ISSN 1330-3651
UDC/UDK 681.51:004.896

DELTA ROBOTS – ROBOTS FOR HIGH SPEED MANIPULATION

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Subject review

This paper is oriented to parallel kinematic robots definition, description of their specific application, comparison of robots made by different producers and determination of velocity and acceleration parameters, kinematic analysis – inverse and forward kinematic. It brings information about development of Delta robots at Academia, including the University of Žilina and Delta robots in the market. Two models of Delta robots called M-1iA and M-3iA have been developed by FANUC Robotics during the last several years. These robots are ideal to automate tasks which so far were too fast and too complex for standard robots. In addition, this new family of robot series offers the motion flexibility of a human wrist, fast cycle times, ultra compact arm and high precision. It is also possible to support intelligent functions using Computer Vision System. In this paper is described the development of training workplace with Fanuc Delta robot FANUC M-1iA 0.5A with examples of robot application.

Keywords: *Delta robot, parallel kinematic structure, parallel robot, training workplace*

Delta roboti – roboti za rukovanje velikom brzinom

Pregledni članak

Ovaj je rad usmjeren definiranju paralelnih kinematičkih robota, opisu njihove specifične primjene, usporedbi robota raznih proizvođača i određivanju parametara brzine i ubrzanja, kinematičkoj analizi – inverznoj i unaprijednoj kinematici. Obaviještava o razvoju Delta robota na Akademiji, uključujući i Sveučilište u Žilini, te o Delta robotima na tržištu. Dva su modela Delta robota, M-1iA i M-3iA razvijena u FANUC Robotics zadnjih nekoliko godina. Ti su roboti idealni za automatiziranje poslova koji su bili previše brzi i složeni za standardne robote. Uz to, ova nova serija robota nudi fleksibilnost pokreta ljudskog zgloba, brzo vrijeme ciklusa, krajnje kompaktnu ruku i visoku preciznost. Također je moguća podrška inteligentnim funkcijama korištenjem Computer Vision sustava. U radu se opisuje razvoj mjesta za obuku s Fanuc Delta robotima FANUC M-1iA 0.5A, uz primjere o primjeni robota.

Ključne riječi: *Delta robota, paralelna kinematička struktura, paralelni robota, trenažno radno mjesto*

1 Introduction
Uvod

Mechanical systems that allow a rigid body (called end-effector) to move with respect to a fixed base play a very important role in numerous applications. A rigid body in space can move in various ways, in translation or rotary motion. These are called its degrees of freedom (DOF). The position and the orientation of the end-effector (called its pose) can be described by its generalized coordinates. As soon as it is possible to control several degrees of freedom of the end-effector via a mechanical system, this system can be called robot [1, 3].

From this aspect, **robot represents an integrated mechatronic system** consisting of three subsystems: sensorial, control and decision-making, and actuation subsystem.

The sensorial subsystem establishes a feedback with the environment. The control and decision-making subsystem represents the 'thinking' centre of the robot, its 'brain'. Together, the sensorial and control subsystems make up a cognitive system. Finally, the actuation subsystem is used to affect the environment, making such an impact on it that the environment changes [2].

It was concluded that the serial robots are inappropriate for tasks requiring either the manipulation of heavy loads, or a good positioning accuracy, or to work with high dynamic parameters.

2 Delta robots
Delta roboti

A generalized parallel manipulator is a closed-loop kinematic chain mechanism whose end-effector is linked to the base by several independent kinematic chains.

Parallel robots can also be defined as follows: A parallel robot is made up of an end-effector with *n* degrees of freedom, and of a fixed base, linked together by at least two independent kinematic chains. Actuation takes places through *n* simple actuators.

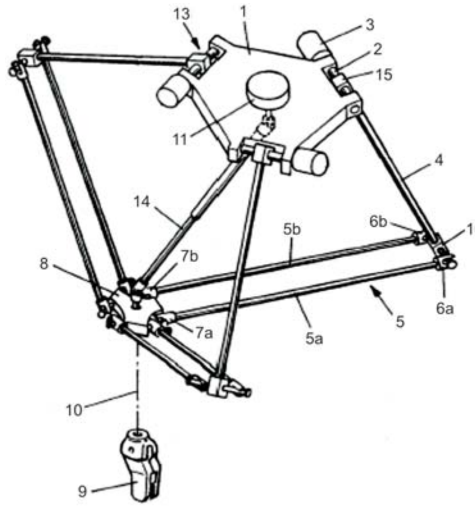
This type of mechanism is interesting because when the actuators are locked, the manipulator remains in its position (this is an important safety aspect), and because of the number of actuators sensors are minimal.

The basic idea behind the Delta parallel robot design is the use of parallelograms (Fig. 1). A parallelogram allows an output link to remain at a fixed orientation with respect to an input link. The use of three such parallelograms restrains completely the orientation of the mobile platform which remains only with three purely translational degrees of freedom. The input links of the three parallelograms are mounted on rotating levers via revolute joints. The revolute joints of the rotating levers are actuated in two different ways: with rotational (DC or AC servo) motors or with linear actuators. Finally, a mechanism is used to transmit rotary motion from the base to an end-effector mounted on the mobile platform.

The use of base-mounted actuators and low-mass links allows the mobile platform to achieve large accelerations up to **50 times the gravity (*g*)** in experimental environments and **(12 - 15)*g*** in industrial applications.

There are two kinds of Delta Robot: ***high-speed robot*** (objects that weigh up to 1 kg) and ***robots to handle heavy objects.*** Both of them have a low inertia structure.

Delta robots are not for every application. In many cases a tabletop serial-link robot may be a much better fit than a delta robot. Delta robots are best-suited for high-speed pick-and-place applications involving lightweight parts with simple geometries and the reason is timing.



1 - Base element	9 - Working element
2 - Shaft	10 - End-effector joint
3 - Fixed parts	11 - Fixed motor
4 - Arm	12 - Control system
5a, 5b - Linking bars	13 - Actuator
6a, 6b - Revolute joints	14 - Telescopic arm (optional)
7a, 7b - Revolute joints	15 - First extremity
8 - Movable element	16 - Second extremity

Figure 1 *Delta robot parts (extract from US Patent 4,976,582)*[6]
Slika 1. *Dijelovi Delta robota (izvadak iz US Patent 4 976 582)*[6]

However, there are some applications that cannot manage these high speeds and accelerations due to the weakness of the parts involved in the process. Some products could be damaged if accelerated at 15*g* or more. For the gripping of the products, vacuum cups are the preferred ones because of their light weight and fast actuation.

