Parallel robots with configurable platforms

Lambert, Patrice; Herder, Just

Publication date
2015

Document Version
Final published version

Published in
Mikroniek: vakblad voor precisie-technologie

Citation (APA)
Lambert, P., & Herder, J. (2015). Parallel robots with configurable platforms. *Mikroniek: vakblad voor precisie-technologie*, *55*(6), 14-19.

PARALLEL ROBOTS WITH CONFIGURABLE PLATFORMS

Conventional parallel robots are formed by several independent serial chains, connecting in-parallel a single rigid platform, or end-effector, to the base. The novel concept behind a parallel robot with configurable platform is that the rigid end-effector is replaced by a closed-loop chain, which can provide additional grasping capability or additional rotational degrees of freedom, while all motors remain on the base. Fundamental aspects of parallel robots with configurable platforms are presented, as well as two functional prototypes based on this concept.

PATRICE LAMBERT AND JUST HERDER

Introduction

The majority of current industrial robots are based on a serial structure that resembles a human arm. The rigid links and the joints are assembled in a serial chain where each joint must be actuated to fully control an end-effector relative to a base. The main drawback of such open-loop structures is that each motor must carry the weight and inertia of the motors further in the serial chain. Mechanically, a serial chain is also in general less stiff than a closed-loop structure. High inertia and low stiffness lead to a low mechanical bandwidth that ultimately limits the dynamic performance of the robot.

Alternatively, it is possible to use a mechanical structure in which the links and joints are assembled into closed loops. By using a so-called parallel architecture [1], it is possible to fully control the whole mechanism by placing motors on only a subset of the joints. Preferably, actuated joints are located on or near the base of the robot so that the motors give little contribution to the global inertia and heavier, more powerful motors can then be used. In addition, the parallel mechanical structure between the base and the end-effector will have in general a better mechanical stiffness than a comparable serial structure. Lower inertia and higher stiffness both lead to a higher mechanical bandwidth.

Parallel robots are generally used for applications in which high mechanical bandwidth is needed, such as flight simulators, high-speed pick-and-place robots, and haptic devices. They are commonly used to position a single rigid body, the end-effector, in six or less than six degrees of freedom (DoFs). However, in certain tasks where the interaction with the environment requires multiple contact points, for example when mechanical grasping is needed, additional end-effectors as well as additional controlled DoFs between them must be provided from the mechanical architecture.

Robotic grasping

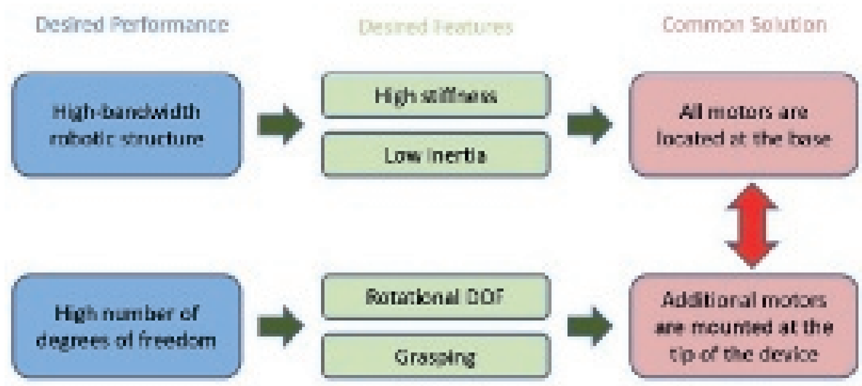
As an example, in the pick-and-place industry, where the common solutions to handle products rely on vacuum gripping when the product has a flat surface, mechanical grippers are needed for other products that have a surface which is rough, porous or not flat, or has holes. For haptic interfaces, a trend in the field is the development of interfaces that provide multiple points of contact to the operator, allowing them to use their fingers to grasp virtual objects in order to feel their shape and stiffness, which results in a much more natural interaction with the virtual or remote environment than a single contact point.

