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Executive summary

This deliverable presents, firstly, hardware that enables real workcell reconfiguration and secondly, how this hardware can be used to optimize the robots' performance in the cell through rearranging the workspace, e.g. by changing the position of a workpiece with respect to the robot's base. The developed hardware is described in two sections; we start by presenting workcell components with passive degrees of freedom (except for the novel gripper described in Section 1.3) that enable automatic reconfiguration with a robot, while in Section 2 we present the components that support manual reconfiguration. To reduce cost and energy consumption in the cell, the developed hardware components do not contain active degrees of freedom. Similarly to the previous deliverable **D1.2**, which tackled optimum reconfiguration in a simulated environment, we show how the optimality of workcell reconfiguration can be evaulated in a real-world setting.

1 Automated reconfiguration

This section of the deliverable describes the use of reconfigurable elements that allow automated reconfiguration. These elements were developed following the ReconCell paradigm, i.e. reconfiguration should be affordable without impeding precision. Therefore the reconfigurable elements do not posses any measuring or actuating equipment. This role is carried out by the robot arm. This solution does have a drawback – the reconfiguration is slower and the robot cannot do any other tasks while it is reconfiguring the cell.

1.1 Reconfigurable jig

The reconfigurable jig (later refered to as Hexapod) is a crucial part of the reconfigurability aspect of the ReconCell workcell. It uses a passive Gough-Stewart mechanism (hexapod) explained in detail in deliverable **D1.1**, Section 1 "Reconfigurable jigs".

Three hexapods were used in the ELVEZ use case for fixating the light housings. The hexapods were arranged to form a Plug and Produce module (see Section 2.2) connected to the main cell frame via the Plug and Produce connector (described in detail in **D1.1**, Section 3.2 "Plug & Produce connector design"). By doing so we were not only able to quickly adapt to a different product from the same family, but also to quickly manually change the production process to a new product family altogether.

Reconfiguration within a product family is achieved by grasping the tool changer part mounted to the top plate of the hexapod (see **D1.1**, Section 1.3 "Hexapod mounted clamps and supports"), releasing the breaks, and repositioning the top plate. This can be done manually or automatically. The automatic approach was successfully tested for the assembly of two different models of automotive light housings. Two different models of the light housings fixated by

