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DESIGN OF THE ‘GRANIT’ PARALLEL KINEMATIC MANIPULATOR

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ABSTRACT- This work describes the development of the GRANIT parallel-kinematic robot. The robot endorses a multifunctional end effector, a stiff and precise device aimed at the assembly of heating coils for hairdryers. Such assembly task require repeatability and releability, therefore we developed a custom manipulator which has 4 degrees of freedom like a SCARA robot, although offering a superior rigidity and precision thank to a custom parallel-kinematic design.

This robot uses a two-drives, four-bar linkage scheme for the horizontal motion, and a custom differential transmission based on a precision ballscrew, both for the vertical motion and for the rotation of the effector.

By performing dynamical analyses with our in-house multibody software, we simulated working volumes and motor torques. This helped us in choosing the best compromise for sizing, drives and transmissions.

Using electro-discharge machining and aerospace alloys, we built honeycomb structures for the four arms: this approach offers remarkable stiffness and limited mass. Taking advantage of a multi-functional scheme, three different tools are grouped together in a compact end-effector, whose main tasks are: cutting resistive wires, crimping connectors with sturdy pliers, and inserting mica plates.

The GRANIT robot has been built and successfully tested, showing high repeatability and stiffness.

Keywords: Robotics, Parallel kinematics, Automation, Multifunctional end-effector.

INTRODUCTION

Robots based on parallel-kinematic designs can exploit high stiffness and low inertia, hence leading to very fast and precise manipulators. This work describes the development of the GRANIT parallel-kinematic robot, aimed at the assembly of heating coils for hairdryers.

In Figure 1 one can see the heating coil whose assembly process is assisted by the GRANIT robot. Automating the assembly process for heating coils is a difficult task because thin resistive wires must be crimped and cut into small metallic connectors (hence the need for high repeatability and high operating speed), while the supporting mica plates must be connected each other by pushing them into small gaps, thus requesting a stiff effector [1].

In detail, the GRANIT robot must perform three main tasks:

- it must be able to pick mica plates of different sizes from different dispensers, and mount them into the rotating shaft which will wrap the wires,
- it must cut the wires at the beginning and at the end of the cycle, in six different positions,
- it must crimp the wire ends into the four connectors, in four different positions.

Since the parts are very small, no positioning errors can be tolerated. Meanwhile, the motion of the robot must be fast enough to allow high paces in coil production.

Given all these needs and constraints, we developed a custom manipulator which has 4 degrees of freedom like a SCARA robot, although offering a superior rigidity and reliability thank to a special parallel-kinematic design.

Figure 2 shows part of the assembly line: the robot must operate in a small cluttered workspace, so it was mandatory to develop a compact and space-saving solution. In fact most commercial parallel-kinematic manipulators adopt large struts [2], hence increasing the risk of collisions when accessing the cluttered workspace from the top. Our hybrid parallel-serial scheme copes better with the small workspace: the GRANIT robot uses a two-drives, four-bar linkage scheme for the horizontal motion, and a custom differential transmission based on a precision ballscrew, both for the vertical motion and for the rotation of the effector, like in the wrist of a SCARA.

KINEMATICS

The end-effector of the GRANIT robot has four degrees of freedom (three translations and a rotation about a vertical axis). Motion on the