It is possible to find a Delta robot in many different kinds of industries. Some of them are:

- Manufacturers of solar panels use Delta robots to place photovoltaic silicon wafers onto glass substrates.
- Manufacturers of energy-efficient lighting use Delta robots to place lenses into LED arrays.
- They are also used to snap together several plastic parts and place the finished assembly into a box.

Although Delta robots excel at pick-and-place applications, they can perform other operations like dispensing a thermal adhesive onto heat sinks for solar collectors, assembling small gears with feedback from force sensors and a Delta robot is being used as a microscope stand at the Necker hospital in Paris [11].

2.1 Determination of the jointed velocities and the twist
Određivanje brzina rotacije spojnih zglobova

It is usually possible to determine analytically the inverse kinematic Jacobian matrix $\boldsymbol{J}^{-1}$ that linearly relates the jointed velocities θ' to the twist W of the end-effector, for example:

$$\theta' = \boldsymbol{J}^{-1} \cdot W. \quad (1)$$

But it is generally difficult, for 6 DOF robots, to invert $\boldsymbol{J}^{-1}$ in order to obtain an analytical formula for the kinematic Jacobian matrix: a numerical procedure will therefore generally be used to calculate the twist from joined velocities. For a given pose of the end-effector, we may, for example, use a numerical inversion algorithm, to determine the Jacobian from its inverse:

$$W'_k = W_k + \boldsymbol{J}_0 \cdot (\theta' - \boldsymbol{J}^{-1} \cdot W_k). \quad (2)$$

W_k is the twist in the k iteration and $\boldsymbol{J}_0$ is the Jacobian matrix in a nominal position.

Accelerations:

We note that parallel robots may present excellent characteristics as to acceleration. The high-speed Delta robot, for example, presents a maximal acceleration at about 500 m/s^2.

General methods exist to obtain accelerations for closed-loop mechanisms although for parallel robots it is generally easy to obtain these relations directly. Indeed, from equation (1) we obtain by differentiation:

$$\theta'' = J^{-1} \cdot W' + J^{-1'} \cdot W. \quad (3)$$

For the various categories of parallel manipulators, the determination of the acceleration equations thus amounts to the determination of the derivate of the inverse kinematic Jacobian matrix; the problem is more complex for redundant robots [1].

2.2 Kinematic analysis
Kinematička analiza

If we want to build our own Delta robot, we need to solve two problems. First, if we know the desired position of the end effector (for example, we want to catch some object in the point with coordinates X, Y, Z), we need to determine the corresponding angles of each of the three arms (joint angles) to set motors (and, thereby, the end effector) in proper position for picking. The process of such determining is known as **inverse kinematics.**

And, in the second case, if we know joint angles (for example, we have read the values of motor encoders), we need to determine the position of the end effector (e.g. to make some corrections of its current position). This is a **forward kinematics** problem [7].

To be more formal, we can look at the kinematic scheme of a delta robot. The platforms are two equilateral triangles: the fixed one with motors is green, and the moving one with the end effector is pink. Joint angles are $theta_1$, $theta_2$ and $theta_3$, and point E_0 is the end effector position with coordinates (x_0, y_0, z_0). To solve inverse kinematics problem we have to create the function with E_0 coordinates (x_0, y_0, z_0) as parameters which returns ($theta_1$, $theta_2$, $theta_3$). Forward kinematics functions gets ($theta_1$, $theta_2$, $theta_3$) and returns (x_0, y_0, z_0).

2.2.1 Inverse kinematics
Inverzna kinematika

First, let's determine some key parameters of the robot's geometry. Let's designate the side of the fixed triangle as *f*, the side of the end effector triangle as *e*, the length of the upper joint as r_f, and the length of the parallelogram joint as r_e. These are physical parameters which are determined by the design of Delta robot. The reference frame will be chosen with the origin at the centre of symmetry of the fixed triangle, as shown below, so z-coordinate of the end effector will always be negative.

Because of the robot's design the joint F_1J_1 (Fig. 2) can only rotate in YZ plane, forming a circle with the centre in point F_1 and radius r_f. As opposed to F_1, J_1 and E_1 are so-called universal joints, which means that E_1J_1 can rotate freely relatively to E_1, forming a sphere with the centre in point E_1 and radius r_e.

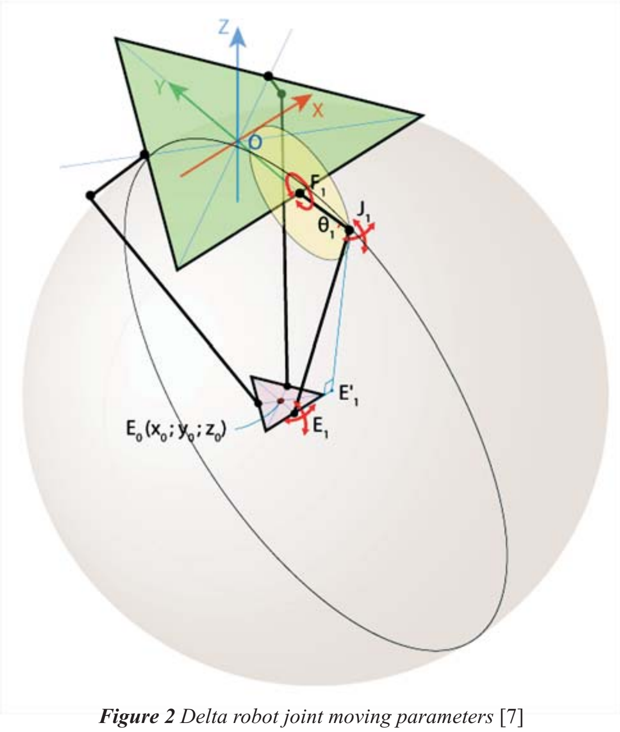


Figure 2 *Delta robot joint moving parameters* [7]
Slika 2. *Parametri gibanja spojeva (zglobova) Delta robota* [7]

Intersection of this sphere and YZ plane is a circle with the centre in point E'_1 and radius E'_1J_1, where E'_1 is the projection of the point E_1 on YZ plane. The point J_1 can be found now as intersection of two circles of known radius with centres in E'_1 and F_1 (we should choose only one intersection point with smaller y-coordinate). And if we know J_1, we can calculate θ_1 angle [7].

