Design and experimental test of a pneumatic translational 3dof parallel manipulator

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Abstract: Parallel robots exhibit high stiffness, low weight and low dynamic forces, mostly because of the closed loop chains implied by their structure, and allow the positioning of the actuators on the truss. These characteristics outline the possibility of actuating such kind of robotic devices by means of pneumatic actuators.

The position control of pneumatic cylinders through proportional valves satisfies the positioning accuracy of many industrial applications, where the features of the parallel robots and the performances of the servo-pneumatic cylinders may allow fast spatial movements with high pay-load.

The current work presents the mechatronic design of a low-cost pneumatic parallel manipulator, named TORX, where three pneumatic cylinders have been used to control the three translational DOFs of the end effector through three couples of universal joints.

1 Introduction

Mechanical industries are showing a growing interest to devices based on parallel kinematics, because these architectures often provide excellent performances in terms of stiffness/weight ratio if compared to traditional serial robots. This is expecially true when considering applications involving packaging applications, assembly lines, or *pick and place* automation in general, where the benefit of a stiff architecture allows the achievement of light -hence extremely fast- robotic manipulators.

In similar contexts, parallel robots can perform many tasks which are traditionally performed by 4 DOF SCARA robots, that is applications where high operating speed is mandatory. For example, the DELTA architecture developed by R.Clavel [1] has been adopted with success in cookie-packaging lines, thank to the fast speed of this extremely light, yet stiff, parallel robot.

A definite advantage of parallel architectures is the fact that, in most cases, actuators can be placed on the truss, hence allowing the design of very light moving parts, even when adopting powerful and huge motors because their mounting won't move as the end-effector moves. This is one of the main reasons which encouraged us to adopt linear pneumatic actuators for a low-cost parallel robot. In fact pneumatic cylinders could be hardly used for serial robots, but they can be easily employed in a parallel device because cylinders and accessories would be simply fixed to the truss, thus achieving a limited weight for the moving parts.

Also, most applications of *pick and place* do not require all 6 degrees of freedom for the end effector, since 3 or 4 can be enough. This means that specific parallel kinematic

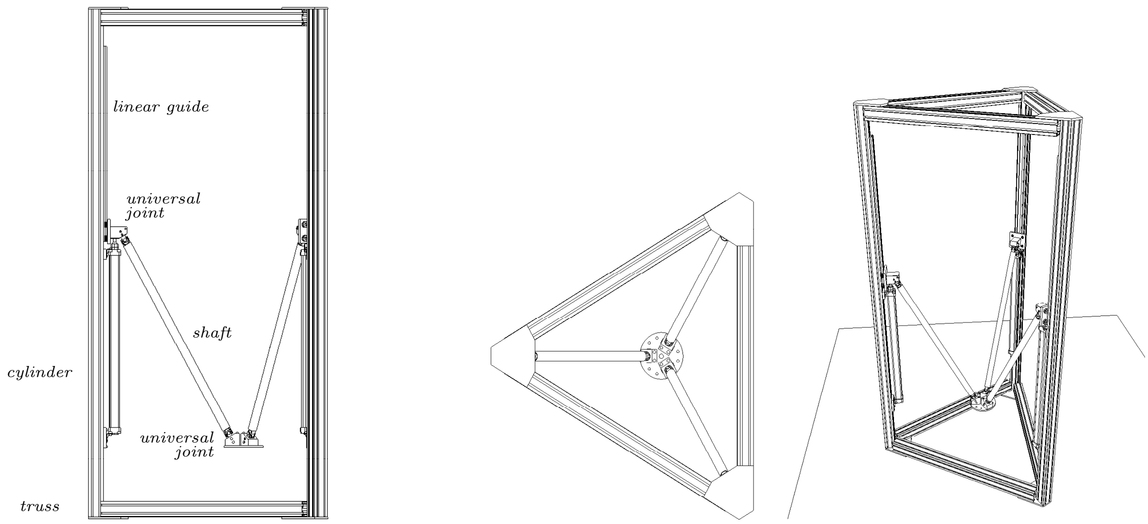

Figure 1: Side, top and perspective view of the TORX parallel robot.

schemes can be developed in order to provide just the three x,y,z translation in space of the end effector, avoiding extra complexity of further actuators like in the 6-DOF Stewart platforms. Therefore, different solutions have been developed to obtain pure x,y,z traslation of the end effector, without rotation, such as the 3-UPU scheme [2] where three couples of universal joints are used to keep the end-effector alignment constant and independent from its cartesian motion.