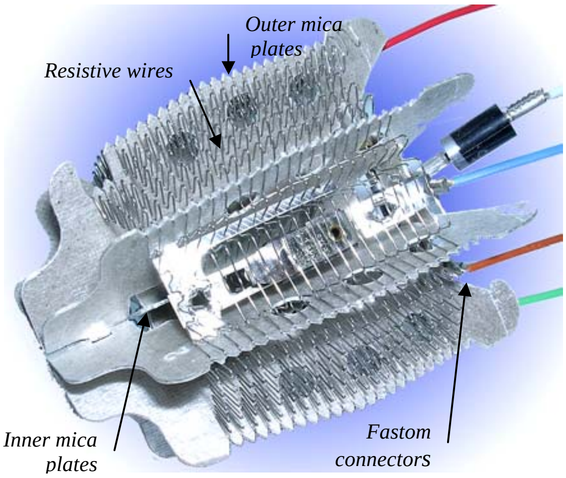

Fig.1 : Heating coil to be assembled

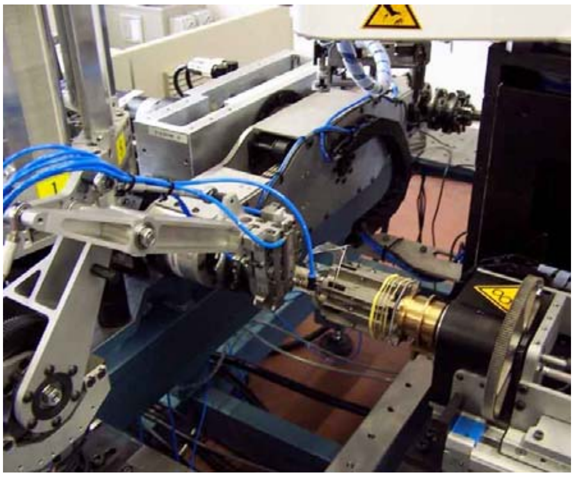

Fig.2: Part of the assembly line (robot environment)

horizontal plane must be as fast as possible in order to cope with the production cycle: this is achieved by using a five-body closed chain, with two motors M1 and M2 mounted on the truss as depicted in Figure 3. These two motors act on the four articulated arms, positioning the tool on the XY plane. Meanwhile, the two small motors M3 and M4 act on a differential screw mechanism nested in the wrist of the robot, controlling the vertical motion Z of the end effector, as well as its rotation. Even if the last two degrees of freedom are obtained with a serial kinematic scheme, this doesn't affect too much the precision and weight of the robot (in fact motors M3 and M4 are moving together with the arms, but their weight is almost irrelevant).

It is interesting to see that this design offers a fairly huge working volume, if compared with other classical parallel-kinematic solutions (almost as wide as the working volume of a SCARA).

The equations for the inverse kinematics and direct kinematics can be worked out quite easily. Here we present these functions in a plain scalar form. Our formulas had to be as simple as possible so that they can be implemented effortlessly in a robust and fast real-time controller.

