Task-oriented design of a high-speed parallel robot for pick-and-place operations

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Abstract— **This paper deals with a task-oriented design procedure for a two degree-of-freedom translational parallel manipulator, named IRSBot-2, dedicated to fast and accurate pick-and-place operations. This procedure aims to: (*i*) define an optimal test trajectory along which the dynamic performances of the robot are evaluated; (*ii*) find the optimal design parameters of the robot for given specifications. Here, two design optimization problems can be solved in cascade as the decision variables of the second problem do not affect the objective function and the constraints of the first problem. The Pareto-optimal solutions of the overall design problem are obtained and a set of optimal design parameters for the IRSBot-2 is selected. Finally, the CAD design of an industrial prototype of the IRSBot-2 is shown and some key technological solutions are described.**

I. INTRODUCTION

Parallel robots are more and more attractive to be used in high-speed pick-and-place operations. The drive for higher operational speeds and higher payload-to-weight ratios is shifting their designs to more lightweight architectures [1]. The fastest industrial robot, the Quattro by Adept Technologies Inc.[1], reaches more than 15 G of acceleration, allowing up to four standard pick-and-place cycles to be performed per second. However, as for all high-speed mechanisms, vibratory phenomena appear that worsen accuracy and dynamic performance. This critical issue prevents industrial sector from using high-speed parallel robots for special tasks requiring good accuracy and high accelerations such as the assembly of electronic components on printed circuit boards.

Several robot architectures for high-speed operations have been proposed in the past decades [2], [3], [4]. Many of them have four degrees of freedom (DOF): three translations and one rotation about a fixed axis, i.e., a Schoenflies motion [5]. Some simple operations need only two translational DOF in order to move a part from a working area to another. Therefore, several robot architectures with two translational (2T) DOF have been proposed. Among them, those that have the capacity to fix the orientation of the platform via the use of a planar parallelogram (also called a Π joint) are necessary in numerous operations[2] [4], [6], [7], [8]. However, most of the proposed architectures are not stiff enough along the normal to the plane of motion while some applications require the mechanism to be stiff along that direction. The optimal design parameters of a new 2T DOF parallel robot named IRSBot-2 are obtained in this paper. As shown in [9], it appears that the IRSBot-2 outperforms its two-dof counterparts in terms of stiffness along the normal to the plane of motion.

TABLE I
SPECIFICATIONS OF THE IRSBOT-2

Motion type	2T 1R
Repeatability ε_{lim}	20 μm
Resolution r_{lim}	2 μm
Acceleration max	20 G
Cycle time	200 ms
Path dimension	25 mm × 300 mm × 25 mm
Regular workspace size	800 mm × 100 mm
Deformation $\boldsymbol{\delta}_{tlim}$ under a force $\mathbf{f}_s = [0, 20, 0]$ N and a moment $\mathbf{m}_s = [1, 1, 1]$ N.m	$[0.2, 0.2, 0.2]$ mm, $[0.1, 0.1, 0.1]$ deg
Maximal payload (including motor)	1.5 kg

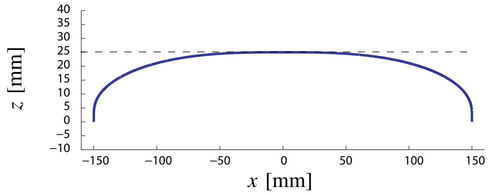

Fig. 1. Optimal test path

II. DESIGN SPECIFICATIONS

In the scope of the French National Project named ARROW, including two academical (IRCCyN and LIRMM) and one industrial (Tecnalia France) partners, the IRCCyN focuses on the design of a robot for fast and accurate pick-and-place operations and dedicated to the assembly of electronic components on printed circuit boards. More than 20000 components should be assembled per hour, i.e., more than 5 components per second, with a positional error lower than 100 μm throughout a large operational workspace. Besides, the robotic cell should be cheaper than the existing machines used to realize those operations[3].