A common solution to provide robotic grasping in a parallel robot is to mount an additional actuator and robotic gripper at the tip of the already existing robot. However, in case of parallel robots, their main advantages rely on the fact that all the motors are located on the base and that only

AUTHORS' NOTE

Patrice Lambert is a postdoctoral researcher in the Precision and Microsystem Engineering department (PME) at Delft University of Technology, the Netherlands. Just Herder is professor in the PME department and at the University of Twente in the field of interactive mechanisms, mechatronics and robotics.

p.lambert@tudelft.nl
www.pme.tudelft.nl
www.utwente.nl/ctw/wa



1

mechanical links connect the end-effector with its base. Adding a grasping motor is increasing the mass of the structure at the worst possible location for its mechanical bandwidth, namely at the end-effector location where the weight of the motor must be carried over the whole workspace, resulting in lower dynamic performance of the robot.
Sometimes, motors are also mounted at the tip of the robot to provide additional rotational DoFs. This is commonly known as a robotic wrist mechanism. Figure 1 shows a schematic representation of the problem.

The relatively new class of parallel robots described in this article, parallel robots with configurable platforms (PRCPs), retains the advantages of classical parallel robots, i.e. that all the motors are grounded on the base, while offering mechanical grasping capabilities via multiple contact points.

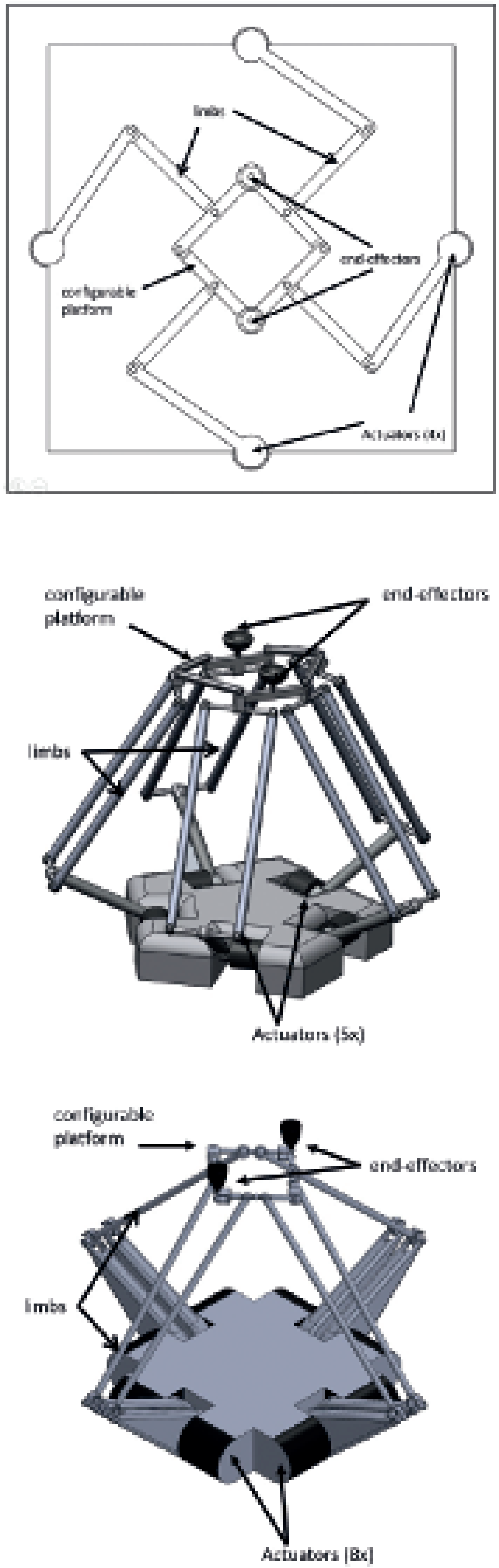
PRCP architecture

Conventional parallel mechanisms are formed by two rigid links, the base and the end-effector connected in parallel by serial chains, called limbs. The concept behind parallel mechanisms with configurable platforms [2],[3] is that the rigid-link (non-configurable) end-effector is replaced by an additional closed-loop chain (i.e. the configurable platform). Some of the links of this closed loop are attached to the limbs so that both the pose and the configuration of the configurable platform (CP) can be fully controlled by the motors located on the base.

