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Ergonomic mouse based interface for 3D orientation control of a tele-sonography robot

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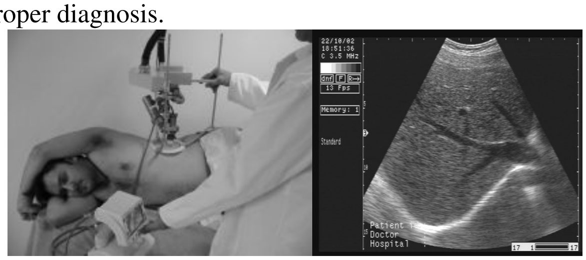
Abstract— **This paper proposes a new ergonomic frame to describe the attitude of a robot arm and to be used for human-machine interface in telerobotic with application to tele-sonography. A three part psychophysical analysis enabled us to design this new system of angles exhibiting a good decorrelation among its degrees of freedom. A decorrelation improvement of up to 83% can be noticed compare to the standard 3-1-3 Euler angles. This new frame has been exploited to conceive human-machine interface with a low cost input device such as the standard IT mouse. Psychophysical results show indisputable superiority of our new system compare to the standard Euler one for orientation tracking in teleoperation conditions.**

I. Introduction

The present work aims at proposing and exploiting a new attitude coordinate system adapted for the particular task of teleoperated medical ultrasound (US) examination. For such a coordinate system to be ergonomic, it needs to have a clear and manually reproducible degrees of freedom (DOF) to allow a good hand-eye coordination [1] of the operator during teleoperation since this is a key criterion for telepresence [2]. Indeed in such a tele-echography application we have experienced [3, 4] that it is desirable to provide the operator with an ergonomic and immersive interface to make him forget about the robot's mechanical constraints which can be taken care by suitable smart control laws (fig.1a shows OTELO robot prototype). In such a case the choice of the control interface DOF is critical to allow a medical expert to remotely control the attitude of the robot held ultrasound probe used to scan a patient and make a proper diagnosis.



(a) (b)

Fig. 1. (a) OTELO tele-ultrasound robot; (b) an ultrasound scan sample of hepativ vein.

This paper focuses on the orientation control since our clinical trials have shown that attitude positioning is a more critical task than cartesian positioning for this kind of application [5]. Salcudean proposed to use a single force–feedback joystick for the remote control of a heart echography robot [6]. Masuda makes use of a two-axis joystick (Compact analog stick, Hori Co. Ltd) [7]. However it is known that best teleoperation performances are achieved when the teleoperation system provides similar functioning modes than those of human [8]. That is why the authors of this paper could obtained excellent immersion of the operator with their patented "fictive probe" [9] since it is a free hand input device that mimics a true ultrasound probe (prop interface [10]). With this device, medical experts could have the same cognitive behavior during tele-echography than for standard US examination. Indeed they were only relying on the feedback of the US image to rotate the fictive probe and didn't even care about the true orientation applied by the robot on the medical US probe through visual feedback. This behavior lets think that the teleoperation system was assimilated by the operator as an extension of his reachable domain and lets him exploit his knowledge on the practice of standard sonography. With any other interface, one could expect a different cognitive behavior, requiring more adaptation from the operator. Our aim is to design a new interface for attitude control which provides a good compromise between low cost, availability while it is still ergonomic and easy to use. This interface must also allow the setting of every possible orientation in an hemisphere with tilt angle up to 45° from north pole, according to the medical requirements we have reported in a previous work [11]. For that purpose we have previously proposed a new orientation coordinate system [12] to minimize the adaptation effort with a non-prop like interface. This new coordinate system is made up of decoupled DOF, with respect to the human hand sensorimotor ability for the task of orientation control in tele-ultrasound. It can be used to provide a teleoperation interface as simple as a computer mouse without denaturing the medical gestures since it is based upon intuitive and self explanatory DOF to restore hand-eye coordination. **The new contribution** of this paper is to provide the reader with the complete analysis justifying the use of our new frame of angles and to show how to exploit this frame to conceive an IT mouse based interface for 3D orientation control. The remainder of the paper is organized as follows: the first section presents the three parts analysis we have carried out to identify decoupled DOF for orientation control. In the second section we build our new attitude coordinate system

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taking into account the previous analysis. The third section is dedicated to show the decorrelation improvement of our coordinate system compare to existing standard Euler angles. Last but one section proposes, before concluding, a biomimetic based control of the probe orientation with a standard wheeled computer mouse. Some psychophysical results show practically the strong improvement in orientation tracking with our new system of angles compare to the Euler system.