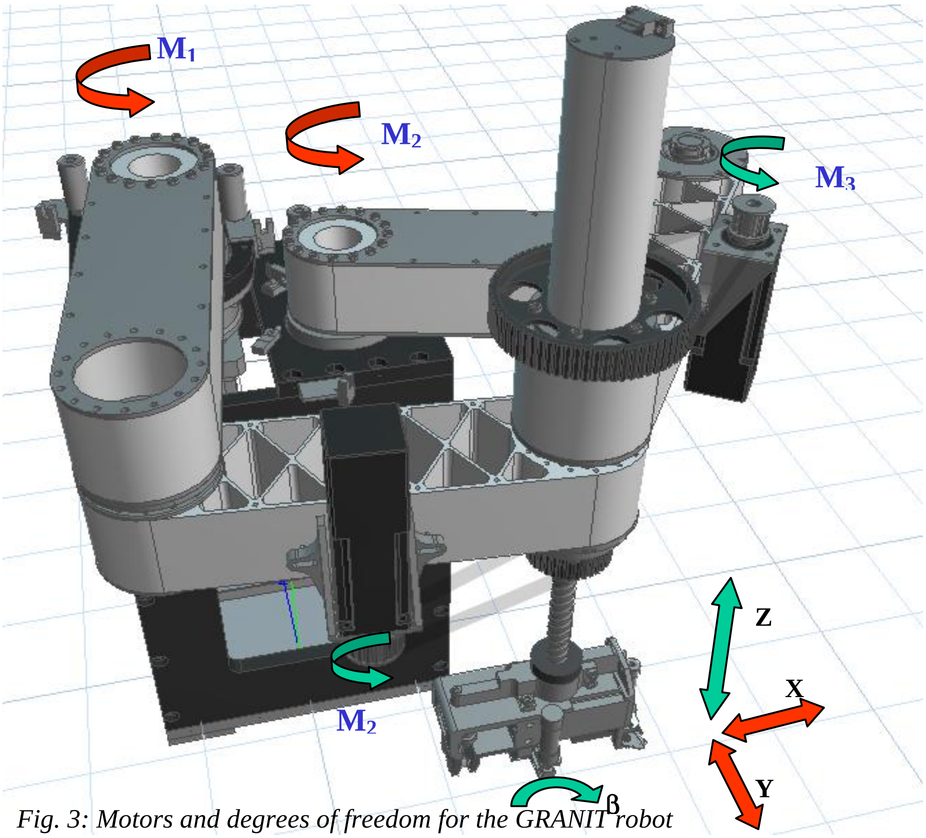

Fig. 3: Motors and degrees of freedom for the GRANIT robot

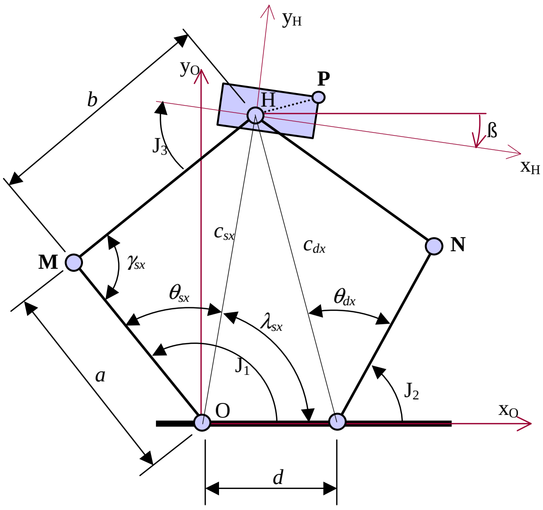

Fig.4 : Inverse kinematics

The inverse kinematics (IK) function is a vectorial mapping from working space *Q* to joint space *G*:

$$f_{IK}: \mathbf{q} \in Q \subset \mathsf{R}^4 \rightarrow \mathbf{J} \in G \subset \mathsf{R}^4 \qquad (1)$$

Vector **q** contains all the degrees of freedom of the end-effector in Cartesian space (absolute reference frame ‘O’):

$\mathbf{q} = \{P_{x,O}, P_{y,O}, P_{z,O}, ß\}$

while the **J** vector contains the joint coordinates:

$\mathbf{J} = \{J_1, J_2, J_3, J_4\}$

The most important constants are:

- *d* = distance between shoulders,
- *h* = robot height, from XY plane to arms
- *a* = lengths of biceps
- *b* = lengths of forearms
- $\mathbf{P}_H$ = coordinate of end-effector $P_{x,H}$, $P_{y,H}$, $P_{z,H}$ in tool reference ‘H’.

Looking at Figure 4, it is easy to see that the components of **J** can be easily computed with the following steps. First, compute the position of the origin of the tool reference in absolute coordinates:

$$H_{x,O} = P_{x,O} - \left(P_{x,H}\cos\beta - P_{y,H}\sin\beta\right)$$
$$H_{y,O} = P_{y,O} - \left(P_{x,H}\sin\beta + P_{y,H}\cos\beta\right)$$
$$H_{z,O} = P_{z,O} - P_{z,H}$$

At this point, the fourth component of **J** is:

$$J_4 = H_{z,O} - h \qquad (2)$$

Also, applying the Carnot theorem on the triangles OMH and ONH:

$$c_{sx} = \sqrt{H_{x,O}^{\,2} + H_{y,O}^{\,2}}$$
$$\lambda_{sx} = \operatorname{atan2}\left(H_{y,O}\ ,\ H_{x,O}\right)$$
$$\vartheta_{sx} = \operatorname{acos}\frac{\left(c_{sx}^{\,2} - b^2 + a^2\right)}{2\,a\,c_{sx}}$$

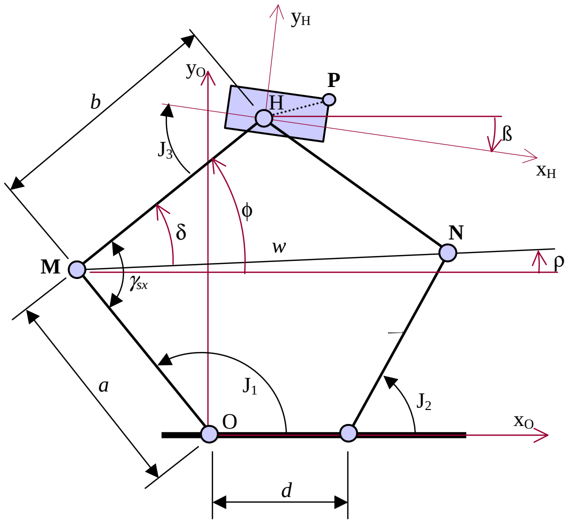

Fig.5: Forward kinematics

$$J_1 = \vartheta_{sx} + \lambda_{sx} \qquad (3)$$
$$\gamma_{sx} = \operatorname{acos}\frac{\left(-c_{sx}^{\,2} + b^2 + a^2\right)}{2\,a\,b}$$
$$c_{dx} = \sqrt{\left(H_{x,O} - d\right)^2 + H_{y,O}^{\,2}}$$
$$\lambda_{dx} = \operatorname{atan2}\left(H_{y,O}\ ,\ \left(H_{x,O} - d\right)\right)$$
$$\vartheta_{dx} = \operatorname{acos}\frac{\left(c_{dx}^{\,2} - b^2 + a^2\right)}{2\,a\,c_{dx}}$$
$$J_2 = -\vartheta_{dx} + \lambda_{dx} \qquad (4)$$

