H4 Parallel Robot: Modeling, Design and Preliminary Experiments

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Abstract. This paper first recalls the concept of H4 parallel mechanism; the kinematic models necessary for real-time control are derived. A simple and efficient control system based on a combination of Windows NT and RTX is used to demonstrate its performances. Results prove the efficiency of H4 serving as a high-speed pick-and-place robot.

1. Introduction

In the late 80's, after the first ideas of parallel mechanisms proposed by Gough [1] or Stewart [2], Clavel proposed the famous Delta structure [3] as a base for a "family" of parallel machines dedicated to high-speed applications. As far as industrial use is concerned the Delta robot is definitely a success, and this is not so common among the large number of different structures proposed by Academic researchers in the last 20 years. Indeed, only the so-called "hexapod" built with 6 *U-P-S* chains in parallel (*U-P-S*: Universal-Prismatic-Spherical) has been also used intensively in industry (see [4] and [5] for an extensive coverage of this issue). This may be seen as a result of, on one hand, the exceptional simplicity of the Delta 3-dof solution, and on the other hand, the enormous research effort dedicated to the so-called "hexapod".

Of course, many alternate designs have been proposed (some of them close to the Delta family, e.g. the machine proposed by Toyoda, HexaM [6] which is an evolution of Hexa robot [7]). But it is clear today that most efforts are dedicated to 6 dof machines which are now well known (see [8] for an exhaustive enumeration) or 3 dof machines (see [9] and [10] for good examples of such devices).

However, we strongly believe that there is a need for equipment providing more than 3 dof arranged in parallel *and* based on simpler arrangements than 6-dof structures. As a matter of fact, for most pick-and-place applications, at least four dof are required (3 translations and 1 rotation to arrange the object in its final location). On the Delta robot, this is achieved thanks to an additional *U-P-U* link between the base and the gripper. In some cases, this solution is smart and elegant. In those other cases (namely, for Delta with huge workspace, or even more, for linear Delta), this does not seem as efficient as a fully parallel arrangement.

On the other hand, 6-dof fully-parallel machines currently in use in machining suffer from their complexity (they need at least 6 motors while the cutting process requires only 5 controlled axis –plus the spindle rotation–) and from their limited tilting angle. Solutions to these drawbacks have been proposed such as the smart -but complex- Eclipse machine [11], or the hybrid parallel-serial Tricept. We believe that another approach could be valid too: one can provide the spindle with 4 axis and let the work piece be moved by an additional 5th axis, following the left-hand/right-hand robotics paradigm.

It is amazing to remark that only few efforts have been devoted in the past to 4 dof parallel mechanisms. Apart from Koevermans flight simulator [12] and Reboulet 4-dof wrist [13], which both provide 3 rotations and 1 translation, we can mention few hybrid (that is to say, non fully-parallel) mechanisms as in [14] or [15].

In the following sections we recall the concept of H4 mechanism that was described in [16]; we describe the detailed design of one possible implementation of H4 concept and briefly derive its kinematic modeling. Our control implementation, based on a combination of Windows NT and a Real-Time Kernel, RTX, is then described and preliminary results show its effectiveness.

2. H4 Concept

In [16] we proposed to build a fully-parallel mechanism with no passive chain, able to provide high performances in terms of speed and acceleration. Those considerations lead to three important consequences: the mechanism is based on 4 independent chains between the base and the nacelle; each chain is actuated; each actuator is fixed on the base. We did so because such ideas have already proven their efficiency for high-speed equipment like the Delta robot, the Hexa robot and the HexaM machine-tool.

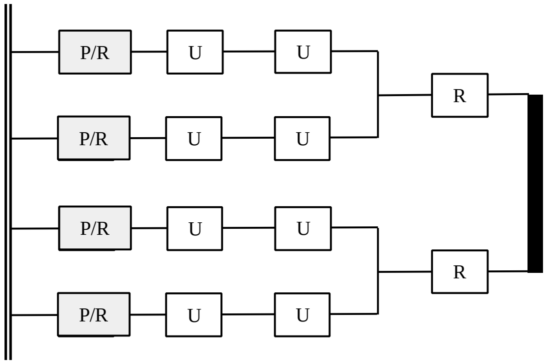

Figure 1. The basic idea of H4.