II. Psychophysical analysis of the orientation task

This section is dedicated to provide a better understanding of the way orientations are coded by the brain to perform a manual task of orientation in ultrasonography. We have carried out this analysis by following three different ways: first, habits of medical practice in ultrasound scanning have been investigated; second, we have analyzed experimental data acquired during a real examination by a medical expert; and third, neuroscience literature has been reviewed.

A. Medical practice

An US transducer works by generating a planar wave of US. Reflected waves by the tissues are measured by the probe along with their time of flight, which enables to build a density map of the tissues (fig. 1b). Hence a medical expert has to think to rotate a plane in a 3D space to visualize the desired slice of the patient's body. In fact sonographers are used to describe their scan orientation by reference to three basis rotations [13, 14]: probe angulation, probe rocking (fig.2) and self rotation. And in common medical practice the examination is executed in two phases combining these three basis rotation: first, choosing an initial incidence for the ultrasound plane combining probe angulation and probe rocking so as to perform a narrow sweep of the scanned organ. This first move is intended to grossly identify lesions or cysts. Second phase consists in rotating the US plane around the probe axis so as to identify small structures as tumors or traumas and precisely locate their extent. An ergonomic orientation frame should exhibit this same combination of movements.

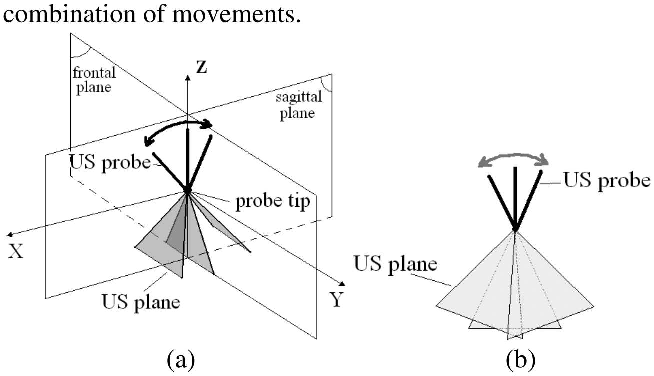


Fig. 2. *Two basic moves in medical US scanning. (a) probe angulation for organ sweeping (in this example move the US probe remains in the sagittal plane. (b) probe rocking used to extend the scanning plane.*

B. Experimental data

1) Experimental protocol

To analyze the task to be performed by the robot we have acquired the 6 DOF movements of a real US specialist performing abdominal examination of a healthy patient.

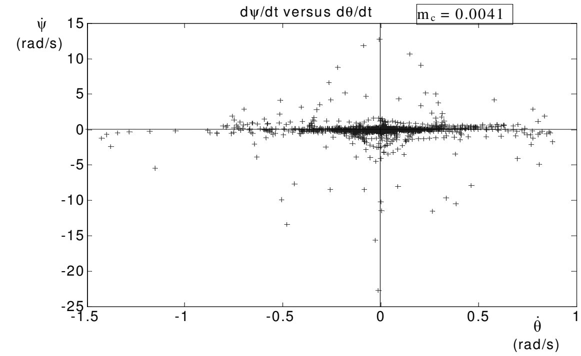


Fig. 3. *Phase plot* $\dot{\psi}$ *versus* $\dot{\theta}$ *and correlation measure* m_c.

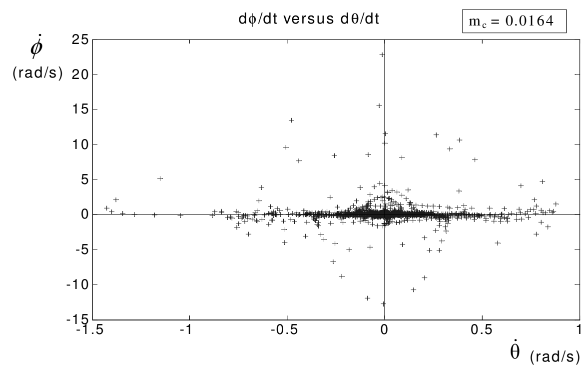


Fig. 4. *Phase plot* $\dot{\phi}$ *versus* $\dot{\theta}$ *and correlation measure* m_c.