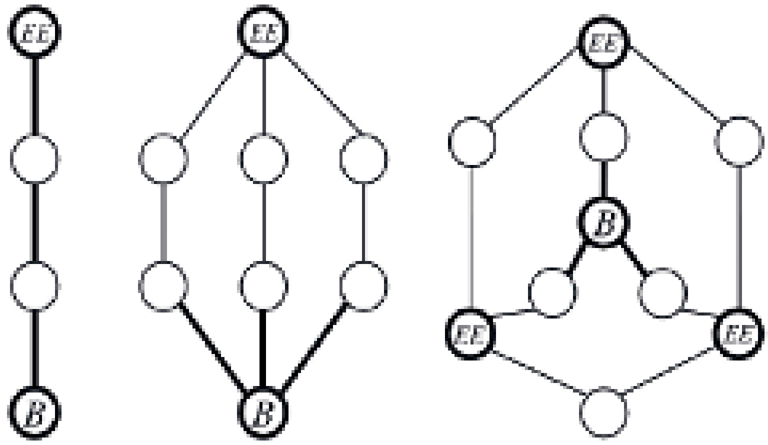
The use of a closed loop instead of a rigid end-effector allows the robot to interact with the environment from multiple contact points on the platform. The contact points have a relative mobility between each other that can be fully controlled by the actuators located on the base. This results in a robot that can combine motions and grasping capabilities into a structure that provides an inherent high structural stiffness since all the actuators are located on the

1 The current solution for mechanical grasping consists of locating additional motors at the distal end of the robotic device, which conflicts with the desire of having high stiffness and low inertia.

2 Parallel robots with configurable platforms with, from top to bottom, four, five and seven DoFs, respectively. Each robot is formed by a set of base-located motors, a configurable platform hosting two end-effectors, and a set of parallel limbs connecting the motors to the configurable platform.



2



3 *From left to right: graph representation of a particular serial robot, a parallel robot, and a parallel robot with a configurable platform. The actuated joints (in bold edges) are used to fully control the motion of each end-effector (EE) relatively to the base (B).*

base. High-speed pick-and-place robots and haptic interfaces are examples of applications which can benefit from this type of architecture. Figure 2 shows three PRCP examples with four, five and seven DoFs, respectively.

In the planar 4-DoF robot, three DoFs are used to position the platform and the fourth DoF is used to vary the distance between the two end-effectors. Similarly, the configurable platform of the 5-DoF robot can move in three translation directions, while two internal DoFs in the platform provide rotation and grasping. Finally, the platform of the 7-DoF robot can move in any position/orientation and provide one DoF grasping, while using a redundant actuation scheme with eight motors to avoid singularities and increase the effective workspace.

To illustrate some fundamental difference of PRCP with other classes of robot architectures, it is interesting to analyse their topology with a graph representation. The term 'mechanism topology' refers here to the network of joint connections between the various rigid links of the robot, regardless of the type of joint, their specific position and orientation on the links, or which joint is actuated. The topology of a mechanism ultimately determines which formula and methods are used in order to calculate its kinematic relations, and can be used to classify different types of robotic architectures. In a graph representation of a mechanism, each edge is a joint and each vertex is a rigid link. Figure 3 shows a graph representation of a serial robot, a parallel robot, and a parallel robot with a configurable platform, respectively.

Kinematic model

The kinematic model of a mechanism describes the relations between the relative motion of the various rigid bodies of the system. Of special interest is the motion mapping between the joints equipped with motors/sensors and the end-effector parts, which interact with the environment. These relations directly influence the precision, workspace, force transmission, stiffness and dexterity of the device.

Inverse kinematics

The inverse position kinematics (IPK) is the non-linear relation that describes the position of the motors as a function of the end-effector position. This relation is needed to control the robot in position. While the inverse position kinematics in conventional parallel robots can be calculated independently for each limb, the IPK of PRCP involves a two-step method where the IPK of the CP (configurable platform) must be calculated separately from the IPK of each leg. The same holds for the linear inverse velocity kinematics calculation leading to the Jacobian matrix, where the inverse platform Jacobian J_p^{-1} must be first computed.