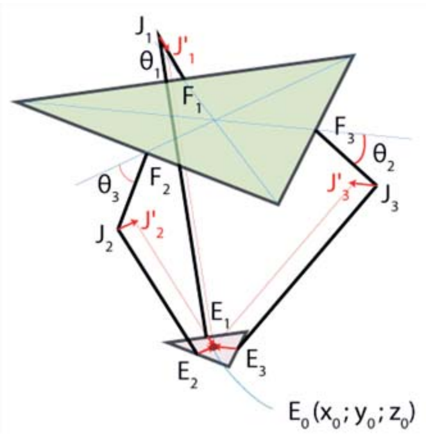


Figure 3 *Coordinates of end effector (E_0 calculation)* [7]
Slika 3. *Koordinate krajnjeg efektora (E_0 izračun)* [7]

2.2.2
Forward kinematics
Unaprijedna kinematika

In this case the three joint angles $theta_1$, $theta_2$ and $theta_3$ are given, and we need to find the coordinates (x_0, y_0, z_0) of end effector point E_0. As we know angles theta, we can easily find coordinates of points J_1, J_2 and J_3 (Fig. 3). Joints J_1E_1, J_2E_2 and J_3E_3 can freely rotate around points J_1, J_2 and J_3 respectively, forming three spheres with radius r_e.

Now let's do the following: move the centres of the spheres from points J_1, J_2 and J_3 to the points J'_1, J'_2 and J'_3 using transition vectors E_1E_0, E_2E_0 and E_3E_0 respectively. After this transition all three spheres will intersect in one point E_0. So, to find coordinates (x_0, y_0, z_0) of point E_0, we need to solve the set of three equations like $(x-x_j)^2+(y-y_j)^2+(z-z_j)^2=r_e^2$, where coordinates of sphere centres (x_j, y_j, z_j) and radius r_e are known.

3
The development of Delta Robots in Academia
Razvoj Delta robota u Akademiji

Delta robot design has attracted a great interest not only in industry but also in university laboratories. A number of variants have been proposed in the literature but most of those that have been prototyped stay close to the original design. One such modified Delta robot was built at the **University of Maryland**. Another modified version was constructed at the **University of Genoa**. In that design, the parallelograms are replaced by equivalent mechanisms.

Yet another highly-optimized version, NUWAR, was built at the **University of Western Australia**. The NUWAR is claimed to reach **accelerations up to 600 m/s²** and differs from the other delta robot versions in its non-coplanar arrangement of the axes of its rotary actuators (Fig. 4).

Three linear-motor versions were also constructed at Ferdinand-von-Steinbeis Schule, **ETH Zurich**, and the **University of Stuttgart**.

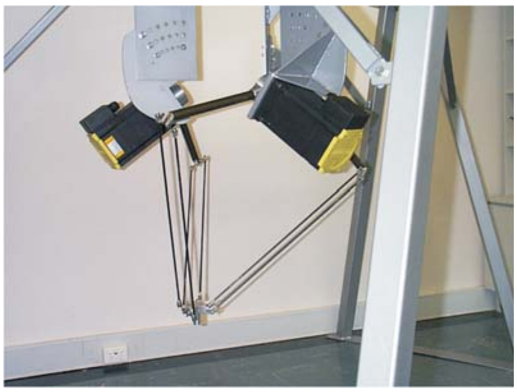


Figure 4 *Delta robot developed at the University of Western Australia* [13]
Slika 4. *Delta robot razvijen na univerzitetu Western Australia* [13]

There was a lot of delta robots developed at the universities but the greatest concentration of this kind of robot is found at its birthplace, **l'École Polytechnique Fédérale de Lausanne (EPFL).** There is a haptic device built by EPFL's Virtual Reality and Active Interfaces Group. Their Delta Force Feedback Device is commercially available for about 20 000 USD. Another typical Delta robot was also constructed at he EPFL's Automation Institute. And of course, several Delta robots were built by the Parallel Robotics Group headed by Prof. Reymold Clavel.

3.1 The design of a training delta robot at the University of Žilina
Projekt delta robota za vježbanje na Univerzitetu Žilina

At the University of Žilina we have designed own Delta robot (Fig. 5). The design of the upper fixed platform was based on the requirements of just-mounting construction, which would be sufficient for our purpose. Therefore we have selected construction with standard aluminium profiles and Minitec dural components. All connections are designed with the screw connections – with brackets and with the profiles (profiles of basic dimensions of 45×90 mm, 45×45 mm, and angles 60°×45 mm).

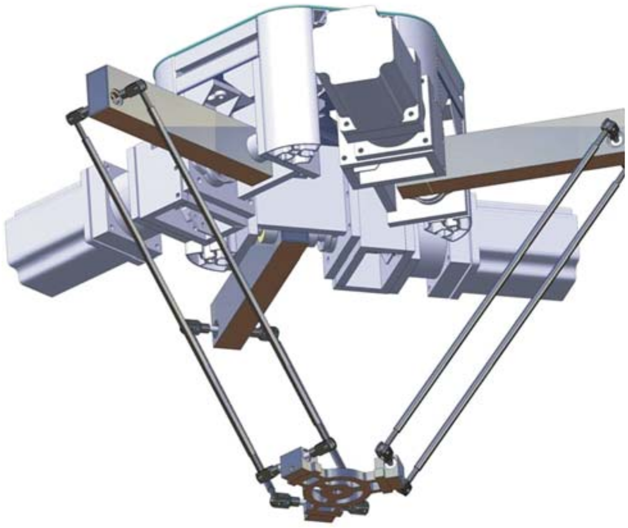


Figure 5 *Design of delta robot Caertec rk 2010 at the University of Žilina*
Slika 5. *Projekt delta robota Caertec rk 2010 na Univerzitetu Žilina*

The rotary arms are designed from thin-walled rectangular profiles. They are mounted on the drive shaft by shrink connection.

The structure of parallelogram contains two slim parallel rods connected together by the joints with 3DOF.

The moving platform is similarly dealt with a simple design, meeting the requirements for attaching the end effector or any member. Affixed parallelogram is designed as pivot and thrust bearings.

Because of the fact that the robot contains three identical rotary arms (Fig. 5 and Fig. 6), it was necessary to design the appropriate frame (console) which provides the fixation of the first revolute joint of each arm in required position. The angle between the planes perpendicular to the axes of every neighbourhood arms is set to 120°.