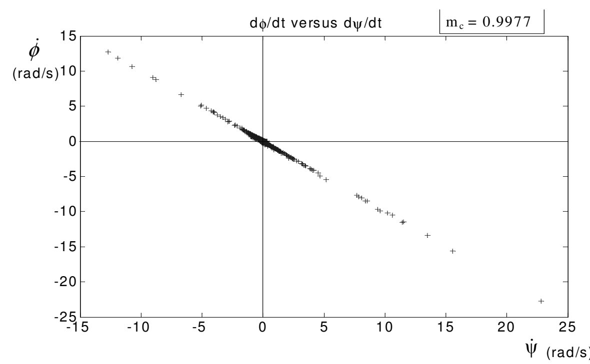


Fig. 5. *Phase plot* $\dot{\phi}$ *versus* $\dot{\psi}$ *and correlation measure* m_c.

This kind of examination is frequently performed in routine and the trajectories applied to the US probe by any expert would be roughly the same since these gestures come from the learning of recommended medical practice and not from individual experience and is also subject to the human hand limitations. We have chosen to describe the orientation with the 3-1-3 Euler angles triplet: (ψ, θ, ϕ), where ψ is the precession, θ is the nutation and ϕ the self-rotation [15]. These are the successive rotation angles about the Z-X-Z axis respectively. This choice comes from the tele-echography context where this frame is preferably used ([4, 16, 17]) because it was found to be the one **among existing standard frames** that best suits the required mobilities during an ultrasound examination according to medical specialists [16]. This qualitative information will be verified with the following analysis (section II.B.3). To better identify the correlation between angles and to be independent of the angles range and rollover we have considered the angles velocities.

2) Correlation in the angles

To emphasize the dependencies among the Euler angles for this kind of application, we have analyzed the phase plots of each angle derivative versus the other ones (fig. 3, 4, 5). To obtain a measure of dependency of two signals, one should compute their mutual information, estimation of which is still under research. However we can easily obtain a correlation measure by considering the absolute value of the Pearson correlation coefficient [18]. Let us name this measure m_c which is null for uncorrelated signals and is equal to 1 when the signals are linearly dependent. Figures 3, 4 and 5 report also the correlation measure. From these plot and correlation measures one can conclude that $\dot{\psi}$ and $\dot{\theta}$ are uncorrelated, $\dot{\phi}$ and $\dot{\theta}$ are also uncorrelated, but $\dot{\psi}$ and $\dot{\phi}$ are strongly correlated. Consequently the 3-1-3 Euler system is not perfectly suited for this application, as it can't provide decoupled DOF to describe the US scanning task.

3) Data analysis and requirements

The previous observations lead to state that a suitable frame must exhibit a nutation angle since it is a free DOF for this task. This fact eliminates the quaternions from the potential candidates. Moreover since we want three decoupled DOF, among standard existing systems [15] only the following Euler systems can provide us with the ability to define a θ nutation for vector z: 3-1-3, 3-2-3. Both systems are equivalent and the 3-2-3 frame will exhibit the same correlation than 3-1-3. This analysis shows the need for the definition of a new non standard frame capable of providing decoupled DOF for this kind of task. Since according to fig. 5, ψ and ϕ angles are strongly correlated, a principal component analysis (PCA) of the phase plots of the moves expressed in the 3-1-3 Euler system should provide us with decorrelated DOF. Indeed we can define a new coordinate system by using the Karhunen-Loève transform [19] which provides a very good decorrelation of the DOF. However this system doesn't take into account the general practice for every kind of examination (abdominal, renal, costal, thyroid…). Moreover this PCA based system doesn't provide meaningful and intuitive variables for the hand-eye coordination needed with this kind of medical practice.