The basic idea of H4 is described by a simple architectural scheme (Figure 1) where joints[1] are represented by rectangles[2], and links between those joints are represented by lines. Each kinematic chain is a **P**-U-U or a **R**-U-U chain that must satisfy geometrical conditions to guarantee that the mechanism offers 3 translations and 1 rotation about a given axis (see [16] for details). We have shown in [16] that this concept is indeed a complete family of 4-dof parallel mechanisms: the **P**-U-U (respectively **R**-U-U) chains can be replaced by **P**-(U-S)$_2$ or **P**-(S-S)$_2$ chains (respectively by **R**-(U-S)$_2$ or **R**-(S-S)$_2$) as shown in Figure 2 and Figure 3.

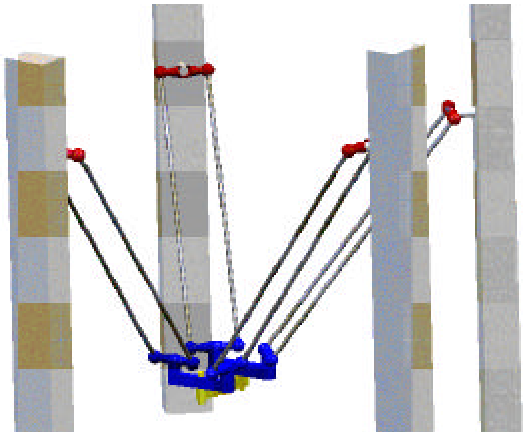

Figure 2. H4 mechanism with 4 linear drives and (S-S)$_2$ chains.

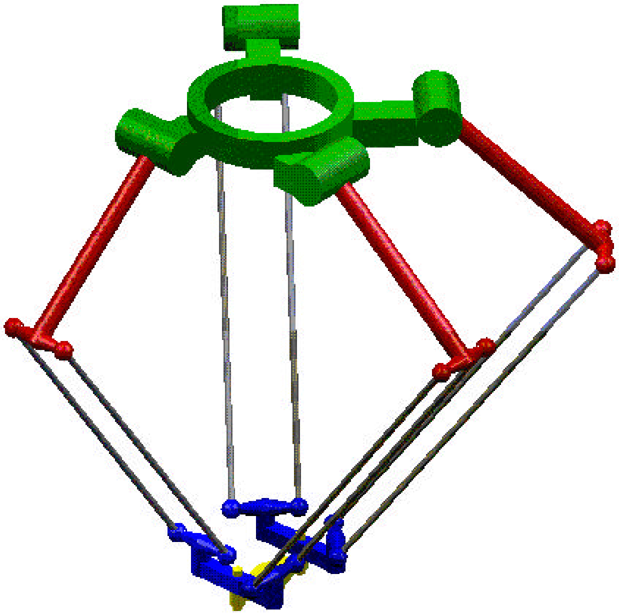

Figure 3. H4 mechanism with 4 rotary drives and (S-S)$_2$ chains.

We have also shown that the two passive revolute joints located originally on the nacelle can be grouped together with other joints to lead to the architectural scheme of Figure 4, called "Asymmetrical H4", which makes use of two Delta-like chains and two Hexa-like chains. Again, the **P**-U-U chains can be replaced by **P**-(S-S)$_2$ chains as shown in Figure 5 and Figure 6.

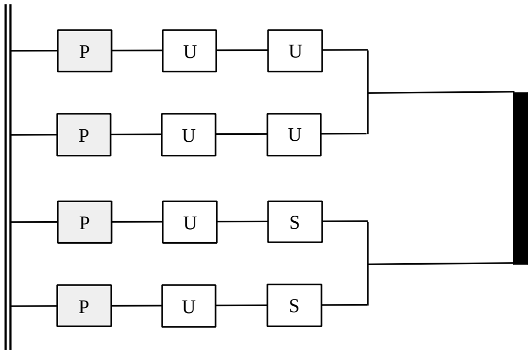

Figure 4. The concept of H4 with asymmetrical design.