The last component of **J** is:

$$J_3 = \beta - J_1 - \gamma_{sx} + \pi \qquad (5)$$

During the evaluation of the inverse kinematics, the controller should check for the following situations, corresponding to non-reachable positions:

$c_{sx} > a+b$, $c_{sx} < |a+b|$, $c_{dx} > a+b$, $c_{dx} < |a+b|$.

The forward kinematics (FK) function is a vectorial mapping from joint space *G* to working space *Q* :

$$f_{FK}: \mathbf{J} \in G \subset \mathsf{R}^4 \rightarrow \mathbf{q} \in Q \subset \mathsf{R}^4 \qquad (6)$$

The following steps will easily compute the components of **q**, as suggested in Figure 5:

$$M_{x,o} = a\cos(J_1)$$
$$M_{y,o} = a\sin(J_1)$$
$$N_{x,o} = a\cos(J_2) + d$$
$$N_{y,o} = a\sin(J_2)$$
$$w = \sqrt{\left(M_{x,o} - N_{x,o}\right)^2 + \left(M_{y,o} - N_{y,o}\right)^2}$$

Note that a warning must be issued if $w > 2b$.

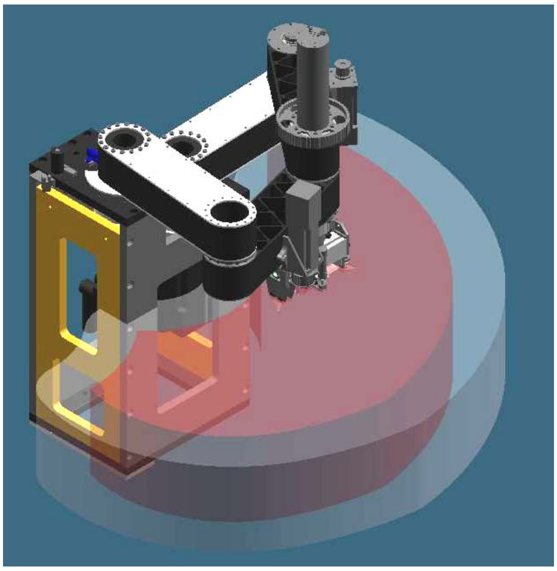

Fig. 6: Working volume

$$\rho = \operatorname{atan2}\left(\left(M_{y,o} - N_{y,o}\right), \left(M_{x,o} - N_{x,o}\right)\right)$$

$$\delta = \operatorname{acos}\frac{-b^2 + b^2 + w^2}{2\,w\,b}$$

$$\gamma_{sx} = \pi - J_1 + \rho + \delta$$

For $\gamma_{sx} > \pi$ a warning should be issued (reversed elbow). Finally compute the absolute rotation and position of end effector:

$$\phi = J_1 + \gamma_{sx} - \pi$$

$$\beta = \phi + J_3$$

$$P_{x,O} = M_{x,O} + b\cos(\phi) + P_{x,H}\cos(\beta) - P_{y,H}\sin(\beta)$$

$$P_{y,O} = M_{y,O} + b\sin(\phi) + P_{x,H}\sin(\beta) + P_{y,H}\cos(\beta)$$

$$P_{z,O} = J_4 + P_{z,H} + h$$

Choosing the size of robot arms is a matter of finding a good compromise between weight, stiffness, ability to reach the entire workplace. Depending on robot sizing, an optimal choice [3] of motors and transmission ratios of reducers should be addressed.

The working volume of the GRANIT robot is shown in Figure 6. To avoid near-singular positions, the end effector should operate only in a subset of the working volume, that is where the condition number of the jacobian matrix of the f_{IK} mapping is low enough: $\operatorname{cond}([\partial \mathbf{q}/\partial \mathbf{J}]) < C_{threshold}$.

Aiming at the optimal selection of reducers and motors, many analyses have been performed by means of our multibody software CHRONO: this tool can simulate working volumes and requested motor torques [4], therefore it helped us in choosing the best compromise for drives and transmissions.