Suitable design of the console should fulfil certain standards not only of strength and stiffness but also in terms of efficient assembly. To ensure the reliable mechanism running and torque transmission, suitable rotary shaft bearings are needed for the first axis of the arms. There are two ways how to solve this requirement by using:

- components with integrated bearing,
- special bearing unit.

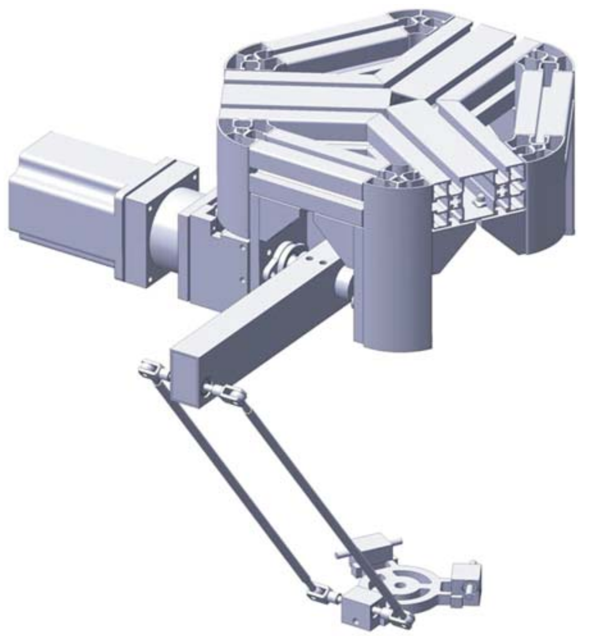


Figure 6 *Detailed view on one kinematic chain includes rotary arm, parallelogram and moving platform*
Slika 6. *Detaljni pogled na jedan kinematički lanac uključuje kružnu ruku, paralelogram i pokretnu platformu*

In the first case we can use for example the gearbox with output shaft and the last bearing strong enough to carry the whole arm. In the second case we can apply the structure composed of drive unit, gearbox, coupling and specialized bearing unit. The bearing unit is needed to restrain the forces from the rotary arm.

We decided for the second alternative. Then the main shaft, which carries the mass and the forces applied on the arm, is separated from the output shaft of the gearbox or drive unit. This main shaft is connected to the base frame by two special bearing units. The mechanical coupling is inserted between the system of the drive unit (contained the bearing too) and the main shaft of the rotary arm. For the rotary arm fixing in the static position the electromagnetic brake is linked to the main shaft.

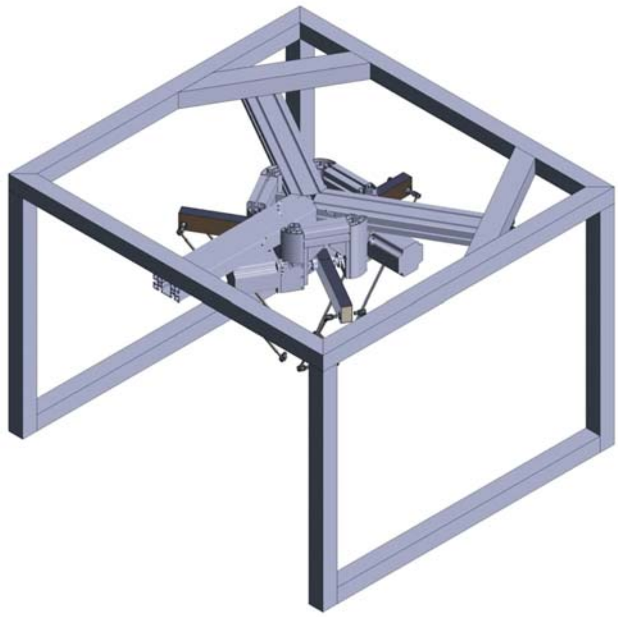


Figure 7 *Robot cell with the training Delta robot Caertec rk 2010 application*
Slika 7. *Ćelija robota s primjenom Delta robota Caertec rk 2010*

As a drive for the rotary arm is used the servo drive Q1AA04010D with low inertia made by company ALL motion. It was selected according to the calculated minimal torque.

With respect to the drive unit we have selected the suitable gearbox too. We have chosen the gearbox AE050-100 made by company ALL motion. It can be characterized by enough torque to ensure the required movement, low inertia and low backlash.

After the design phase of delta robot we have done also the structural design of the main frame for carrying it. In this way we have obtained the basic scheme of robotic cell with the delta robot in the middle. A work table or belt conveyors, magazines and fixture devices can be placed under the robot (Fig. 7).

4 Delta Robots in the Market
Delta roboti na tržištu

The history of the Delta robot marketing is long, complicated, and intriguing. It all started in 1983 when the two Swiss brothers Marc-Olivier and Pascal Demaurex created the company Demaurex based in Romanel-sur-Lausanne, Switzerland.

Demaurex Delta robots

After purchasing a license for the Delta robot in 1987, their major objective became to commercialize the parallel robot for the packaging industry (Fig. 8). After several years, Demaurex succeeded in occupying a major place in this new difficult market. The company product went through a number of modifications and finally, they sold 500 Delta robots worldwide.

Figure 8 *Demaurex's Line-Placer installation for the packaging in an industrial bakery* [9]
Slika 8. *Demaurexova Line-Placer instalacija za pakiranje u jednoj industrijskoj pekari* [9]

The patent on the Delta robot was bought by the brothers Demaurex from EPFL in 1996 and some years later ABB acquired a license to manufacture Delta robots. Many other brands such as Renault Automation Comau, GROB-Werke, Krause & Mauser Group, have acquired the license as well.

Hitachi Seiki

Demaurex sold licenses to the Japanese company Hitachi Seiki for the production of smaller Delta robots for drilling operations (Fig. 9). In fact, Hitachi Seiki Company

Figure 9 *Hitachi Seiki Delta robots* [6]
Slika 9. *Delta roboti Hitachi Seiki* [6]

represents Demaurex in Japan.

ABB Flexible Automation

ABB Flexible Automation launched its Delta robot in 1999 under the name IRB 340 FlexPicker (Fig. 10). Three industry sectors were aimed at the food, pharmaceutical, and electronics industries. The FlexPicker is equipped with an integrated vacuum system capable of rapid pick and release of objects weighing up to 1 kg. The robot is guided with a **machine vision system** by Cognex and an ABB S4C controller. Optionally, the robot may be equipped with a motion controller and vision system by Adept Technology.