C. Neuroscience literature review

To complete the requirement analysis, for ergonomic design purpose, we have explored the neuroscience literature about human psychophysics representation of orientation. Baud-Bovy and Gentaz [20] indicate that the orientation is internally coded with respect to the sagittal and frontal planes letting open the possible coordinate system satisfying this requirement. This is compatible with a system exhibiting a nutation angle. Indeed one can notice that the intersection of sagittal and frontal planes generates the vertical axis which is a strong reference in human sensorimotor capability which can be related to the feel of the gravity axis [21]. This vertical axis constitutes a reference for the nutation angle. Soechting and Ross [22] have early demonstrated psychophysically that the system of angles elevation-yaw, which is isomorphic with the nutation-precession system, is preferred for the perception of the arm orientation. The precession angle can be seen as a proximity indicator of an oriented handled rod with respect to the sagittal and frontal planes. Our analysis of the medical trajectory considered above reveals that nutation and precession are uncorrelated DOF. Consequently an orientation frame composed of nutation and precession angles is consistent with the human sensorimotor abilities. We have deduced a third DOF for 3D orientation from medical US scanning technique recommendations described in next section.

III. A NEW ATTITUDE COORDINATE SYSTEM

A. Movements combination

From previous analysis we have defined a new frame of angles denoted as (ψ_n, θ_n, ϕ_n) and obtained by two consecutive rotations as for medical practice. Notice that Euler angles are obtained by three successive rotations parametrized by only one angle. Let's denote the main framework by R_0 = (O, X0, Y0, Z0) with center O, axis (X0, Y0, Z0) and basis $B_0 = (\vec{x_0}, \vec{y_0}, \vec{z_0})$. We denote the basis obtained by the first transform on basis B_0 by $B_1 = (\vec{x_1}, \vec{y_1}, \vec{z_1})$. The first movement is a complex rotation. This first move has two main functions:

- defining vector $\vec{z_1}$ by its nutation $\theta_n \in [0; \pi]$ and precession $\psi_n \in]-\pi; \pi]$, which is consistent with the requirements depicted in §II.B.3 and II.C;
- forcing vector $\vec{y_1}$ to stay in the plane ($\vec{z_1}$ O $\vec{y_0}$) so as to constrain the first move to be only a combination of probe angulation and probe rocking as for medical practice (II.A).

Fig. 6 provides a graphical overview of this first move, where the origin's definition of ψ_n angle has been made in analogy with the precession of the 3-1-3 Euler angles.

The second transform is a simple rotation about vector $\vec{z_1}$ of angle $\phi_n \in]-\pi; \pi]$ which we name as "self rotation". On setting the same value for the precession and nutation angles in the 3-1-3 Euler system and in the new proposed system, we obtain the same position for vector $\vec{z_1}$. Hence the difference resides in the self rotation angle and so our new system can be considered as a particular Euler system.

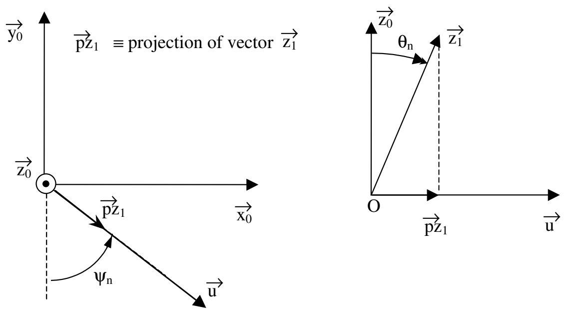


Fig. 6. *First movement from B_0 to B_1. Only the obtainment of vector z_1 is described here.*

B. Rotation matrix

According to the previous definition the global rotation matrix M can then be computed as a function of the new attitude representation angles (Eq. (1)).

$$M = \begin{bmatrix} \frac{\cos\theta_n\cos\phi_n + \frac{1}{2}\sin^2\theta_n\sin(2\psi_n)\sin\phi}{\sqrt{1-\sin^2\theta_n\cos^2\psi_n}} & \frac{-\cos\theta_n\sin\phi_n + \frac{1}{2}\sin^2\theta_n\sin(2\psi_n)\cos\phi_n}{\sqrt{1-\sin^2\theta_n\cos^2\psi_n}} & \sin\theta_n\sin\psi_n \\ \sin\phi_n\sqrt{1-\sin^2\theta_n\cos^2\psi_n} & \cos\phi_n\sqrt{1-\sin^2\theta_n\cos^2\psi_n} & -\sin\theta_n\cos\psi_n \\ \frac{\sin\theta_n(-\sin\psi_n\cos\phi_n + \cos\theta_n\cos\psi_n\sin\phi_n)}{\sqrt{1-\sin^2\theta_n\cos^2\psi_n}} & \frac{\sin\theta_n(\sin\psi_n\sin\phi_n + \cos\theta_n\cos\psi_n\cos\phi_n)}{\sqrt{1-\sin^2\theta_n\cos^2\psi_n}} & \cos\theta_n \end{bmatrix} \quad (1)$$