Figure 7 and 8 show an example of output from the multibody simulation tool: given a benchmark trajectory which must be followed by the end effector (in this example, a 400mm horizontal pick-and-place trajectory lasting 0.5s), the software performs the dynamical analysis and computes the requested motor torques and speeds.

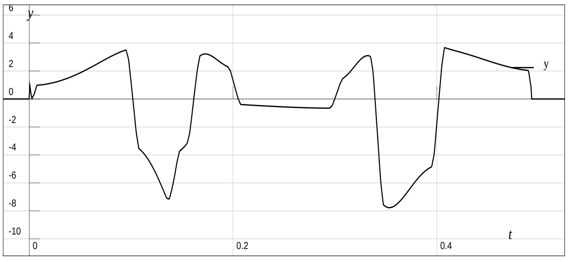

Fig: 7: Simulation of motor M1 *torque,* [Nm]

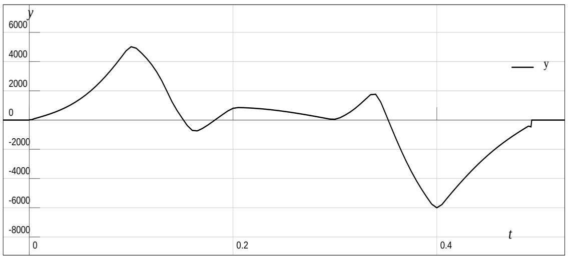

Fig. 8: Simulation of motor M1 *speed,* [rpm]

The final version of the GRANIT robot endorses two Mavilor BLS74 brushless servomotors (peak torque M_p=13.6 Nm, stall torque M_s=3.6Nm, rotor inertia J=0.097 kg $m^2 10^{-3}$), and two smaller Mavilor BLS40 brushless servomotors (peak torque M_p=1.44 Nm, stall torque M_s=0.36Nm, rotor inertia J=0.0024 kg $m^2 10^{-3}$). Reducers for shoulder rotations have a transmission ratio τ=1/61.

MECHANICAL DESIGN

Using electro-discharge machining and aerospace alloys, we built honeycomb structures for the four arms: this approach offers remarkable stiffness and limited mass. Tools for finite element analyses improved a lot this design process.

In order to increase the rigidity of the structures, we also adopted special thin-section bearings, whose large diameter and low weight fit well into our design constraints.

The rotation and the vertical motion of the end effector are obtained with a differential mechanism, shown in Figure 9. A roller mounted at the upper end of a ball-screw must slide into a vertical prismatic guide. The M4 servomotor acts on the screw nut via a synchronous belt, hence causing the vertical motion. Moreover, if the M3 servomotor rotates the prismatic guide about its vertical axis, the rotation of the end effector is obtained. Both M3 and M4 rotations can be combined for mixed motions.

Special care has been paid in avoid backlash in all parts of the robot: zero-backlash, high-precision epicycloidal reducers have been used for the