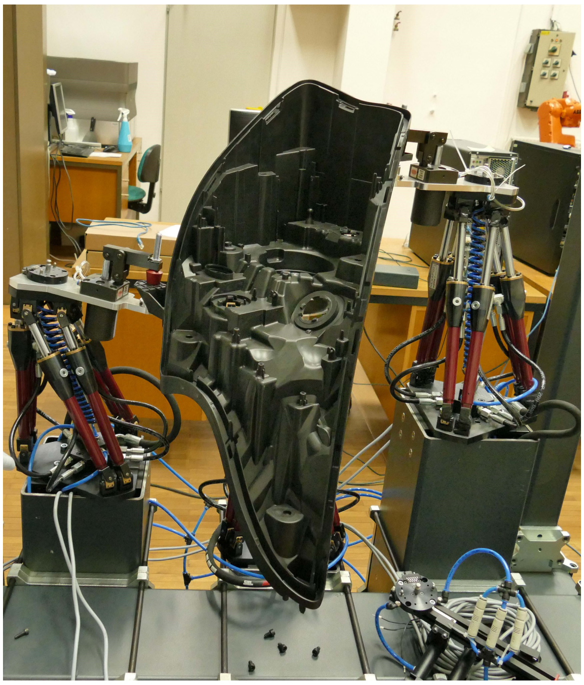

Figure 1: Hexapods holding automotive headlight model X82

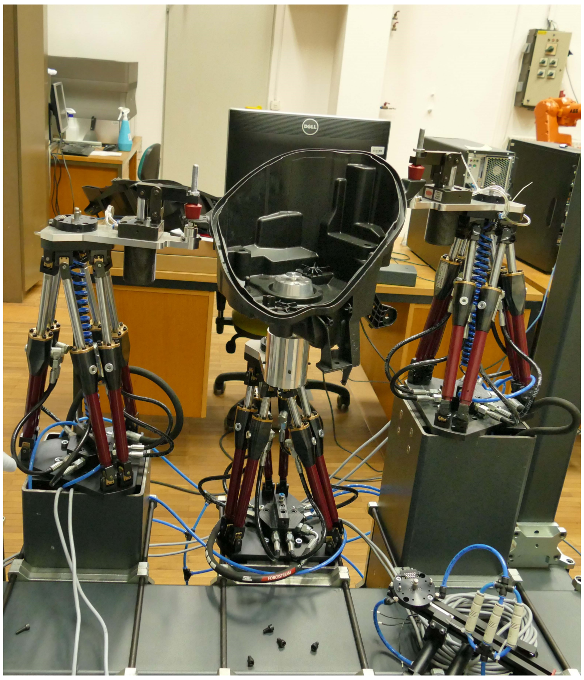

Figure 2: Hexapods holding automotive automotive headlight model X07

differently configured hexapods can be seen in Figure 1 and 2.

A production part approval process (PPAP) test was successfully performed on a sample of 50 pieces of the two variants of automotive headlights. The reconfiguration was also tested. It takes approximately 5 minutes and requires no operator intervention. This can bee seen in the video available at:

`http://www.reconcell.eu/content/space/videos/X07_to_x82_fast.mp4`

In the ReconCell project the innovative fixtures based on hexapods were extensively tested. It shows great potential for managing quickly changing production, typical when producing personalized few of a kind products. We have also shown that the Hexapods are a product ready for wide industrial use. A new company FlexHex was started to commercialize the hexapods.

1.2 Linear unit

As part of the ReconCell project, an innovative passive linear unit was developed. It uses no additional actuators or measuring equipment to re-position the robot base. The movement is performed using the robots own actuators and measuring systems. The robot re-positions the base by connecting the tip to the workcell frame, releasing the brakes, and then moving its own base along the linear guides. The motivation and the development process is described in detail in deliverable **D1.1**, Section 4 "Passive linear unit".

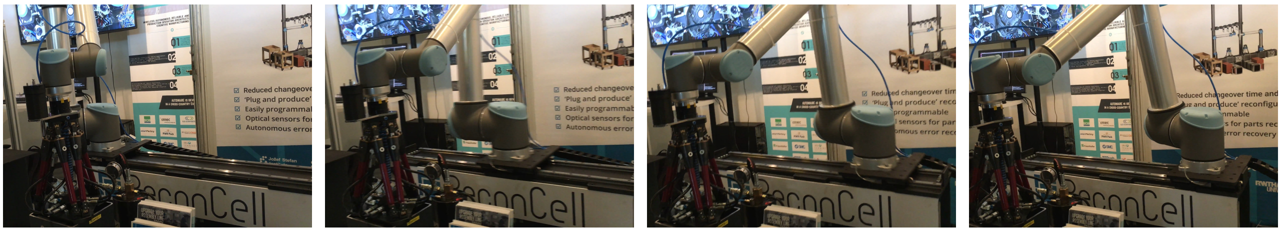

Figure 3: Robot base reconfiguration using the passive linear unit by connecting the tip of the robot to the frame.

The linear unit was implemented as a peripheral module and is connected to the cell via a PnP connector. Although none of the selected experiments made use of the passive linear unit, we still managed to test its viability within the project. We showed that the robot can move its own base with ease. The concept was shown at 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) help in Madrid, Spain, on October 1st - 5th, 2018, and at International trade Fair for Automation & Mechatronic (IFAM), held in Ljubljana, Slovenia, on February 11th - 13th, 2019. During the demonstration the robot base moved along the linear rail with speeds up to 1m/s. The forces needed to move the base were not measured but were low enough to not cause the robot emergency stop to trigger. The positional accuracy was sufficient to enable object grasping after re-positioning the robot without repeating the calibration process. While we did not formally measure the accuracy of the re-positioning movements, it is safe to assume that it is comparable to that of the robot tip. Thus the approach shows great potential for industrial use where reconfiguration does not happen too often. The video of the linear unit demonstration can be seen at