For a PRCP with n limbs and m DoFs, given that $\dot{\chi}$ is a vector representing the end-effector's velocity and $\$_{cj}$ is the twist representing the velocity $\dot{c}_i$ – the velocity vector of the limb attach point on the platform – with respect to the DoF j, we have:

$$\dot{c} = J_p^{-1}\dot{\chi}$$

$$\begin{bmatrix} \dot{c}_1 \\ \vdots \\ \dot{c}_n \end{bmatrix}_{6n,1} = \begin{bmatrix} \$_{c11} & \cdots & \$_{c1m} \\ \vdots & \ddots & \vdots \\ \$_{cn1} & \cdots & \$_{cnm} \end{bmatrix}_{6n,m} \dot{\chi}$$

The second step is to connect the various Jacobian matrices J_{lj}^{-1} of the limbs j to the platform Jacobian J_p^{-1} to obtain the full inverse Jacobian J^{-1} such that:

$$J^{-1} = \begin{bmatrix} J_{l1}^{-1} J_{p1}^{-1} \\ \vdots \\ J_{lm}^{-1} J_{pm}^{-1} \end{bmatrix}_{m,m}$$

Here, J_{pj}^{-1} is the column j of J_p^{-1}. The velocity of the motors $\dot{q}$ is then described by :

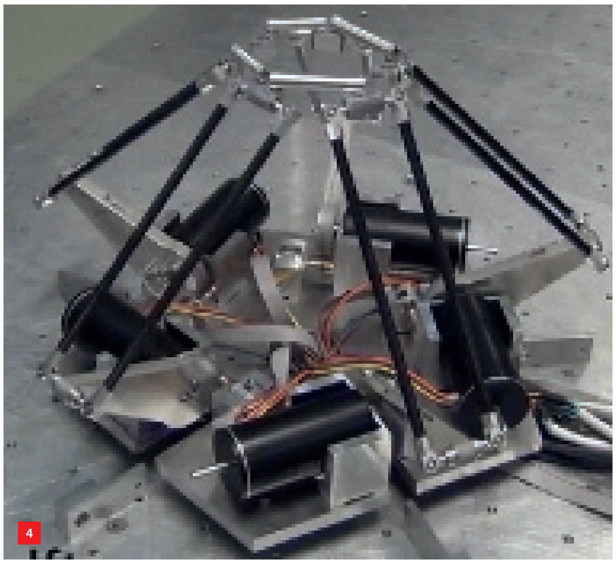
$$\dot{q} = J^{-1}\dot{\chi}$$

Statics and stiffness

Employing the power conservation principle, the transpose of the inverse Jacobian matrix J^{-T} can be used to describe the mapping of the vector of motor torques τ to the vector of end-effector forces f:

$$f = J^{-T}\tau$$

$$J^{-T} = \left[J_{p1}^{-T} J_{l1}^{-T} \quad \cdots \quad J_{pm}^{-T} J_{lm}^{-T} \right]$$



4 *The 5-DoF PentaG haptic master device.*
5 *PentaG device in its pick-and-place version.*

It is also possible to derive a formulation for the stiffness matrix of a general PRCP using the analytical expressions of the platform Jacobian J_p^{-1} and the leg's Jacobian J_l^{-1}. If all actuators are locked and have a linear stiffness k, the stiffness matrix K, mapping a small displacement $\Delta\chi$ of the end-effectors to the end-effector reaction force f is given by:

$$f = K\Delta\chi$$
$$K = kJ^{-T}J = k\sum_{i=1}^{m}\left[J_{pi}^{-T}J_{li}^{-T}J_{li}^{-1}J_{pi}^{-1}\right]_{m,m}$$

Two examples

Example 1: The PentaG robot

The PentaG robot [4] is a 5-DoF parallel robot with a configurable platform, combining three translational DoFs, one rotational DoF around the vertical axis and one grasping DoF. All five motors are fixed on the base, resulting in a very light moving structure and an inherently high structural stiffness. It was initially developed as a haptic device for tele-operation in micro-assembly. Figure 4 shows a fully functional prototype of the PentaG.

The various kinematics parameters of this device have been optimised to maximise the kinematic force mapping and precision sensing while preserving a large workspace in comparison with the size of the structure, i.e. its compactness. The other design parameters (that do not influence the kinematics) have been optimised for low inertia while preserving a certain stiffness.