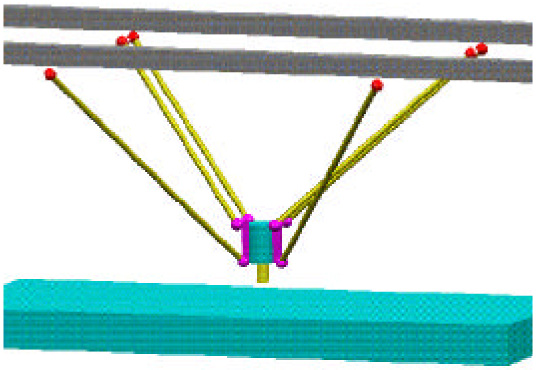

Figure 5. H4 mechanism with 4 linear drives and an asymmetrical design.

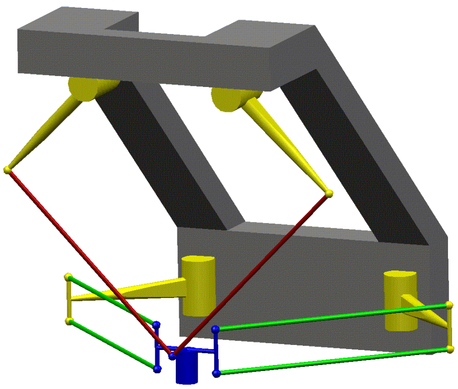

Figure 6. H4 mechanism with 4 rotary drives and an asymmetrical design.

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[1] P: prismatic; R: revolute; U: universal; S: spherical.

[2] Grey rectangles represent actuated joints.

3. Detailed Design

In this paper we focus on one particular design, similar to the one depicted in Figure 3. The practical design is extremely simple thanks to the use of DD motors[3] providing a very good position resolution[4]. Rods are made of carbon fiber; arms, forearms and nacelle are made of aluminum alloy.

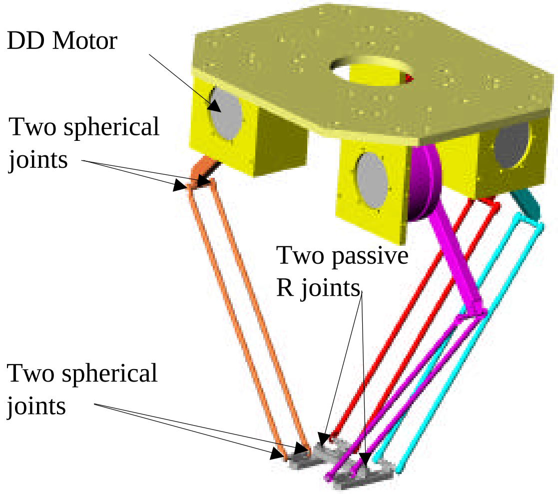

Figure 7. CAD model of the first H4 prototype.

The design shown in Figure 7 is a good base for a 4-dof pick-and-place robot, but suffers from a too limited range of motion on the rotational degree-of-freedom (45 degrees in both direction). To extend this range of motion and reach a 180-degree rotation capability in both direction, we have improved the nacelle design and equipped it with a mechanical amplification system shown in Figure 8. A gear system (with a ratio of 4:1) amplifies the original motion of the nacelle. The complete architecture is described by Figure 9 where the circle-and-arrow pictogram indicates the dependency between the motions of two R joints.

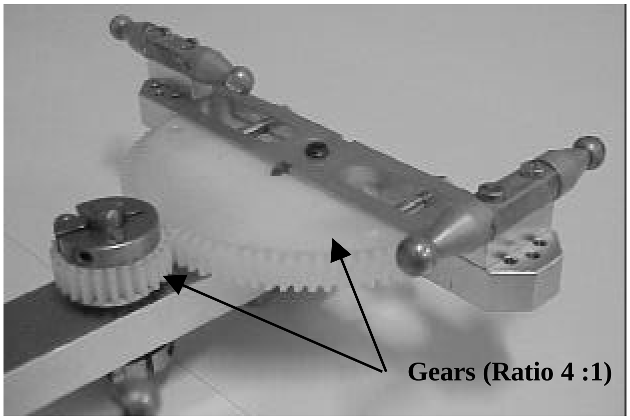

Figure 8. The mechanical amplification system.