`http://www.reconcell.eu/content/space/videos/iros_demo.mp4`

1.3 Power over Ethernet servo gripper

In the ReconCell project we avoided the use of servo grippers mostly due to the fact that the tool changer electric pass-through was full, not allowing additional electrical connections to be fed to the end-effector. We therefore developed a new solution that allowed us to use a servo gripper in the last ReconCell experiment proposed by HOP Ubiquitous (see deliverable **D6.4** "Final demonstrations of use-cases and benchmarking"). The gripper uses a 24 V power supply and a RS232 communication protocol. A cable could be added however this would limit the practicality of exchanging robotic end-effectors. Considering the tool changer electrical connector is already connected to Ethernet, a solution was to use the power over Ethernet (PoE) concept shown in Figure 4.

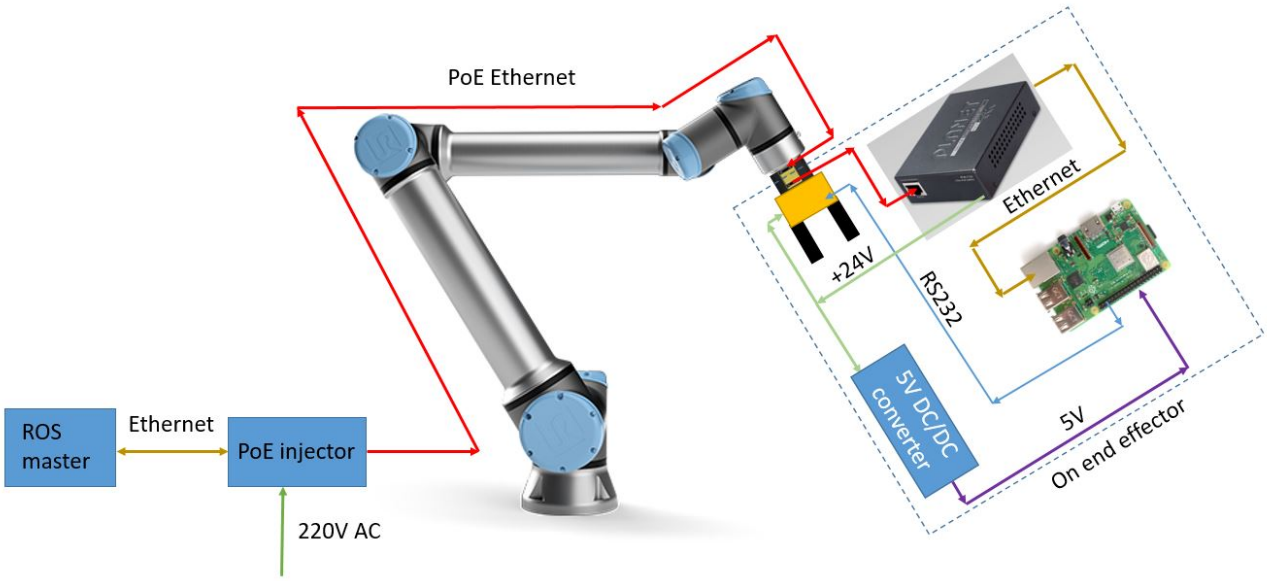

Figure 4: Servo gripper mounted at the tip of UR-10 robot using power over Ethernet

Power over Ethernet is used to add power to a regular Ethernet line. A PoE splitter mounted at the end-effector is then used to separate the signal part from the DC power supply. The PoE splitter is equipped with a DC to DC converter that converts the PoE native 54 V to a more useful 24 V. The 24 V is then used to power the servo gripper.

The servo gripper however cannot be controlled via Ethernet natively. For that an additional Raspberry Pi was used. It is powered by converting the 24V DC to 5 V DC and than feeding it to the appropriate general purpose input output (GPIO) pins. The Raspberry Pi connected via Ethernet to ROS network accepts required servo gripper finger positions and communicates with it via RS232 standard.