After nearly ten years research and experience in the field of packaging technology came FlexPicker IBR 360 with the second generation of Delta ABB robots. This second generation is even more efficient with higher speed and carrying capacity and smaller footprint.

Figure 10 *ABB Flexible Automation IRB 340 FlexPicker* [10]
Slika 10. *IRB 340 FlexPicker firme ABB Flexible Automation* [10]

ABB has installed around 1800 Delta robots all over the world and it is the leader in the field of advanced packaging technologies.

SIG Group

Demaurex, in order to ensure its long term stability, changed its line of production from naked Delta robots to complete robot cells. However, in order to gain a world market, the small Demaurex started looking for a partner. And it is thus that Demaurex became acquired by the Swiss Group SIG at the end of 1999.

The SIG Group consists of three branches, of which the SIG Pack branch, only, employs some 2000 workers, a company big enough to offer Demaurex the so much needed access to the world market. Presently, three different Delta robot models are offered by the SIG Pack Systems. Whereas

Figure 11 *SIG Pack Systems models C33 and CE33* [6]
Slika 11. *Modeli C33 and CE33 firme SIG Pack Systems* [6]

the C23 and C33 are manufactured by Demaurex, the CE33 is built by the SIG Pack Systems (Fig. 11).

BOSCH

In 2004, the German company Bosch Group purchased the SIG and SIG Pack Division Demaurex and included it in their **packaging technologies**.

Sigpack System products have always been known for their superior quality and reliability, and nowadays is one of the world's leading suppliers of handling and packaging systems. Many Delta robot models have been developed by BOSCH, for example:

- XR31: higher performance and higher reliability,
- XR22: a combination of compact design and high accuracy,
- Paloma D2 built in stainless steel in order to meet hygiene standards and regulations for food industry (Fig. 12).

Figure 12 *Paloma D2 – BOSCH Delta robot* [11]
Slika 12. *BOSCH Delta robot Paloma D2* [11]

These robots have been placed in the following production lines:

- MonoPacker LDM: A very flexible system used to place large volumes of products in containers directly from the manufacturing process.
- Feed Placer: A system with a vision-guided high-speed Delta robot that accepts aligned or randomly oriented incoming product flow on a wide belt conveyor and it places the product directly into the moving flights of wrapper, cartoner or thermoformer with smooth efficiency.

Astor Assortment Placer: A high flexible system used for placing products into assortment-packs with vision-guided high-speed Delta robots Adept Quattro.

Adept Technology, Inc. is a global, leading provider of intelligent vision-guided robotics systems and services. Founded in 1983, Adept Technology is the largest U.S.-based manufacturer of industrial robots. In the year 2007 a high-speed Delta robot, under the name of Quattro, was developed [9].

The **Adept Quattro** (Fig. 13) is specifically designed for *high-speed applications in packaging, manufacturing, assembly, and material handling***.** It is the only Delta robot in the world that features a patented four-arm design, advanced control algorithms, and large work envelope, thus making the Adept Quattro the ideal overhead-mount robot for smooth motion, high-throughput applications. The Adept Quattro is powered by ultra-compact controls and embedded amplifiers, which reduces the cycle time and improves footprint efficiency.

Figure 13 *Adept Quattro s650H* [9]
Slika 13. *Adept Quattro s650H* [9]

Thanks to using advanced tracking software, Adept Quattro is able to locate, select and place fast-moving objects. Regarding its maintenance, parallel robotics allows fixed engine and does not require moving electrical wires, which means a longer and easier maintenance. The composite material chosen for the robot arm driving mechanism and the end-effector have been designed for greater strength and power. Lubrication in the joints or drive mechanisms is not required.

Using cutting edge technology in vision systems, Adept Quattro is able to pick-and-place fast moving and randomly located objects with high accuracy.

In addition, this Delta robot has three DOF with an optional fourth DOF, which is helpful during selection and placement tasks. Robots are also able to manage three robots hierarchically [9].

Fanuc Robotics

In 1956 FUJITSU Fanuc was founded as a subsidiary of FUJITSU LTP to develop numerical controls. In 1972, FUJITSU LTD spun off FUJITSU Fanuc and the name was changed to FUJITSU FANUC LTD. The first industrial robot was developed and installed in 1974. The company grew rapidly, changed its name and the USA and EUROPE FANUC were established in 1977 and 1978 respectively. Nowadays, FANUC Robotics has installed over 200 000

Figure 14 *Exposition of Delta robots M-1iA FANUC Robotics at World's Fair Automate 2011 in Chicago*
Slika 14. Izlaganje Delta robota M-1iA FANUC Robotics na svjetskom sajmu Automate 2011 u Chicagu

robots in all over the world and it is the world leader in industrial robotics.

Two models of Delta robots have been developed by FANUC Robotics, **M-1iA** (Fig. 14) with 6 or 4 DOF, and **M-3iA** (Fig. 15) also with 6 or 4 DOF. These robots are ideal to automate tasks which so far have been too fast and too complex for robots. In addition, this new family of the robot series offers the motion flexibility of a human wrist, fast cycle times, ultra compact arm and precision. It is also possible to support intelligent functions using iRVision [5, 12].

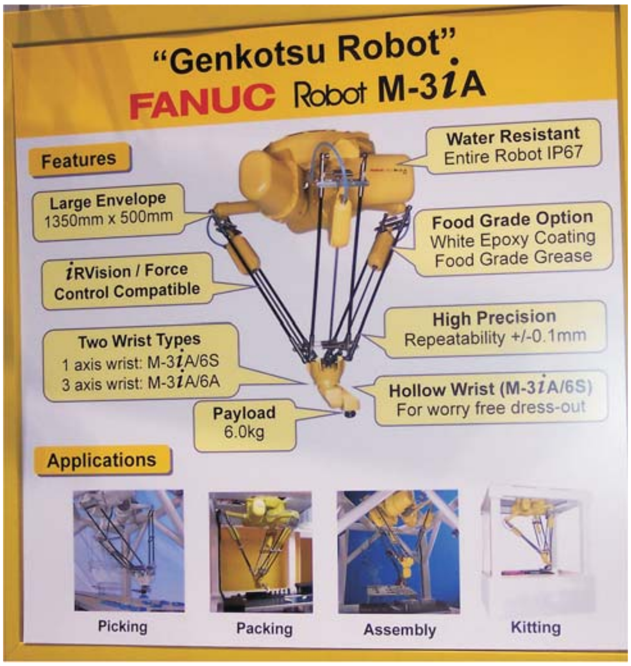


Figure 15 *Characteristics of Delta robots M-3iA FANUC Robotics at World's Fair Automate 2011 in Chicago*
Slika 15. Karakteristike Delta robota M-3iA FANUC Robotics na svjetskom sajmu Automate 2011 u Chicagu

5 The development of training workplace with Fanuc Delta robot

Razvoj mjesta za obuku s Delta robotom Fanuc

The Delta robot FANUC M-1iA 0.5A at the University of Žilina is a novel lightweight robot for electronics, measuring devices and other precision industries. It is extremely useful for ultra compact production cells thanks to the compact and lightweight arm and the compact and powerful Mate Open Air Controller.