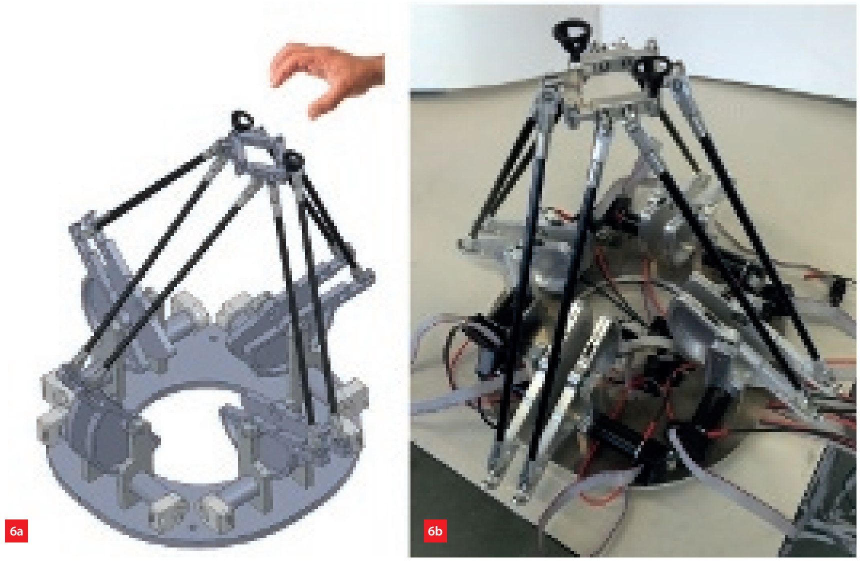
More information on the PentaG device, including a video of the prototype, can be found on the Delft Haptic Lab website [5].

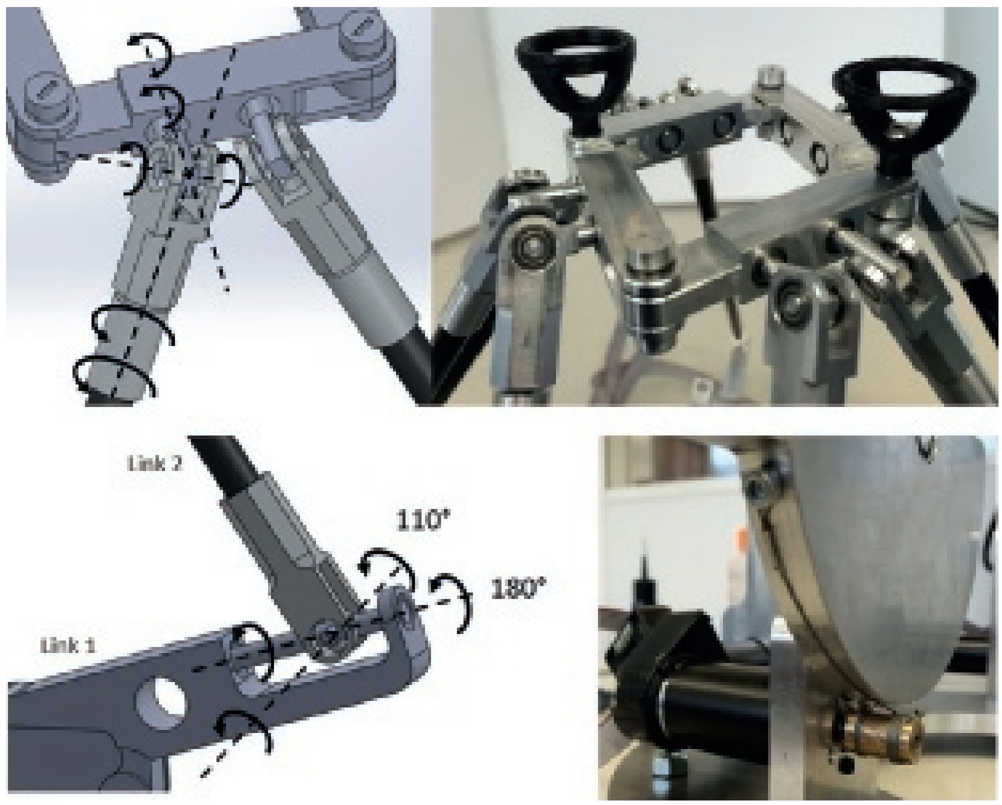
High-speed pick-and-place applications may also benefit from a PRCP architecture since they require high mechanical bandwidth to achieve a certain number of cycles per second and require sometimes a mechanical gripper to handle products. The PentaG prototype has also been tested as a pick-and-place device by replacing the finger tips used in the haptic application by a mechanical gripper and by using the device upside-down. This is shown in Figure 5. This application for the PentaG is currently investigated by the company Penta Robotics [6], which holds the patent rights.