The method described above enables all signals to pass through the existing tool changer electrical connection. The first prototype of a PoE powered servo gripper was implemented and tested in the HOP Ubiquitous use case. In this experiment several different PCB had to be manipulated by a robot. A different pneumatic gripper would have to be used for each type of printed circuit board that is to be manipulated by a robot. Instead a single servo gripper was used. The computational capabilities on the robotic end-effector offer additional options like storing tool center point transformations, maintenance data, and preventing operator errors. The only downside of this design is that when the robot first connects to the gripper, the Raspberry Pi has to boot. This takes, using our design, about 12 seconds during which the servo gripper is not operational. This can easily be solved by adding a battery to the Raspberry Pi computer. The battery would be charging when connected to the robot and would keep the system running (in a power saving mode) during storage.

1.4 Screwdriver

One of the more challenging aspects of reconfigurability is the robotic screw-driving. Current commercially available screw-driving solutions are highly tailored to specific tasks and cannot be reused for another application (e.g. different screw) without modifications. These modifications are trivial to do for a human but would be very challenging if not impossible to execute with a robot. Another mayor factor in the ReconCell project poses the price of the components. Conventional screw-driving systems are expensive, combine that with their inflexibility, and we quickly arrived at the conclusion that using a commercially available solution in the ReconCell project, which is focused on small batch size production, is not feasible.

In response we developed a reconfigurable screwdriver (Figure 5) which could not only be used but also reconfigured for another application by a robot itself. The cost of the developed prototype including development costs is significantly lower than that of a commercially available solution.

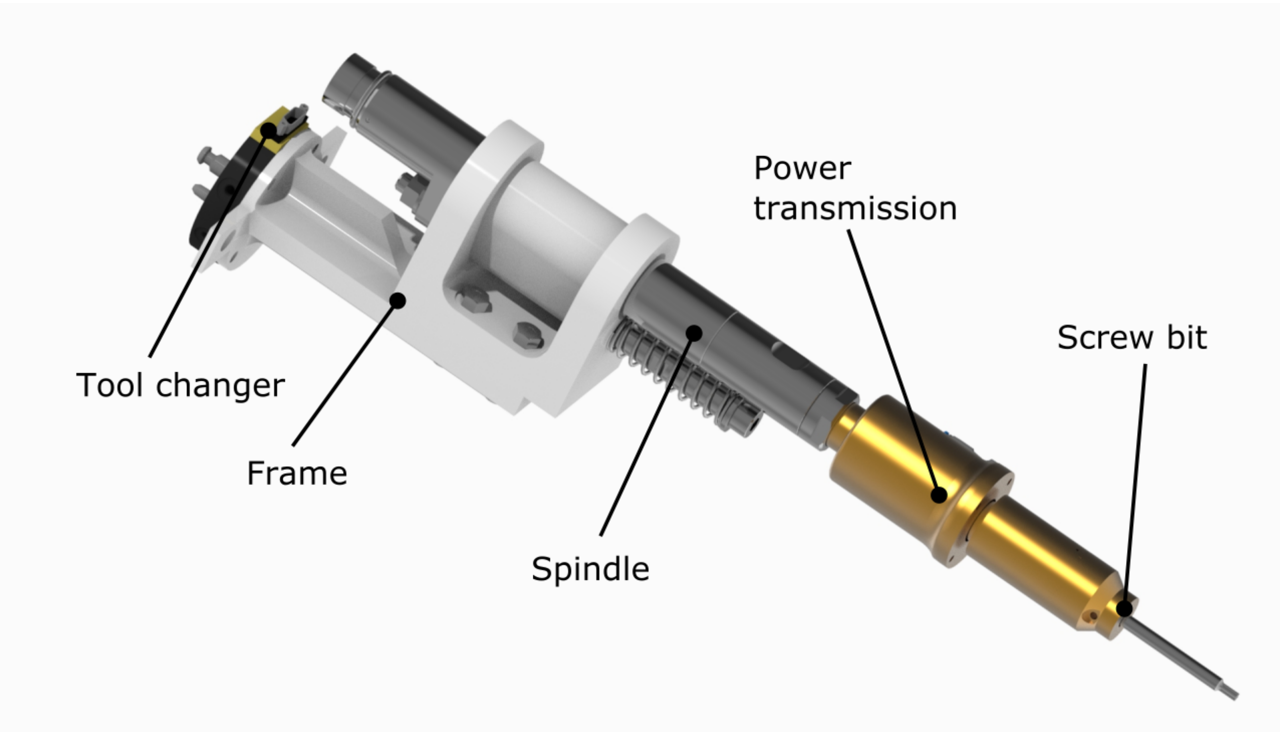

Figure 5: The developed screwdriver prototype

The developed screwdriver consists of a spindle, frame, power transmission with the screw bit exchange system and different screw bits. The frame is the component that holds the spindle