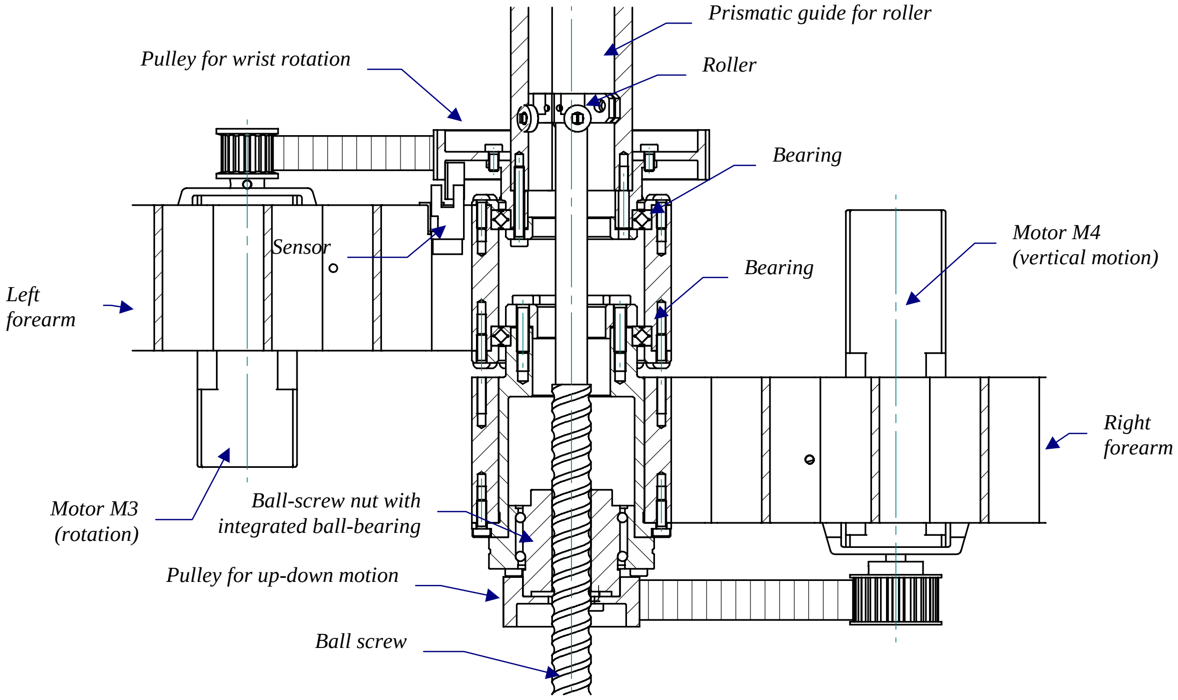

Fig. 9: wrist of the GRANIT robot.

rotation of the shoulders. Special high-quality timing belts have been used for wrist motion.

END EFFECTOR TOOLS

Taking advantage of a multi-functional scheme, three different tools are grouped together in a compact end-effector, whose main tasks are: cutting resistive wires, crimping connectors with sturdy pliers, and inserting mica plates.

The crimping pliers are actuated through a horizontal pneumatic cylinder, mainly for reasons of compactness: a special conical cam translates horizontally and closes the pliers on the vertical plane (see Figure 10).

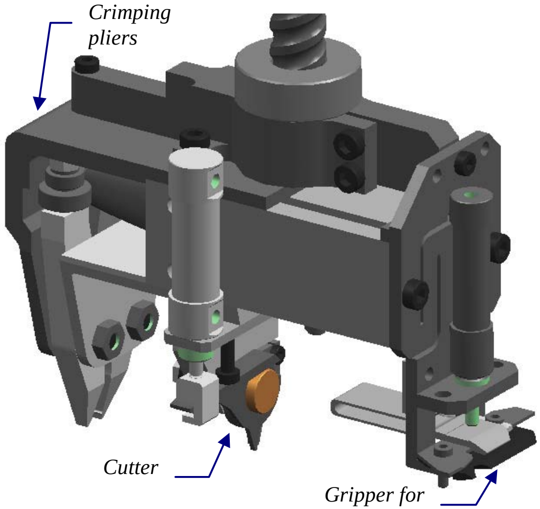

Fig. 10: End effector tools

For wire cutting, instead of using commercial pneumatic nippers, we developed a very light, compact and reliable scissor-like mechanism.

The gripper tool, mounted at the opposite side of the end-effector, is a simple and light compliant mechanism where a pneumatic cylinder bents a thin strip of metal (1mm of downward bending is enough to pick and handle the small mica plates).

Multiple sensors, in sake of the highest safety, check all the motions of the three tools [1].

The gripper tool is mounted on a custom deformable truss: this prevents the risk of crushing the end effector if a collision happens while picking or inserting the mica plates.

The complete end effector weights just 1.5 kg.

CONTROL

A computer running a real-time version of the Linux operating system provides the full-digital-authority control and sends a sustained stream of set-points to the four digital drives by means of a single OpenCAN bus.

The robot can be simulated and easily moved in teach-mode thank to a HMI (human machine interface) running on the computer.

Given that the robot must operate in a cluttered workspace, along odd pick-and-place trajectories, a custom sophisticated control mode has been implemented, where the motion of the gripper can be defined in terms of advanced parametric splines.

During the working cycle, the maximum trajectory error is continuously controlled, to prevent the risk of collision.

The real-time task which controls the robot is synchronized with other real-time tasks which manage the rest of the assembly line.

CONCLUSION

The parallel-kinematic GRANIT robot has been built and successfully tested, showing high repeatability and stiffness. Our tests demonstrated that repeatability is better than 0.01mm at the origin of the end-effector reference frame.

Arms and wrist have been designed with the goal of the highest stiffness and precision, though within the low-mass constraint.

The robot is capable of horizontal accelerations in excess of $40 m/s^2$, thus providing a valuable method to perform precise pick and place trajectories or assembly tasks at very high paces.

All the tools of the multifunctional end-effector proved to be reliable and functional.

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Fig. 11: The GRANIT robot