The specifications to be achieved by the robot that have been expressed with some industrial partners are given in Tab. I. The robot should be as compact as possible due to industrial constraints. Moreover, in order to reject the robot vibrations due to high accelerations, the first natural frequency should be a maximum. A test trajectory was

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[1] `www.adept.com`

[2] see also: `www.veltru.com/dnn01/en-us/products/robots.aspx`, `http://en.autonox24.com/products/ip65_delta_robots` and `www.abi.nl/en/productsgb/mnuabiflexxgb`

[3] `www.siplace.com/doc/aud_tabstrip.aspx?id=14188&domid=10&sp=E&m1=9720&m2=11112&m3=11116&m4=14180&m5=14188`

optimized in [15] in such as way that the moving-platform of the IRSBot-2 follows it within 104 ms with a maximum acceleration equal to 20 G. Figure 1 illustrates the path of this optimized test trajectory that will dedicated to the computation of the dynamic and elastic robot performances.

III. IRSBOT-2 ROBOT ARCHITECTURE

In order to satisfy the specifications given in Tab. I, the IRSBot-2 robot has been developed. The IRSBot-2 is presented in detail in [10], [11] and is shown in Fig. 2. It is a two-DOF translational parallel manipulator and an additional rotary actuator could be mounted on the platform in order to obtain an additional rotational DOF. The spatial architecture of this robot confers also a good intrinsic stiffness [9].

The IRSBot-2 is composed of two identical spatial limbs, each one (Fig. 3) containing a proximal module and a distal module. The proximal module is composed of the actuated proximal arms A_kB_k and the passive proximal arms D_kC_k, both forming an articulated parallelogram perpendicular to $\mathbf{y}_0$. The elbow is composed of segments C_kB_k, H'_kH_k and $E_{2k}E_{1k}$, in which two cardan joints are attached to the distal arms $E_{ik}F_{ik}$. The distal arms are also linked to the moving platform carrying out the motor for the rotational motion about $\mathbf{z}_0$.

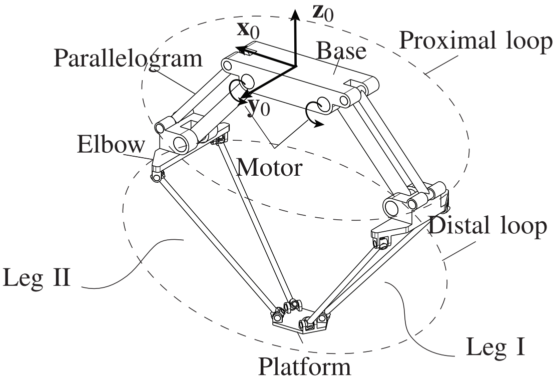


Fig. 2. CAD modeling of the IRSBot-2

The design parameters of the IRSBot-2 are depicted in Fig. 3. Their optimal values are obtained thereafter.

IV. OPTIMAL DESIGN PARAMETERS

The values of fifteen design parameters of the IRSBot-2 have to be defined based on geometric, kinematic, kinetostatic, elastic and dynamic performances [12]. Table II shows the relations between the design parameters, robot performances, motor datasheet and the test trajectory to follow. From Tab. II, only seven design parameters affect the geometric, kinematic, kinetostatic performances of the IRSBot-2. Those design parameters are the components of the decision variable vector $\mathbf{x}_1 = \begin{bmatrix} l_1 & l_{2eq} & b & p & e_x & e_z & \alpha_I \end{bmatrix}$. The other design parameters of the robot only affect its elastostatic, dynamic and elastodynamic performances. Those design parameters are the components of the decision variable vector $\mathbf{x}_2 = \begin{bmatrix} v_1 & v_2 & w_{Pa} & S_{ov} \end{bmatrix}$, where S_{ov} are section parameters.