As a first analysis we can see that matrix M is not defined when $\theta_n = \pi/2$ rad and $\psi_n = 0$ or π rad. However in our application the angle θ can not be greater than $\pi/3$ rad due to the robot bounds, hence this limit case is never met.

The expression of the angles ϕ_n, θ_n and ψ_n as a function of the rotation matrix components and the two singularities of the rotation matrix have been identified and addressed in a previous paper [12].

IV. DECORRELATION RESULTS

In the following we have computed the velocities of the new attitude system angles for the same medical trajectory than in section II with the 3-1-3 Euler angles. As one could expect from the definition of the new system, there are no changes on $\dot{\Psi}_n$ versus $\dot{\theta}_n$ compare to the 3-1-3 Euler angles, hence they are still uncorrelated in our new system. Fig. 7 shows a good decorrelation between $\dot{\phi}_n$ and $\dot{\Psi}_n$ with a low coefficient m_c=0.0116, which is a great improvement, compared to the Euler system. On fig. 8, the correlation m_c = 0.1552 has been raised in a relatively important way compare to the 3-1-3 Euler angles, but this value still remains low enough to consider the $\dot{\phi}_n$ and $\dot{\theta}_n$ variables uncorrelated. To quantify the decorrelation improvement we can compute the average correlation coefficient for each system of angles. Our new system exhibits an average correlation $\hat{m}_{cn}$=0.057 whereas the 3-1-3 Euler angles system exhibits an average correlation $\hat{m}_{cE}$=0.339. Consequently our new system provides a decorrelation improvement of more than 83% with respect to the average correlation measure.

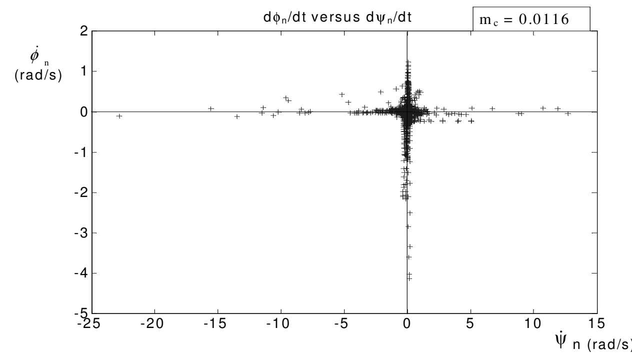


Fig. 7. *Phase plot $\dot{\phi}_n$ vs. $\dot{\Psi}_n$ and correlation measure m_c.*

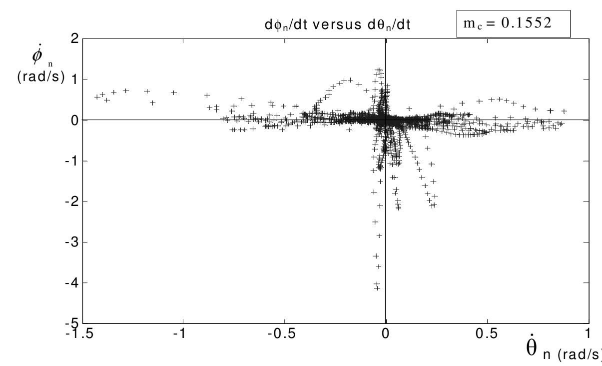


Fig. 8. *Phase plot $\dot{\phi}_n$ vs. $\dot{\theta}_n$ and correlation measure m_c.*