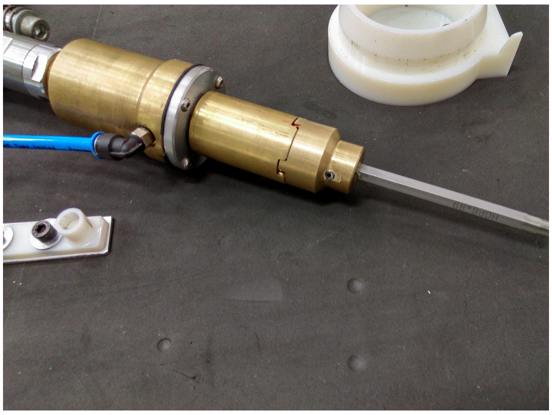

Figure 6: Screwdriver coupling system

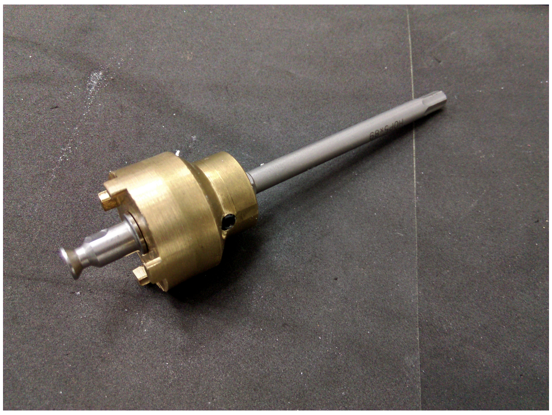

Figure 7: Screw bit

and connects it with a robot. The connection between the frame and the robot is performed using a tool changer, which is also used to connect to other end-effectors in the ReconCell system. The use of the tool changer also enables transfer of pneumatic lines and electrical signals from the robot to the screwdriver.

What separates our screw driver from the conventional ones is the specially designed screw bit exchange system (Figure 6). It consists of two main components, the power transmission shaft and the screw bit plug (Figure 7), which attaches to the shaft. The screw bit plugs can be fitted with any screw bit with a DIN 3126-E6,3 shank and are designed in such a way that they can easily be modified to accommodate any other shank shape.

A secure connection between the shaft and the screw bit plug is achieved using a pneumatically activated coupling system, while the angular lock is achieved using a simplified spline joint. The combination of the spline joint and pneumatic coupling system is very forgiving in regard to the positional accuracy of two parts prior to the coupling. It can compensate for a misalignment of up to about 2 mm in the radial direction as well as for a few degrees of axial misalignment. Despite a very forgiving nature of the joint, the locked state is very stiff and repeatable.

Since the coupling mechanism is built into the end of a rotating shaft, the only way to supply it with the necessary pneumatic signal is through a so called feed-through system. This system has been integrated into the housing of the power transmission to minimise the overall size of the screw driver. The cross section of the power transmission can be seen in Figure 8.

The developed system is about half the size of what we would be able to assemble using commercially available solutions (feed-through and another tool changing system) and at a fraction of the price. This also means that overall price of the screwdriver is low enough that it is feasible to use it in small batch-size production and consequently in the ReconCell project.

The operation of the screw bit exchange system can be seen in the video available at

`http://www.reconcell.eu/content/space/videos/screw_bit_exchange.mp4`

1.5 Rotary table

Working on the Precizika Metal use case, we were faced with another challenge. The final assembly operation was tightening 3 bolts radially distributed around the the shaft. Because of the working area restrictions, the task would be impossible to execute without manipulating the assembly into different orientations. For tasks revolving around symmetrical workpieces or patterns of radially arranged features, rotary tables are a common tool used in machine shops. Thanks to their design, which enables locking the rotation of the table at discreet angles, they can ensure a very good positional repeatability. The mechanism itself is fairly complex due to very small angular increments. In addition, for the application in the ReconCell system, the rotary table needs to be of an actuated type. This brings along a high price tag which makes it unfeasible for small batch size production and consequently for the ReconCell project.