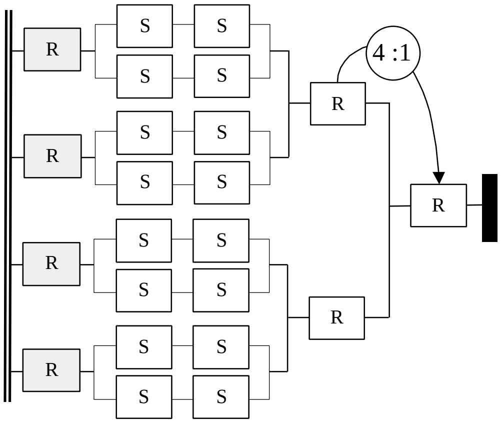

Figure 9. The architectural scheme of the actual prototype.

4. Kinematic Modeling

In this section we derive relationship between actuator's and nacelle's position represented by, respectively, $\boldsymbol{q} = [q_1, q_2, q_3, q_4]^t$ and $\boldsymbol{x} = [x, y, z, q]^t$.

We also present the relationship between actuator's and nacelle's velocity represented by $\dot{\boldsymbol{q}}$ and $\dot{\boldsymbol{x}}$, respectively, since we need it for the forward kinematic model.

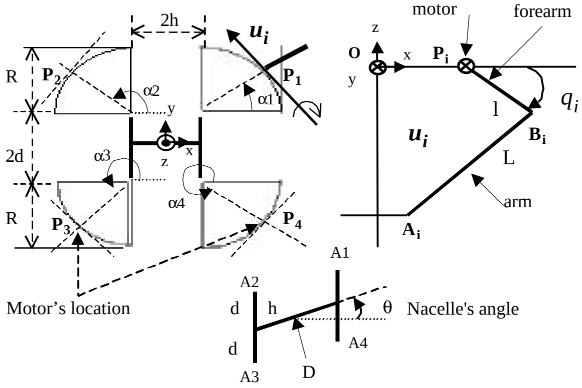

Figure 10. Design parameters.

The design we have selected is described in Figure 10, where the following parameters have been chosen:

$$a_1 = 0, \quad a_2 = p, \quad a_3 = 3p/2 \quad a_4 = 3p/2$$

$$\boldsymbol{u_1} = \boldsymbol{y}, \quad \boldsymbol{u_2} = -\boldsymbol{y}, \quad \boldsymbol{u_3} = \boldsymbol{x}, \quad \boldsymbol{u_4} = \boldsymbol{x}$$

As it is usual for most parallel robot, the inverse position relationship is easy to derive. We can simply write the following equality:

$$\|A_i B_i\|^2 = L^2$$

This relationship leads to :

$$M_i \cos q_i + N_i \sin q_i = G_i \qquad (1)$$

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[3] 15 N.m peak torque, 2.4 rev/sec peak velocity

[4] 654,000 p/rev

where:

$$M_i = -2l\,(P_iA_{ix}\cos \boldsymbol{a}_i + P_iA_{iy}\sin \boldsymbol{a}_i)$$

$$N_i = 2l\,P_iA_{iz}$$

$$G_i = L^2 - l^2 - P_iA_i^{\,2}$$

Resorting to the following new variable:

$$t_i = \tan\frac{q_i}{2}$$

we have:

$$q_i = 2\tan^{-1}\left(\frac{-b_i \pm \sqrt{b_i^{\,2} - 4\,a_i\,c_i}}{2\,a_i}\right)$$

where :

$$a_i = G_i + M_i$$

$$b_i = -2\,N_i$$

$$c_i = G_i - M_i$$

Note that with this way of solving equation (1) a mathematical singularity can occur when $a_i = 0$. It is possible to overcome this problem by introducing the following new variables:

$$\tan \boldsymbol{a}_i = \frac{N_i}{M_i} \qquad \cos \boldsymbol{b}_i = \frac{G_i}{M_i}$$

This leads to another expression of the inverse position relationship:

$$qi = \tan^{-1}\frac{N_i}{M_i} \pm \cos^{-1}\frac{G_i}{\sqrt{M_i^{\,2} + N_i^{\,2}}}$$

As it is usual again, the analytical forward position relationship is much harder to find. Up to now, the simplest model we've got is an 8th degree polynomial equation. The forward model is obtained using the classical recurrent formula :

$$\boldsymbol{x}_{n+1} = \boldsymbol{x}_n + \boldsymbol{J}(\boldsymbol{x}_n, \boldsymbol{q}_n)\,[\boldsymbol{q}_d - \boldsymbol{q}_n]$$

Where $\boldsymbol{J}$ is the robot Jacobian matrix.