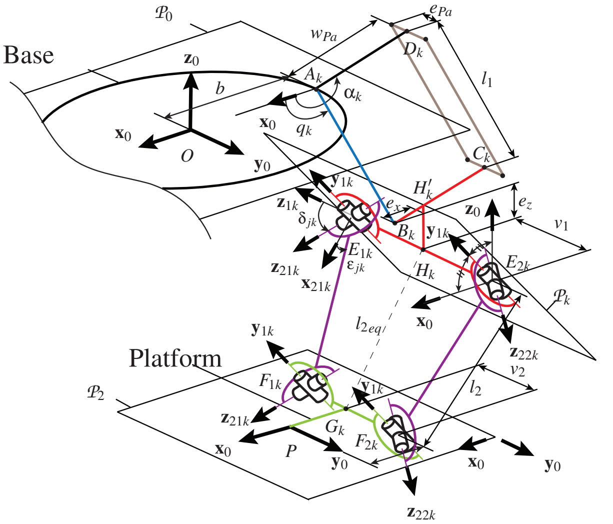


Fig. 3. Kinematic chains and design parameters of the kth leg ($k = I, II$) (The revolute joint axes $(A_k, \mathbf{y}_0)$, $(B_k, \mathbf{y}_0)$ $(C_k, \mathbf{y}_0)$ and $(D_k, \mathbf{y}_0)$ are removed for better clarity)

TABLE II

RELATIONS BETWEEN DESIGN PARAMETERS, ROBOT PERFORMANCES, MOTOR DATASHEET AND TASK TRAJECTORY

Performances	Constraints/ objectives	Design parameters $\mathbf{x}_1$	Design parameters $\mathbf{x}_2$	Motor datasheet	Trajectory
Geometric	Robot size	√ in the motion plane	√ along $\mathbf{y}_0$		
	Workspace	√			
Kinematic	Error and velocity transmission	√		√	
Kinetostatic	Effort in passive joints	√			
Elastostatic	Static deformation	√	√		
Dynamic	Motion torques	√	√	√	√
Elastodynamic	First natural frequency	√	√		√

Thus, two design optimization problems can be formulated, $\mathbf{x}_1$ and $\mathbf{x}_2$ being the decision variable vectors of the first and second problems, respectively. It is noteworthy that the objective function and the constraints of the first optimization problem do not depend on vector $\mathbf{x}_2$. As a consequence, the two optimization problems have been solved in cascade in [13] by considering the optimal set of decision variables of the first optimization problem as fixed parameters for the resolution of the second optimization problem.

The first optimization problem aims to minimize the size of the robot in the plane of motion in order to reach the regular workspace specified in Tab. I. Assembly conditions, velocity and error transmission and internal effort limits have also considered through the constraints (see [12]).

The second optimization problem aims to find the design parameters that minimize the mass in motion and the size

TABLE III

DATASHEET OF THE TMB210–100 ETEL MOTOR

V_{max} [rpm]	r [pt/rev]	T_{peak} [N.m]	T_C [N.m]	Φ [mm]	J [Kg.m^{-2}]
600	280000 × 4	445	92	166	$2.9e^{-3}$

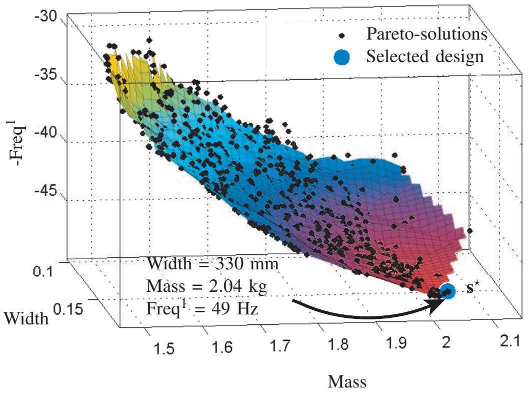


Fig. 4. Pareto Front of the IRSBot-2 and selected solution $\mathbf{s}^\star$. $l_1 = 321\ mm, l_{2eq} = 437\ mm, b = 83\ mm, p = 50\ mm, e_x = 80\ mm, e_z = 0\ mm, \alpha_I = 210\ deg\ v_1 = 165\ mm, v_2 = 30\ mm, w_{Pa} = 110.4\ mm$

of the manipulator along the normal to the plane of motion and maximize the first natural frequency of the IRSBot-2 **at both ends of the optimized test trajectory**. This problem is subject to elastostatic constraints as specified in Tab. I and the required actuated torques should be also smaller than the torque provided by the motor (Tab. III) **along the trajectory**.