Example 2: 7-DoF parallel haptic device

The 7-DoF parallel haptic device [7] is a second prototype based on a PRCP structure, providing three translational DoFs, three rotational DoFs and one grasping DoF. It is the first and only 7-DoF parallel robot in which all the motors are located on the base, using only mechanical links and bearings between the motors and the end-effectors. Both the position/orientation and the grasping configuration of the platform are fully controlled by the combined action of the eight motors located at the base. Actuation redundancy (more motors than the number of DoFs) was selected in this design for purposes of symmetry, homogeneity of performance, improved force transmission, and manufacturability. Figure 6 shows a 3D model of the device and its prototype fully assembled.

Each of the eight limbs is composed of a series of one rotation joint, one universal joint, and one spherical joint. The rotation joints are connected to the motors on the base by a capstan drive, allowing a gearing ratio without backlash and friction. The universal joints have been especially designed with an elongated pin, allowing a greater angular workspace than that of commercially available universal





6 *The 7-DoF haptic device.*
(a) Model drawing.
(b) Realisation.

7 *Figure 7. Joints configuration of the 7-DoF haptic device (model drawing on the left, realisation on the right).*
Top: three intersecting rotation joints provide the spherical attach joint for each limb on the configurable platform.
Bottom: the universal joint and the capstan-driven rotation joint of each leg.

joints. Finally, the spherical joints are emulated by three intersecting pairs of revolute joints, instead of conventional ball-and-socket joints, increasing the angular workspace and reducing friction. Figure 7 shows the various joints of each leg as well as the assembly of the eight spherical joints on the platform.

The kinematic design of the 7-DoF haptic device was complicated by its high number of DoFs. The precision, force transmission, stiffness and dexterity are all dependent on the position within the workspace, and evaluating a particular set of kinematic parameters requires a computer-intensive sampling over the seven dimensions of the workspace.

Table 1. Specifications of the 7-DoF haptic device.

Specification		Value
Workspace	Vertical	150 mm
	Horizontal	300 mm
	Yaw	+/–60º
	Pitch/Roll	+/–45º
	Grasping	50 mm to 90 mm
Resolution	At sensor location	0.024º
	At end-effector, average	0.2 mm
Torque (actuator)	Average	0.4 Nm
	Maximum	3.2 Nm

In order to facilitate the design optimisation, a graphical user interface was developed to show various performance indices over some subspace of the total workspace as a function of the kinematic parameters. The specifications of the selected design are summarised in Table 1.

More information on the 7-DoF haptic device is available [8]. Further development on this device is now carried out by Heemskerk Innovative Technology [9], aiming at the conversion of the prototype into a commercial haptic device. ■

REFERENCES

[1] Merlet, J.-P., *Parallel robots*, Vol. 74., Springer Science & Business Media, 2012.
[2] Mohamed, M.G. and Gosselin, C.M., "Design and analysis of kinematically redundant parallel manipulators with configurable platforms", *IEEE Transactions on Robotics* 21, no. 3, 277-287, 2005.
[3] Lambert, P. and Herder, J.L., "Parallel robots with configurable platforms: Fundamental aspects of a new class of robotic architectures", *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*: 0954406215602511, 2015.
[4] Lambert, P., Langen, H. and Munnig Schmidt, R., "A novel 5 DOF fully parallel robot combining 3T1R motion and grasping". In *ASME 2010 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, pp. 1123-1130, American Society of Mechanical Engineers, 2010.
[5] www.delfthapticslab.nl/device/pentag-haptic-device
[6] pentarobotics.com
[7] Lambert, P. and Herder, J., "A novel parallel haptic device with 7 degrees of freedom". In *2015 IEEE World Haptics Conference*, pp. 183-188, IEEE, 2015.
[8] www.delfthapticslab.nl/device/parallel-haptic-device-with-7-degrees-of-freedom
[9] www.heemskerk-innovative.nl