As for many parallel robots, this matrix comes from the following relationship between velocities:

$$\boldsymbol{J}_{\boldsymbol{x}}\,\dot{\boldsymbol{x}} = \boldsymbol{J}_{\boldsymbol{q}}\,\dot{\boldsymbol{q}} \qquad (2)$$

and, if the mechanism is not in a singular configuration:

$$\boldsymbol{J} = \boldsymbol{J}_{\boldsymbol{x}}^{-1}\,\boldsymbol{J}_{\boldsymbol{q}}$$

To derive equation (2), we use the classical property that relates the velocities, $V(A)$ and $V(B)$ of two points A and B belonging to a single solid:

$$V(A) \bullet AB = V(B) \bullet AB \qquad (3)$$

Applying (3) to the four chains leads to:

$$\boldsymbol{J}_{\boldsymbol{x}} = \begin{bmatrix} A_1B_1 \bullet \boldsymbol{x} & A_1B_1 \bullet \boldsymbol{y} & A_1B_1 \bullet \boldsymbol{z} & (DC_1 \times A_1B_1) \bullet \boldsymbol{z} \\ A_2B_2 \bullet \boldsymbol{x} & A_2B_2 \bullet \boldsymbol{y} & A_2B_2 \bullet \boldsymbol{z} & (DC_2 \times A_2B_2) \bullet \boldsymbol{z} \\ A_3B_3 \bullet \boldsymbol{x} & A_3B_3 \bullet \boldsymbol{y} & A_3B_3 \bullet \boldsymbol{z} & (DC_2 \times A_3B_3) \bullet \boldsymbol{z} \\ A_4B_4 \bullet \boldsymbol{x} & A_4B_4 \bullet \boldsymbol{y} & A_4B_4 \bullet \boldsymbol{z} & (DC_1 \times A_4B_4) \bullet \boldsymbol{z} \end{bmatrix}$$

$$J_x = [A_iB_i^{\,T} \,|\, (DC_j \times A_iB_i) \bullet \boldsymbol{z}]$$

$$\boldsymbol{J_q} = \begin{bmatrix} (P_1B_1 \times A_1B_1) \bullet u_y & 0 & 0 & 0 \\ 0 & (P_2B_2 \times A_2B_2) \bullet -u_y & 0 & 0 \\ 0 & 0 & (P_3B_3 \times A_3B_3) \bullet u_x & 0 \\ 0 & 0 & 0 & (P_4B_4 \times A_4B_4) \bullet u_x \end{bmatrix}$$

$$\boldsymbol{J_q} = diag\big((P_iB_i \times A_iB_i) \bullet \boldsymbol{u_i}\big)$$

Those models have been used to determine the H4 workspace, depicted in Figure 11 for $q = 0$. Obviously, to have a proper condition number, workspace should be limited. In practice, workspace is limited for the actual prototype to a (300x300x300)*mm* cube centered about the workspace center.

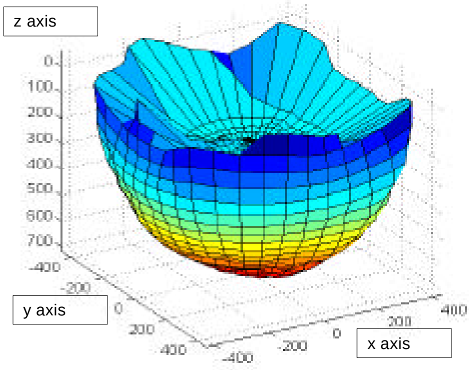

Figure 11. H4 workspace for $q = 0$.

