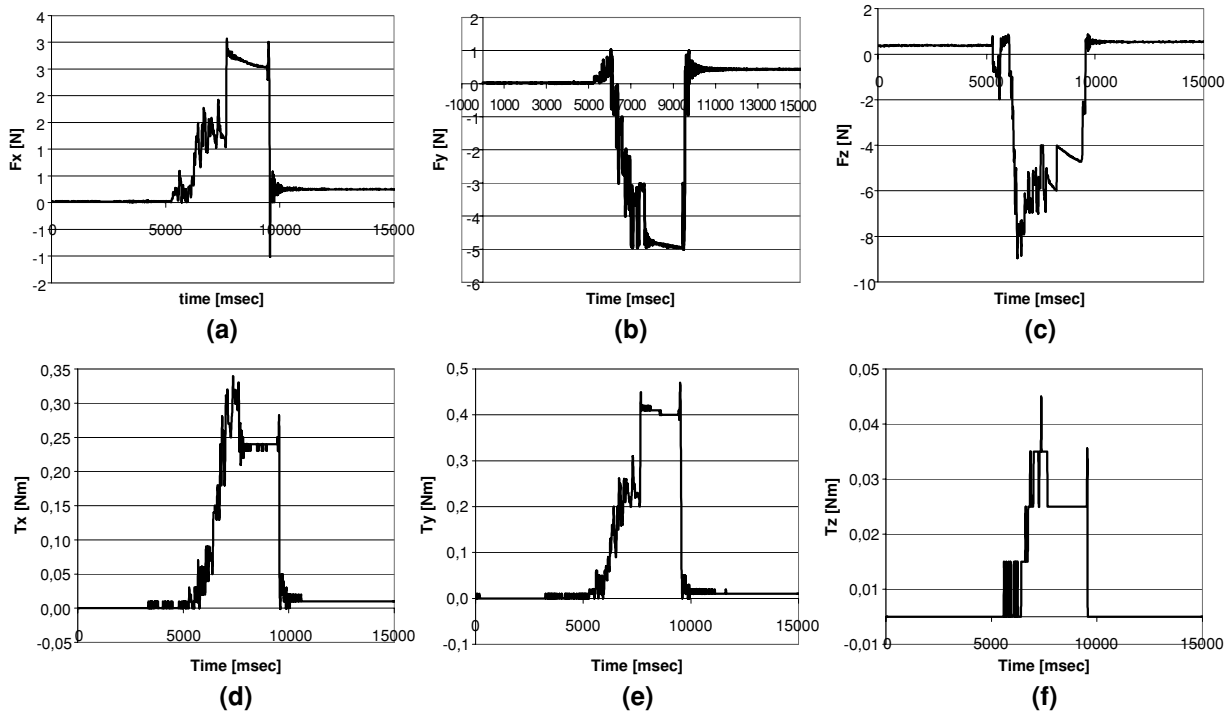


Fig. 17. Forces and torques measured by JR3 sensor installed beneath an object of wood: (a) Fx; (b) Fy; (c) Fz; (d) Tx; (e) Ty; (f) Tz.

6. CONCLUSIONS

In this paper, a new macro-milli serial-parallel robotic system for surgery tasks has been presented in the form of a laboratory prototype assembly. Experimental tests have been carried out on the new built prototype and on a previous robotic system that has been also built at LARM. In particular, workspace and stiffness have been tested since they are critical aspects in robotic surgery. The satisfactory results of the experimental tests validate the operation of the proposed robotic system for surgery tasks.

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https://doi.org/10.1017/S0263574704000967 Published online by Cambridge University Press