This new robot provides a higher productivity for assembly and picking applications, a lightweight mechanism with better cycle times and a unique 6-axes parallel link arm mechanism that allows to automate difficult tasks such as complex insertion, gluing and more.

However, FANUC M-1iA 0.5A will be used at the laboratories of the University of Žilina to prove the advantages of parallel robots, and to show the students how a robot can be programmed and utilized [4].

In addition, FANUC M-1iA 0.5A is a compact and intelligent controller thanks to the integrated iRVision which can locate and check work pieces for flexible parts feeding applications and other intelligent tasks. This vision system allows four possible processes: normal 2D Vision, depalletising 2 ½ D Vision (includes a calculation of Z-height and some special depalletising functions), 2D Multiview Vision and Visual Line Tracking 2D Vision [12].

The workplace has been designed for education in robotics at the University of Žilina. The frame, as the main structure, has been analyzed carefully (including static and dynamic analysis) to develop a wide range of tasks requiring high accuracy. With respect to the dynamics of the robot motion, the table is fixed to the floor with 4 screws.

To start the calculations, we will simplify the model. After the first results, a 3D model of the frame will be analysed in a numerical methods program with the dynamic forced as the Robot operates. Several iterations will be carried out until finding the optimal solution.

- **Conditions:** The maximum deformation of the frame cannot exceed 0,5 mm due to the high accuracy required by some tasks such as the assembly of an electronic device.
- **Simplifications:**
  - 2 D model
  - Infinite stiffness of columns
  - The robot is supported on the very beam of the frame.

As a result of the simplifications mentioned above and applying the highest forces produced by the robot (Emergency stop) at the same time we obtain the following diagrams (Fig. 16).

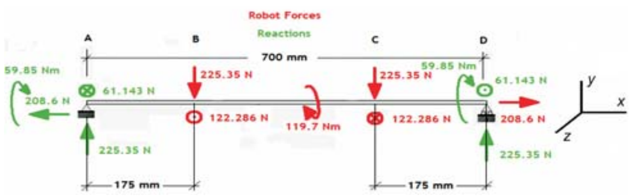


Figure 16 *Diagram of forces for simplified model*
Slika 16. Dijagram sila pojednostavnjenog modela

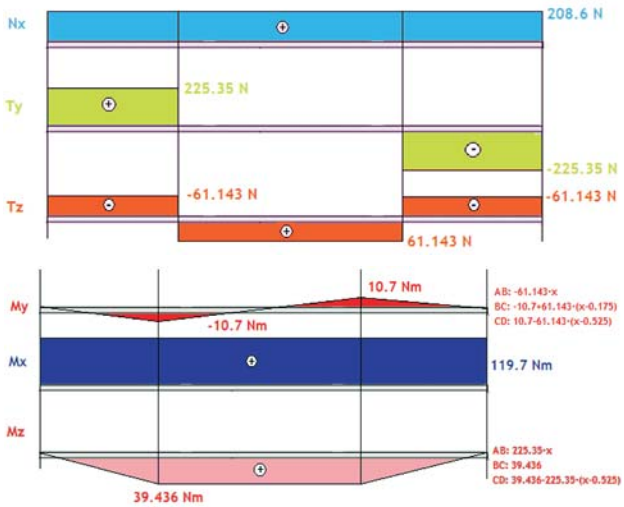


Figure 17 *Strain diagrams of simplified model*
Slika 17. *Dijagrami deformacije pojednostavljenog modela*

As Fig. 17 shows, the critical points are B and C. Then, we calculate the deformation in B and we will decide, using Rexroth Catalogue, which profile's size is the appropriate one. The Castigliano's second theorem has been used to calculate the deformation.

The maximum deformation of the frame cannot exceed 0,5 mm due to the high accuracy required by some tasks such as the assembly of an electronic device.

The *static analysis* was carried out using ANSYS® software. After introducing the input parameters of the materials, meshing and setting the boundary conditions it is possible to execute the analysis. The main purpose of the static analysis is to check the reliability and stiffness of the whole structure.

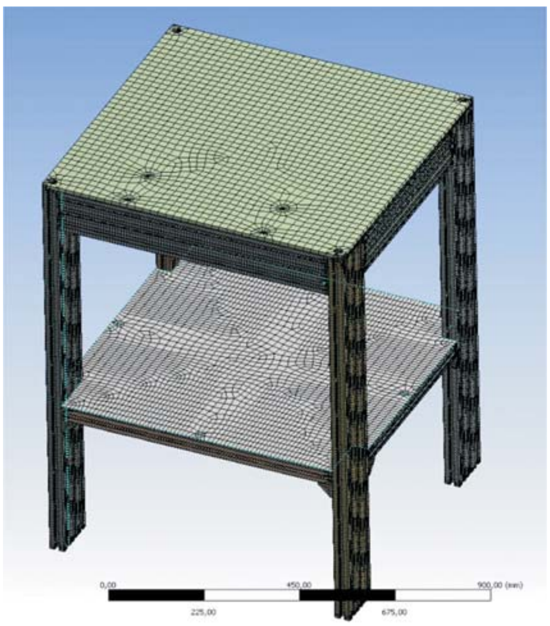


Figure 18 *Meshing of the frame*
Slika 18. *Mrežasta struktura konstrukcije*

The *dynamic analysis* was carried out using ANSYS® software too. The same model of static analysis was used. The main purpose of this analysis was to determine the resonance frequencies of the structure in order to avoid using the robot at these precise frequencies.