Starting from these considerations, we developed a 3-DOF kinematical scheme similar to the 3-UPU robot, with three universal joints mounted on three shafts. However, the pure translational motion of the end effector is provided by driving the pivot points of the three legs along linear guides on the truss, instead of changing the lenght of the shafts with prismatic guides. Hence, our scheme is rather 3-PUU, and allow us to fix on the truss either the pneumatic linear actuators and their heavy prismatic guides, with evident benefits in terms of little moving masses and simplified design.

2 Kinematics of the robot

Let consider the 3-PUU scheme of figure 2, where three inextensible shafts with universal joints on both ends are used to join the end effector to the three linear bearings which slide on vertical ground-fixed guides.

Applying the Kutzback or the Gruebler formulas, one gets the degrees of freedom of the structure. In this case, considering all the revolute joints which build up the universal joints: $n_{dof} = 6 * n_{bodies} - 5 * n_{revolutes} - 5 * n_{prismatics}$ that is, in the three-dimensional case, $n_{dof} = 3$ as expected, showing that three coordinates of the end effector can be controlled by moving the pivot points on the linear guides through three actuators.

Now consider the special case where each universal joint on the end effector shares the same mounting alignment of the corresponding universal joint on the other end of the shaft, that is the pivot on the bearing of the linear guide.

With this assumption one can move the ground position of pivot points and, as far as

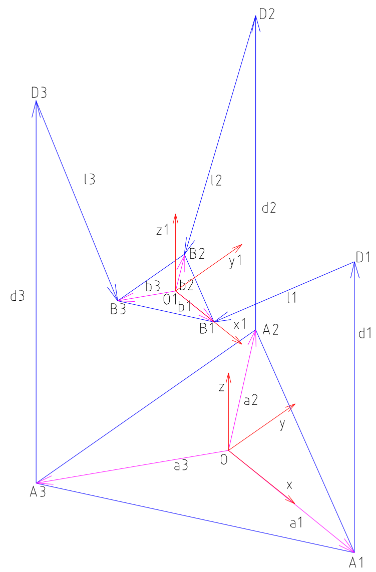

Figure 2: Main geometric parameters of the TORX architecture.

the pivot points are not rotated, the alignment of the end effector will remain constant, thus allowing just pure x,y,z translation. Proof of this property for 3-UPU robots can be found in D.Gregorio [3], and can be extended to the 3-PUU architecture as well.

With the above assumptions on pure translation of the end effector, we can easily write the equations for the direct and inverse kinematics of the robot, using a geometric approach. Considering the geometric parameters of figure 2, we can write the three vectorial closure equations

$$\vec{a}_i + \vec{d}_i + \vec{l}_i - \vec{b}_i - \vec{p} = \vec{0} \tag{1}$$

where the unknown terms are the lenght of $\vec{d}_i$. Hence, after some algebraic manipulations, one gets the inverse kinematics in analytical closed form:

$$d_i = p_z \pm \sqrt{-(\vec{e}_i)^2 - p_x{}^2 - p_y{}^2 + 2e_{ix}p_x + 2e_{iy}p_y + (\vec{l}_i)^2} \tag{2}$$

where $\vec{e}_i = \vec{a}_i - \vec{b}_i$, and d_i is the joint-coordinate of the i-th linear actuator as a function of the carthesian position of the end-effector $\vec{p}_i$.

Note that two solutions exist, according to the fact that there may be symmetric mountings of the rods about the x-y horizontal plane.

The forward kinematic, as for most parallel machines, is more complex than the inverse kinematics. In fact we found both a closed form analytical solution and a numerical solution: here we expose the latter.

Starting from the closure equations 1 one can write the following system:

$$2 \begin{bmatrix} A_{2x} & A_{2y} \\ A_{3x} & A_{3y} \end{bmatrix} \cdot \begin{bmatrix} p_x \\ p_y \end{bmatrix} = \begin{bmatrix} C_1 - C_2 \\ C_2 - C_3 \end{bmatrix} \tag{3}$$

where $A_{ix} = e_{ix} - e_{1x}$, $A_{iy} = e_{iy} - e_{1y}$ and $C_i = (\vec{l}_i)^2 - (d_i - p_z)^2 - (\vec{e}_i)^2$. The system must be solved iteratively, updating $p_z = d_1 - \sqrt{d_1{}^2 - p_x{}^2 - p_y{}^2 + 2e_{1y}p_y + 2e_{1x}p_x + l_1^2 - e_1^2 - d_1^2}$ until convergence.