V. CONTROLLING THE PROBE ATTITUDE WITH A MOUSE

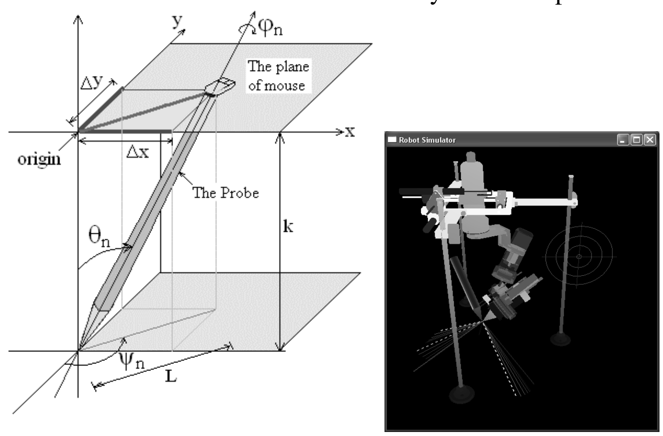
A. Angles coding

To ease the hand-eye co-ordination of the operator, for interface design, it is necessary to take care that the operator can easily assess the orientation changes when moving by hand the control interface [23]. That is why we have chosen a biomimetic approach for the orientation control with a mouse. As discussed previously, an orientation of the handled US probe is applied with a first movement defining the nutation and precession of the probe axis. This observation leads to state that human have the sensorimotor ability to easily control the nutation and precession of a rod. In fact defining the precession and nutation of a constant length rod is the same task than placing a point, representing the end top of that rod, on a sphere. The radius of which is the length of the rod, namely in our application, the US probe length, and the sphere center is the probe bottom tip. In our application only the north hemisphere is to be considered. It is possible to make a mental bijective transform from the orientation hemisphere to the mouse plane. However such a projection is not unique [24]. We have chosen the class of projections that preserves the precession angle, namely the azimuthal projections, which are projections of the sphere on a tangent plane. The chosen tangent point is the North Pole, which defines the so important vertical axis (§.II.C), since the transform generates less distortion around the tangent point. This choice allows also visualizing the mouse control of the probe from an overhead view (fig. 9a), where the origin is the tangent point between the orientation sphere and the plane. This transform guarantees the hand-eye coordination since it allows establishing one to one decoupled relations between the orientation DOF of probe nutation-precession and the visually and kinesthetically perceived polar coordinates of the mouse. Indeed the precession is growing and linearly dependent with the polar angle of the mouse and the nutation is a growing function of the distance from the mouse to the origin. To totally determine the projection, we have to set the perspective point. We made up our choice according to the human hand sensorimotor abilities. It has been reported that, because it is cognitively preferred, the path adopted by hand when moving on a plane from an initial position to a target position is a fairly straight-line [25]. Consequently a sphere to map projection that preserves orthodromy should be preferred (the shortest path between two points on the sphere - which is a great circle - should map to a straight line on the plane). Such a projection is a gnomonic projection where the projection center is at the center of the sphere. Despite the drawback of the chosen sphere-to-plane transform of sending to infinity a nutation of $\pi/2$ radian, it is however well suited to tele-echography application for routine examination. Indeed we have shown in a previous work that the nutation remains lower than $\pi/4$ radians during 95% of the examination time in routine abdominal US scanning [11]. To rotate the probe about its own axis and define the self rotation angle, the mouse scrolling wheel is used. This point can be a limitation since a mouse wheel can generally only allow the setting of increments. Hence a compromise has to be adopted when choosing the increment factor to convert the wheel increment to angle increment. A great factor allows driving fast but reduces the precision whereas a small factor exhibits the contrary. This factor has to be chosen according to the mouse wheel's total number of increments and by considering the application needs.

B. Experimental assessment protocol

The experimental setup is made to resemble the actual tele-echography setting that would be used in real conditions when using a mouse as interface as depicted in previous section. Consequently the setup is made up of a PC workstation displaying in 3D a simulated tele-echography robot handling a bright green probe and which end-effector orientation is controllable by the computer mouse (fig. 9b).

Human-Machine interfaces (HMI) are generally assessed with static targets, which gives no information on their dynamic capabilities. Hence **we have imagined an original** way of interface evaluation consisting for the subjects to track the moves of an opaque red dummy probe which is overlaid on screen and animated from a previously recorded datafile during a real abdominal US examination. We only have considered the orientations in this experiment, hence both the dummy probe and the simulated robot probe are fixed in translation. A three-axis framework was also attached to this dummy probe and displayed for a better visualization of its orientation. Better telepresence could be achieved with a HMD (Head Mounted Display) for depth perception. However this would annihilate the interest in using a computer mouse for proposing simple low cost control interface, so we preferred using a standard 2D screen displaying 3D graphics. We suppose no time-delay during this simulated teleoperation to avoid parasiting effect on the assessment of the new frame of angles. Six different non-medical test users were solicited to carry out the experiment.