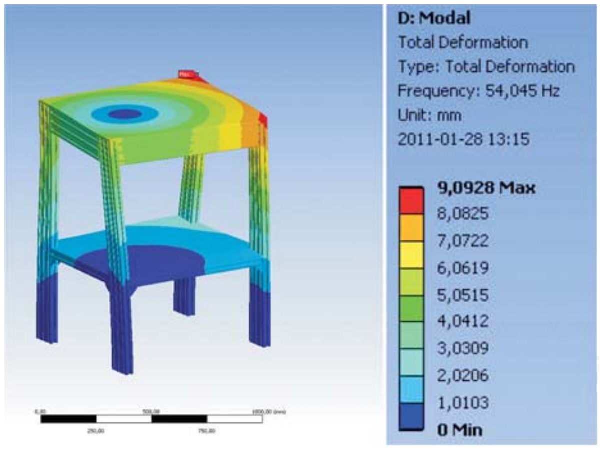


Figure 19 *The third modal of dynamic analysis*
Slika 19. *Treći model dinamičke analize*

Mode	Frequency/Hz
1,	27,726
2,	41,56
3,	54,045
4,	80,323
5,	86,902
6,	133,73
7,	143,19
8,	150,96
9,	163,19
10,	163,39
11,	178,13
12,	237,89
13,	244,94
14,	248,23
15,	262,89
16,	266,03
17,	266,59
18,	272,38
19,	282,17
20,	290,62

Figure 20 *Resonance frequencies of the frame*
Slika 20. *Rezonancijske frekvencije konstrukcije*

Conclusions of calculations and analysis

- The simplified version is a good model to start designing.
- The frame is stiff enough to develop a wide range of tasks.
- The frame must be screwed into the ground.
- It is important to avoid resonance frequencies so as not to damage either the robot or the frame.

The workplace has been designed taking into account some *ergonomic rules* such as NV SR c. 309 2007 and MPSVR 718 202 (Slovakia). Both rules come from European rules thus they are valid in whole Europe.

The emergency stop buttons must be at visible and reachable locations. There is no rule specifying the exact place of these buttons. Therefore the 2 emergency stop buttons are placed near the waist and near the knees respectively because these are considered as good positions.

Furthermore, *five tasks and their pallets* have been designed to show the abilities of the FANUC M-1iA 0.5A. These tasks have also been thought to be programmed by the students thus the difficulty increases. Finally, a magazine has been designed to store the current task pallets and it has been created to house ten pallets.

Figure 21 *Design of workplace with FANUC Delta robot M-1iA* [4]
Slika 21. *Projekt radnog mjesta s FANUC Delta robotom M-1iA* [4]

5.1 The design of Delta robot application tasks
Projektiranje zadataka za primjenu Delta robota

The workplace will be specially designed to carry out five different tasks at the laboratories of the University of Žilina [4]. The end-effector and the pallet must be changed depending on the task.

The first task is oriented to high manipulation with small objects – the balls are being replaced as fast as possible in order to prove the agility of the robot. The second task: 8 cubes are saved to the magazine in order to show the dimensions of the workspace and the dexterity of the robot. The third task is centred on robot application in automatic assembly without computer vision (CV) system application. Further task is oriented to objects sorting in a magazine with the CV system application. In the last task the keys are assembled to sloping keyboard by using the CV system.

The tasks have been designed to be programmed by the students and thus the difficulty of these tasks increases.

Task No 1: Replacing balls

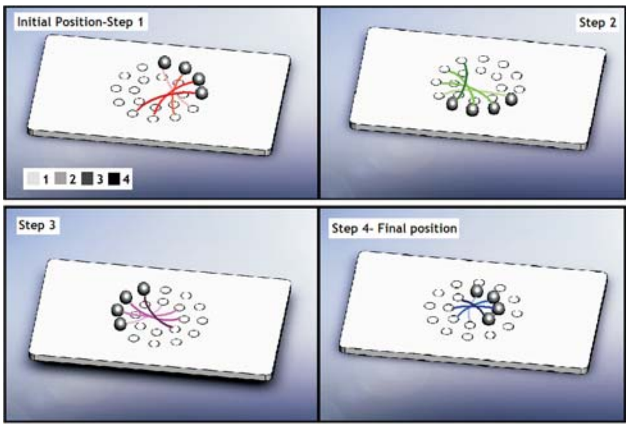


Figure 22 *Description of Task No 1* [4]
Slika 22. *Opis zadatka br. 1* [4]

Characteristics:
- End-effector: Vacuum end-effector.
- iRVision: No.
- Objects: 4 equal-sized balls.
- Initial object position: Known.
- Objective: Replace the balls as fast as possible in order to prove the agility of the robot.
- Degrees of freedom: 3.

Detailed task by steps is shown in Figure 22.

Task No 2: Stacking cubes

Characteristics:
- End-effector: Gripper
- iRVision: No
- Objects: 8 small cubes
- Initial object position: Known
- Objective: Stack 8 cubes placed in a magazine in order to show the dimensions of the workspace and the dexterity of the robot.
- Degrees of freedom: 4

Detailed task No 2 by steps is shown in Fig. 23.

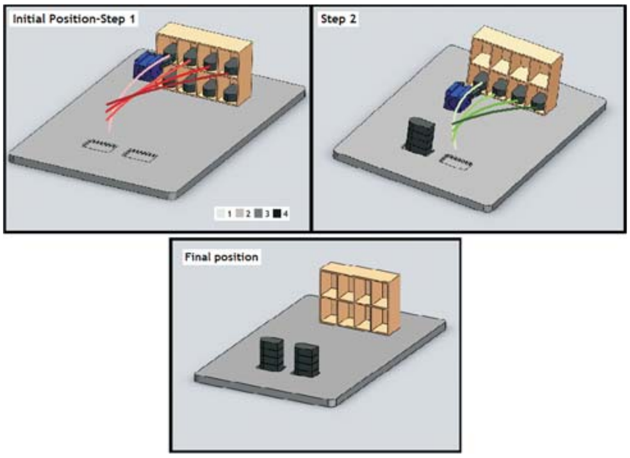


Figure 23 *Description of Task No 2* [4]
Slika 23. *Opis zadatka br. 2* [4]

Task No 3: Assembling an electronic component

Characteristics:
- End-effector: Gripper.
- Objects: Base, connector RS232, 2 sockets.
- Initial object position: known.
- Objective: Assemble a testing board to prove the high dexterity and accuracy of FANUC M-1iA.
- Degrees of freedom: 5.