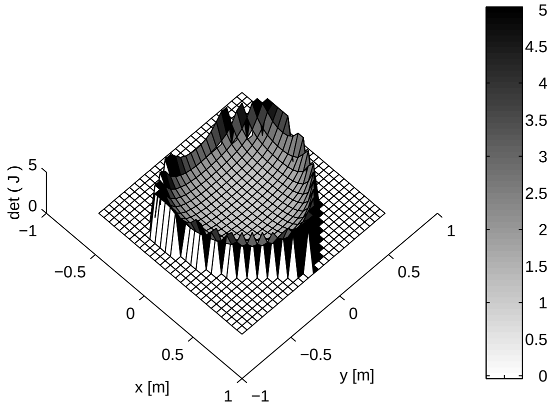

Figure 3: Jacobian in xy plane.

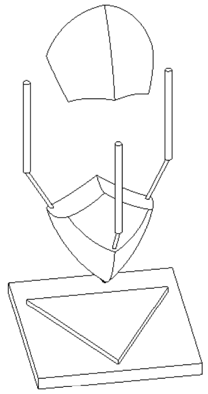

Figure 4: Working volume.

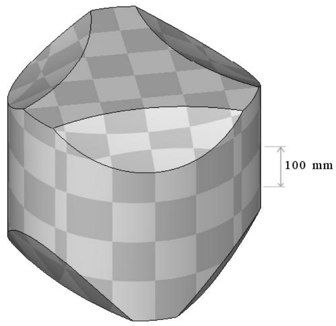

Figure 5: Effective volume.

3 Design and optimization

In order to choose the dimensions of the linkages and the stroke of the actuators it is necessary to find a good compromise between wide working volume and manipulator stiffness [5].

Therefore we developed a MATLAB program which optimized the geometry of our robot, trying to achieve good dynamical performances in the entire working volume. For this purpose, it is necessary to know the determinant of the IK/FK coordinate transformations (see fig.3).

We found that, for actuators with a stroke $\Delta_{max} d_i = 800$mm , we get a good working volume and satisfactory dynamic properties with $l_i = 1100$mm and $a_i = 600$mm. The final working volume is reported in fig.3, showing also the volume of the upward symmetric mounting. Note that the effective working volume is deliberately limited by a cylinder with diameter $r_{wa} = 600$mm, as in fig.5.

We also studied the dynamic performance of the robot by using our in-house multibody software [6], which helped us to choose the proper actuators (namely, three double-acting pneumatic cylinders with a 50mm diameter and 800mm stroke, each providing 1037N of max static thrust at 6bar).

4 Control

The control scheme of a single actuator is represented in figure 6. The signal coming from the linear encoder is processed by an encoder-counter board which is mounted on a commercial PC (550 Mhz Pentium III processor, 128 Mb RAM). Then, through another I/O board, an apposite analog signal is sent to the 5/2 proportional valve which feeds the pneumatic cylinder. The PC performs the closure of the control loop, thank to an operating system working in hard real time (RT-Linux V 2.2, a real-time release of the popular OS [8]) which easily allows a sustained thick of 0.001 s.

The implemented control scheme (fig. 7) is based on the PID theory, consisting on two loops, the inner acting on speed and the outer acting on position. To this controller, we added an open speed loop acting in *feedforward* mode. We obtained experimentally the curve of piston's steady-state speed, as a function of valve opening. This experimental

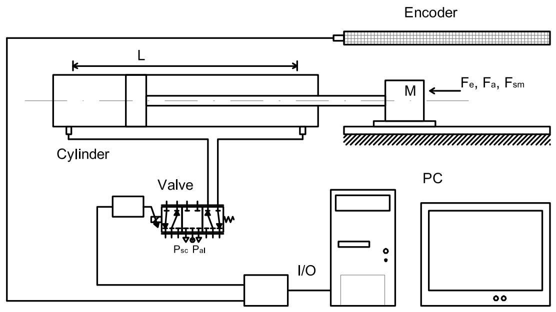

Figure 6: Control devices (single actuator)

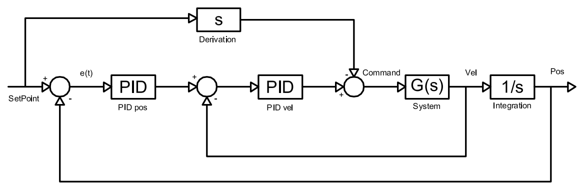

Figure 7: Scheme of controller

data is used to tune the *feedforward* contribute. The formulas used in our controller are based on the mathematical model of the pneumatic system [9], a theoretical background which is founded on the elliptical approximation of flows in outlets [8].