5. Control Implementation

The complete control system is implemented on a single PC (Pentium II, 200 MHz, 64 Mb) running Windows NT4, without any control board; indeed, a lab-made I/O board is plugged on the PCI bus and connects the PC to the amplifiers by means of analog signals, and the position encoders to the PC by means of digital signals.
This means that both the **G**raphical **U**ser **I**nterface and the Position Control are running on the same PC (Figure 12); this relies on the use of **RTX** [17], a software package that enables Real-Time processes to run on a PC that takes advantages of Windows NT environment.

Windows-NT process.
This is a **G.U.I.** that let us set displacement parameters (desired position, maximal velocity …) and control parameters. User can query data as well.

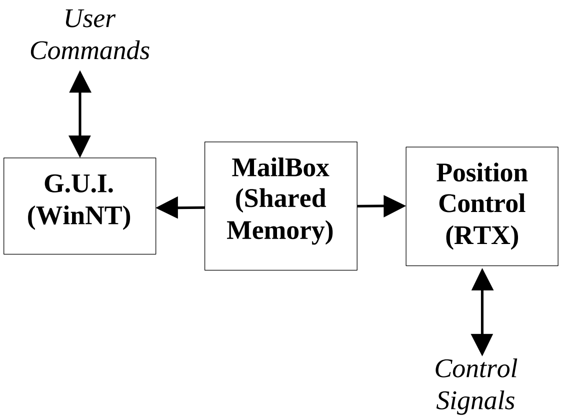

Figure 12. The complete control runs on a single PC.

Real-time process.

Real-time process main tasks are to generate a trajectory and to control the position. Trajectory generation is realized, both in Joint Space and in Cartesian Space, according a 5th order polynomial in position, which insures acceleration continuity (even if it doesn't optimize displacements). The control task is defined as a periodical task wi ri s at a 1kHz frequency.

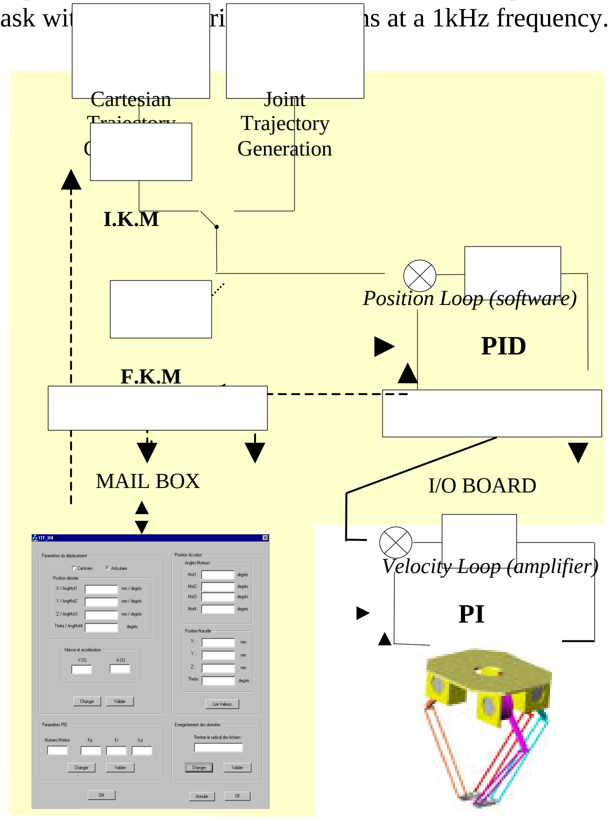

Figure 13. Complete control organization.

Mailbox.

The mailbox is actually a memory shared by real-time and non-real-time processes. It allows the user's interface to place a request on the mailbox and the control process to send a response. A simple communication protocol is implemented and includes functions to send an order, to wait for a response and to reply to an order.

By its nature, this control organization is 100-percent open and is ready for further improvements.