The TMB210-100 ETEL direct drive motors have been pre-selected for the robot actuation. Their characteristics are given in Tab. III.

The first optimization problem is mono-objective and has been solved by a genetic algorithm, i.e., Matlab *ga* function. The second optimization problem is tri-objective and has been solved by a Non Sorting Genetic Algorithm (NSGA-II), which returns a set of Pareto-optimal solutions shown in Fig. 4 [12]. Note that the higher the first natural frequency of the IRSBot-2, the lower its vibrations and the better its accuracy at both ends of the test-trajectory. Therefore, the solution denoted as $\mathbf{s}^\star$ in Fig. 4 has been selected because it leads to a maximum first natural frequency for the robot.

V. TECHNOLOGICAL SOLUTIONS AND PROTOTYPE

A CAD Modeling of the IRSBot-2 prototype is illustrated in Fig. 5. Its main dimensions are those obtained in Sec. IV. In this section, some key technological solutions for the realization of the IRSBot-2 prototype are highlighted.

A special attention is paid to: (*i*) the realization of the proximal arms; (*ii*) the motor selection; (*iii*) the realization of the universal joints; and (*iv*) the choice of the gripper.

1) Proximal arms: As shown in [9], the proximal arms of the IRSBot-2 were the weakest elements in some preliminary designs of the robot. Therefore, those parts have been strengthened and also redesigned in order to reduce the redundant constraints in the parallelogram linkages by means of an adjustable length link corresponding to the segment D_kC_k (Fig. 3). Figure 6(a) illustrates the final design of the proximal arms. Two lateral thin sheets covered the I-shape of each proximal arm. Ball bearings have been used for the realization of their revolute joints.

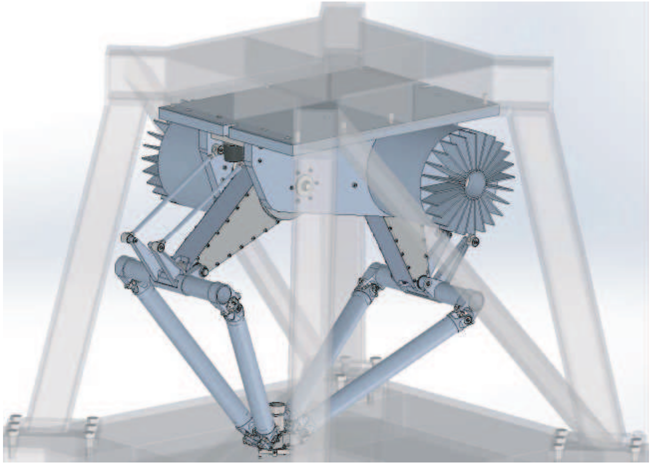


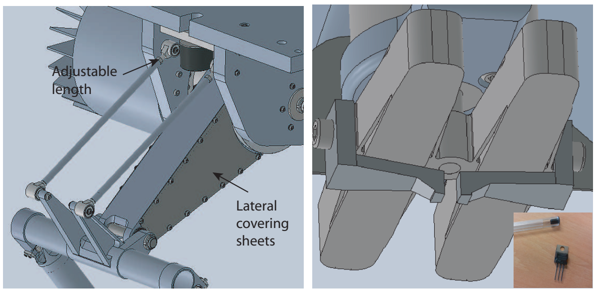
Fig. 5. CAD Modeling of the IRSBot-2 prototype

2) Motor selection: In order to avoid backlash effect in the power transmission system on the moving-platform pose error, TMM210-150 ETEL direct drive motors have been selected. The actuated torque required to follow the test trajectory is illustrated in Fig. 7(a). This figure also highlights the contributions of the proximal arms, the elbows, the distal modules and the moving-platform to the required motor torques.