Detailed task No 2 by steps is shown in Fig. 24.

Task No 4: Sorting a magazine

Characteristics:
- End-effector: Vacuum end-effector.
- iRVision: Yes.
- Objects: 3 square-shaped and 3 round-shaped pieces made of metal sheet.
- Initial object position: Unknown (pieces stacked in a magazine).
- Objective: Stack the square-shaped pieces in magazine

A and the round-shaped ones in magazine B, in order to prove the reliability of the iRVision.

- Degrees of freedom: 4.

Detailed task by steps is shown in Fig. 25.

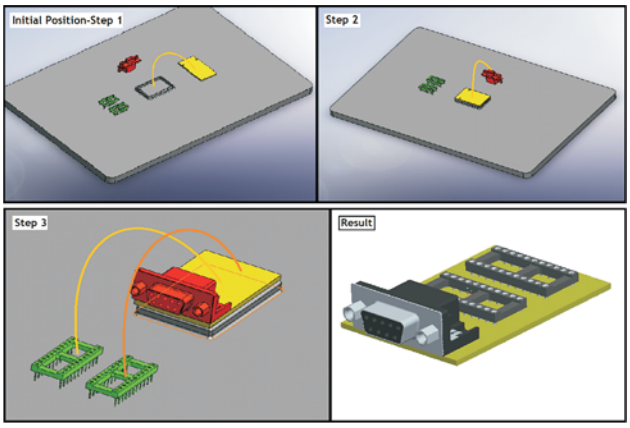


Figure 24 *Description of Task No 3 and final result* [4]
Slika 24. *Opis zadatka br. 3 i konačni rezultat* [4]

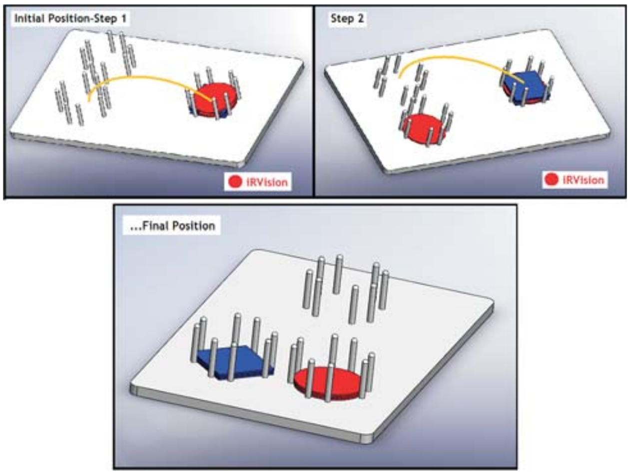


Figure 25 *Description of Task No 4* [4]
Slika 25. *Opis zadatka br. 4* [4]

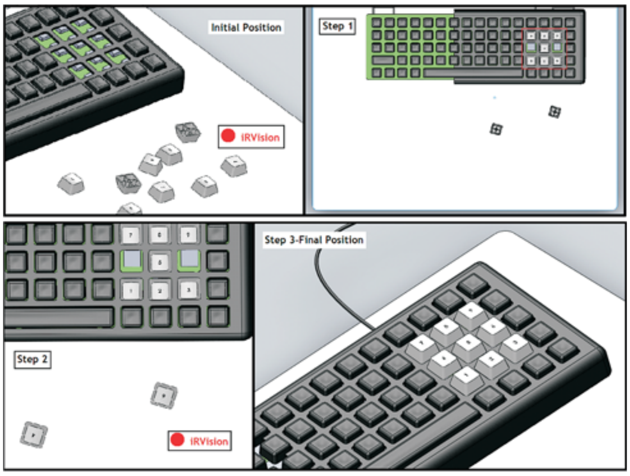


Figure 26 *Description of Task No 5* [4]
Slika 26. *Opis zadatka br. 5* [4]

Task 5: Assembling a keyboard

Characteristics:

- End-effector: Vacuum end-effector
- iRVision: Yes
- Objects: Keyboard keys
- Initial object position: Unknown (alleatory)
- Objective: Assemble the numbers of a sloping keyboard in order to prove the high dexterity of FANUC M-1iA 0.5A by using iRVision system
- Degrees of freedom: 6

Detailed task by steps is presented in Fig. 26.

6 Conclusions
Zaključci

The parallel kinematic structure is a closed-loop kinematic chain mechanism whose end-effector is linked to the base by several independent kinematic chains.

Parallel structures are interesting due to their great stiffness and high positioning accuracy compared to serial robots. This kind of kinematic structure can be used in many fields but most of them are used as robots or as numerically controlled machine tools. Specific applications such as spatial, medical, joysticks and simulators are also possible.

Delta robot design has attracted great interest not only in industry but also in university laboratories. A number of variants have been proposed in the literature but most of those that have been prototyped stay close to the original design. The use of base-mounted actuators and low-mass links allow the mobile platform to achieve large accelerations up to 50 times the gravity (g) in experimental environments and 12g in industrial applications.

This paper informs about the development of mechanical subsystem of training Delta robot called *Caertec rk 2010* at the University of Žilina.

Two models of Delta robots have been developed by FANUC Robotics, M-1iA and M-3iA. These robots are ideal to automate tasks which so far have been too fast and too complex for robots. In addition, this new family of robot series offers the motion flexibility of a human wrist, fast cycle times, ultra compact arm and precision. It is also possible to support intelligent functions using Computer Vision System (iRVision).

The workplace with Delta robot M-1iA FANUC Robotics has been designed at the University of Žilina. The frame, as the main structure, has been analyzed carefully (including static and dynamic analysis) to develop a wide range of tasks requiring high accuracy. Furthermore, 5 tasks and their pallets have been designed to show the abilities of the FANUC M-1iA 0.5A. These tasks have also been thought to be programmed by the students thus the difficulty increases. Finally, a magazine has been designed to store the current task pallets and it has been created to house 10 pallets.

It is very important to work with iRVision as well as create the end-effector to develop the mentioned tasks. In the future is possible to automate the pallet feeding by using a belt conveyor and work with other companies to improve the knowledge about parallel robots.

Acknowledgement
Zahvala

This article was created by the solution of project - code ITMS 26220220046: "The Development of Parallel Kinematic Structure Prototypes for Application in the Area of Machine Tools and Robots" supported by the operational program Development and research, financed from the European foundation for regional progress.

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