(a) (b)

Fig.9. *(a) Use of a computer mouse as telerobotic control interface to set the new frame of angles; (b) virtual-reality simulator for psychophysical assessment.*

They were all used to mouse manipulation and computer interaction. Each untrained user was shown the animation once just to accustom him with the trajectory. Then he had an unlimited training session to understand how to control the robot orientation by the mouse and to have a preview of the trajectory to track. No more than five minutes of training was sufficient for every experimenter. The medical reference trajectory duration is three minutes long. Each test user had three trials to track this trajectory by using the new attitude coordinate system associated to the mouse, and next they had three other trials using the standard 3-1-3 Euler system, for comparison purpose. The session of orientation matching with the Euler system is intended to assess the performance improvement provided with the new system.

C. Psychophysical results

The orientation tracking error is computed as the minimum rotation angle between the frameworks of the controlled probe and dummy probe. Let us notice this angle as Ω. Fig. 10 reports the average of Ω orientation error among the users versus time of trajectory tracking. First plot is for the mouse used to set the Euler angles and second plot for the mouse used to set the angles of the new proposed system. Plots of fig.10 reveal practically an indisputable superiority of our new system compare to standard Euler system. With our new system the tracking error remains most of the time lower than 10°, whereas with the Euler system the error rarely drops below 10°. Whatever the experimentation time considered, the error with the new system is at least two times lower than with the Euler system. From testimony of the test users the new system acts as if the self-rotation were anticipated. Whereas with the Euler system the tracking were confusing mainly because of the singularity of this system tending to produce fast variations of the X and Y axis when the nutation is close to zero.

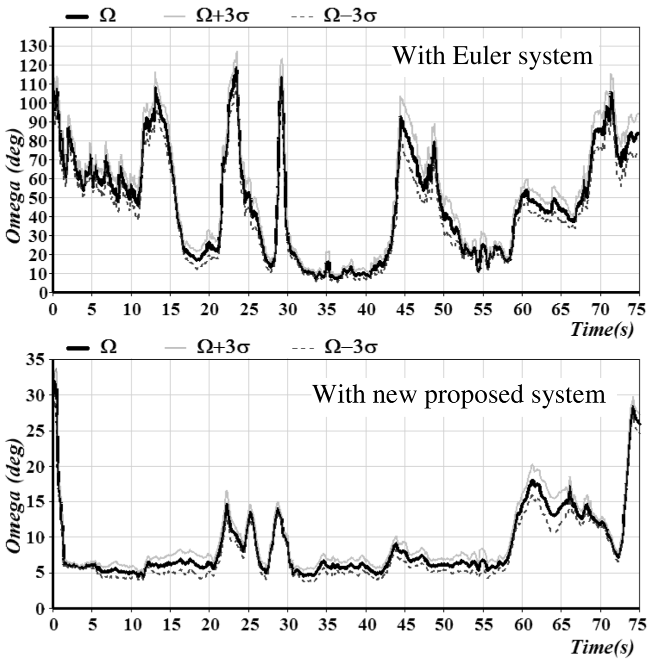


Fig.10. *Observed variation in average Ω values with bounding curves at Ω plus or minus three times the standard deviation σ.*

VI. CONCLUSION

We designed a new coordinate system to be ergonomic according to psychophysical considerations, and according to general practice expressed by the medical experts when performing any US examination. We also have exploited this new frame of angles to design a computer mouse based interface, which satisfies the hand-eye co-ordination needs for the purpose of poly-articulated robot orientation telecontrol through computer network. An original psychophysical evaluation with six test users of this 2D interface for 3D orientation of a tele-sonography robot tends to confirm that it is effectively intuitive and proves practically its superiority to Euler system. Our system allows imagining the performing of 6D mouse-based teleoperation by using switching modes between orientation and translation control with a standard wheeled mouse.

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