6. Preliminary Results

This section presents preliminary results obtained for the following typical displacement:

StartPoint	[0 (mm), 0 (mm), -300 (mm), 0 (deg)]
EndPoint	[25 (mm), 75 (mm), -500 (mm), 20 (deg)[5]]
Duration	150 ms

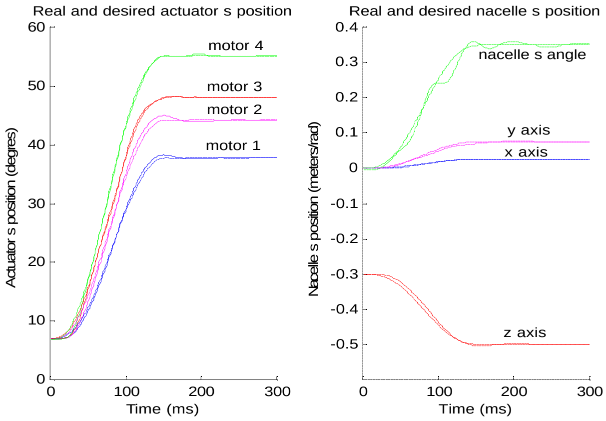

Figure 14. A typical motion in Joint Space and Cartesian Space.

Figure 14 shows actuator's position and corresponding nacelle's position (obtained with the forward kinematic model) during displacement. Maximal tracking errors are 15 mm for nacelle's position and less then 3 degrees for nacelle's angle (see Figure 15).

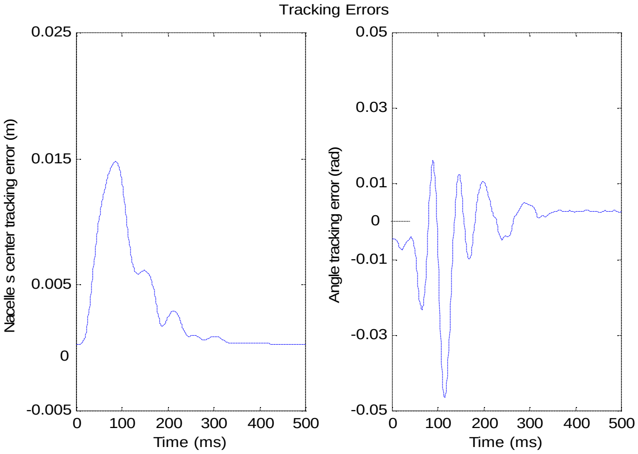

Figure 15. Tracking errors.

During displacement, nacelle's maximal velocity is close to 3 m/s and maximal acceleration is 5 *g* (Figure 16). A **.avi** movie can be downloaded from our web site [18].

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[5] This is the nacelle angle before mechanical amplification. The actual tool motion is then 80 degrees.

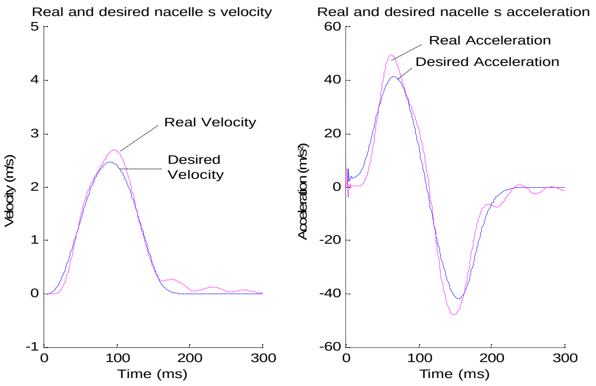

Figure 16. Velocity and acceleration.

7. Conclusion

In this paper, after recalling the concept of H4, we have derived the models necessary for its control in real-time. We have shown it is possible and efficient to control such a high-speed mechanism thanks to a single PC. This is made feasible by resorting to the combination of WindowsNT (for the easiness to develop the G.U.I. and its efficient programming tools) and RTX (for the real-time facilities). A simple PID controller in the joint position loop (together with a PI controller in the velocity loop) leads to nacelle's accelerations of 5*g*.

With such preliminary results, the H4 robot, which is based on proven technologies coming from Delta and Hexa robots, have demonstrated its ability to serve as an efficient pick-and-place robot.

Further developments will be conducted towards the direction of more demanding applications such as machining, where we expect H4 to be part of an hybrid mechanism able to do 5-axis machining at high speed.

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