We improved the controller by implementing a strategy which compensates the asymmetric shape of cylinder chambers (as a consequence of the piston rod). Depending on the direction of the movement of the actuator, different sets of constants for the PID controller have been used, for a total of 3 sets. The first set of constants is used for piston's shrinking, the second for expansion, the third is applied to the situation of zero speed. Customizing this latter set of values is mandatory if one wants to achieve an high stiffness of the robot in stationary conditions, and exploits very high values in PID constants.

In order to avoid the discontinuities caused by sudden activations of the *feedforward* effect, we decided to modulate such contribution as a function of the acceleration of the system: the *feedforward* effect works when the speed must change, but fades away when speed must be constant.

5 Tests

We tested the prototype of the robot (fig.8) with different pay loads and various trajectories, in order to measure the precision and the upper limits for performances. As an example, for a 20 kg pay-load repeating a pick-and place trajectory of 300x300mm with v_{max} = 2m/s, the cartesian error is less than 10 mm while moving, and less than 2 mm at the positioning.

Our tests showed that the disadvantage of low precision of pneumatic actuators is counterbalanced by the benefit that the robot performances are scarcely affected by increasing payloads, because the precision remains almost constant even when moving heavy loads, up to 30-40 kg. For instance, the graph of fig. 9 shows the set-point error for an axis, while moving 30 kg on a fast and oddly-shaped trajectory: the joint error is under 20 mm during fast motion and about 1 mm at the positioning.

6 Conclusion

The adoption of standard pneumatic actuators allowed us to design a low cost parallel robot with high pay-load and high operating speed. This design, based on a 3 degrees of freedom kinematic scheme, can perform basic tasks like pick-and-place cycles with

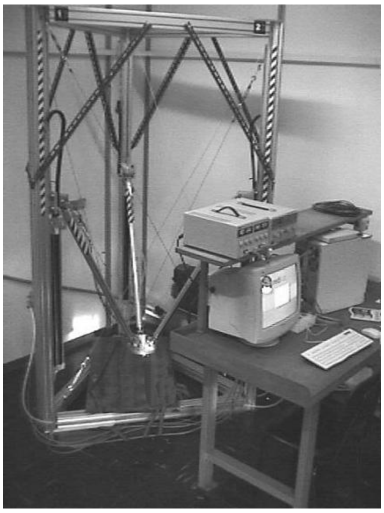

Figure 8: The TORX robot

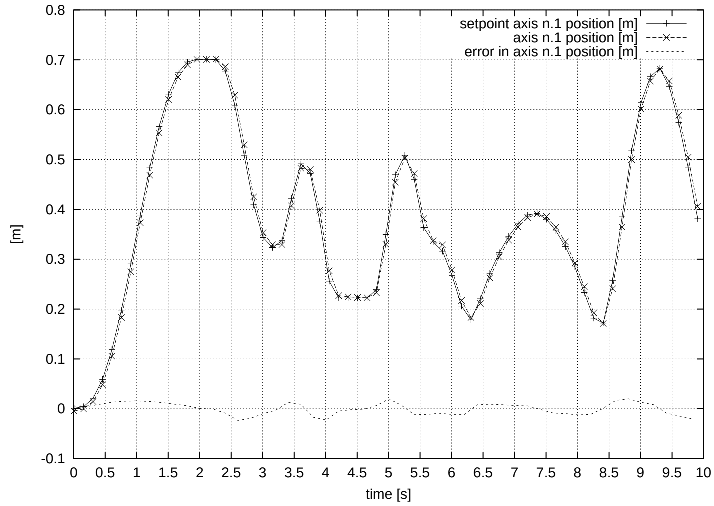

Figure 9: Example of setpoint vs. real motion

enough precision for industrial applications. Future researches will be addressed either at improved control strategy, either at a new joint design exploiting reduced backlash.

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