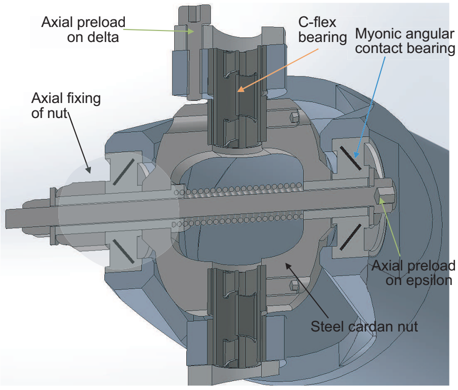
3) Universal joints: The manufacturing and assembly of universal joints, also called Cardan joints, of parallel manipulators dedicated to accurate operations is always challenging. Considering thus located at E_{ik} and F_{ik} (Fig. 3), as the range of variations in angles δ_{jk} is smaller than 6 deg, C-FLEX (Type F-30) backlash free flexible bearings from C-flex have been selected for the realization of the corresponding joints. The revolute joints associated with ε_{jk} angles (see Fig 3), for which the range of variation can be up to 66 deg, have been made up of standard angular contact bearings (from Myonic). Figure 6(c) represents a CAD modeling of the final universal joint.

4) Gripper: In order to perform five pick-and-place cycles per second, the gripper must have a low response time and be light. Here, a light piezoelectric gripper (mass smaller than 50 g) with a response time lower than 2 ms has been selected. Note that two actuators are combined with the gripper fingers, as shown in Fig 6(b), because of the low stroke of the piezoelectric gripper, which is about 700 μm around the nominal width 17 mm.

Finally, the performances of the industrial prototype of the IRSBot-2 are summed up in Figs 7(a) and 7(b). The reachable operational workspace of the robot is shown in Fig 7(c).

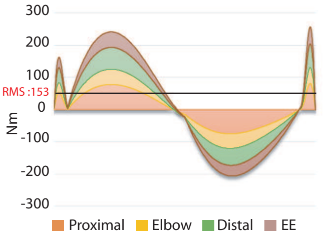


(a) Proximal arm (b) Gripper



(c) Cardan joint

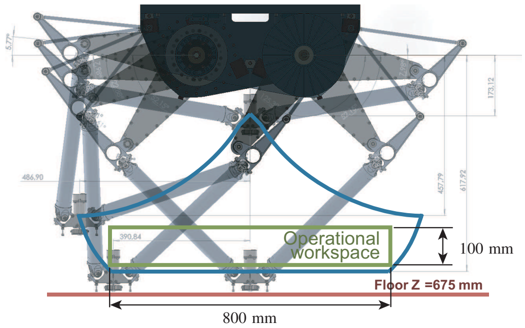
Fig. 6. Key technological solutions



(a) Required motor torque along the test trajectory

Elastic displacement along $\mathbf{y}_0$	160 μm
First natural frequency	
in the motion plane	45 Hz
along $\mathbf{y}_0$	55 Hz

(b) Elastic and elastodynamic performances computed at the end of the test trajectory



(c) Operational workspace

Fig. 7. Performances of the industrial prototype of the IRSBot-2

VI. CONCLUSIONS

This paper dealt with a task-oriented design procedure for a two degree-of-freedom translational parallel manipulator, named IRSBot-2, for fast and accurate pick-and-place operations and dedicated to the assembly of electronic components on printed circuit boards. First, an optimal test trajectory along which the dynamic performance of the robot are tested has been obtained. Then, two optimization problems have been formulated and solved in cascade in order to find the optimal design parameters of the IRSBot-2. Finally, the CAD design of an industrial prototype of the IRSBot-2 and its key technological solutions have been described. The experimental validations of the theoretical results obtained in the framework of the ARROW project will be made soon thanks to the industrial prototype of the IRSBot-2 under construction.

ACKNOWLEDGMENT

This work was conducted with the support of the French National Agency (Project ANR-2011-BS3-006-01-ARROW)[4].

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