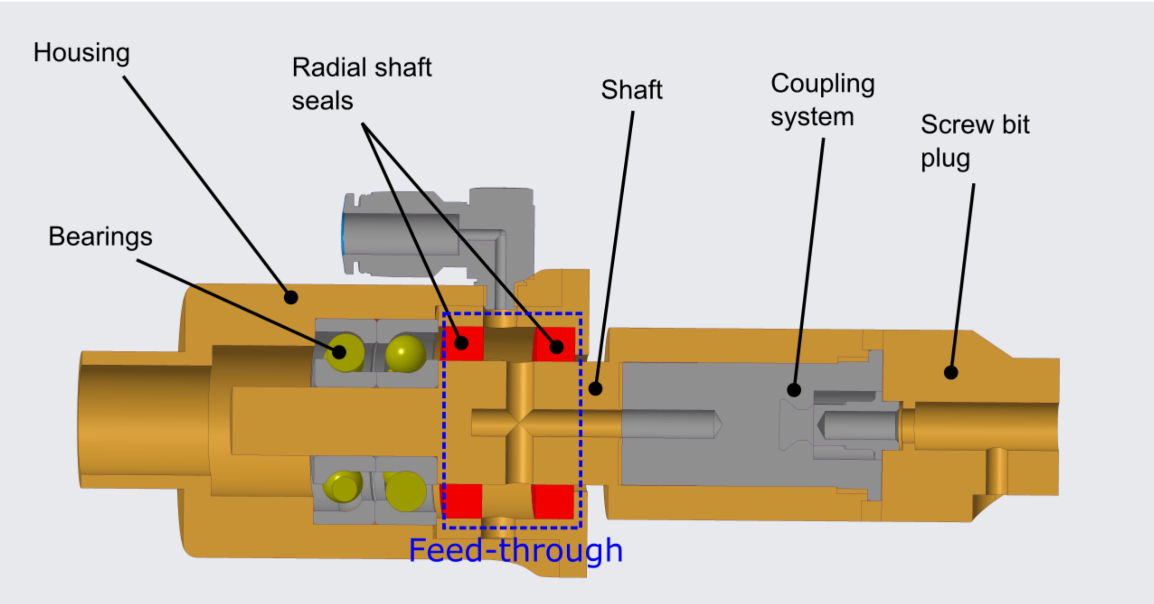

Figure 8: Cross section of the power transmission showing the feed-through system

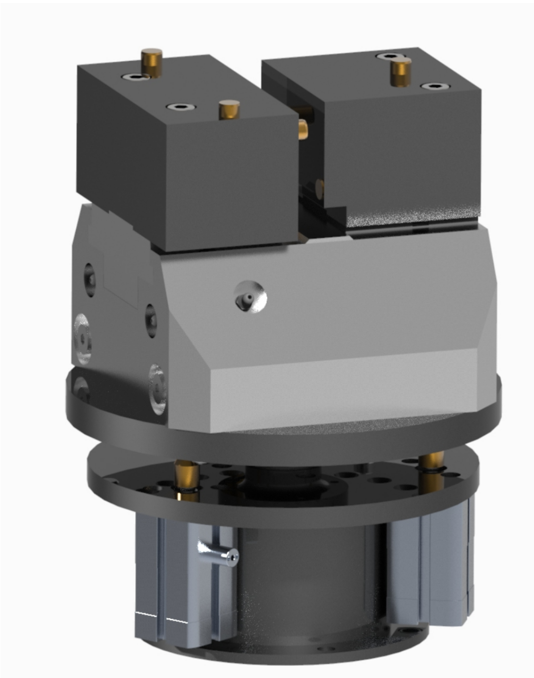

Figure 9: Rotary table model

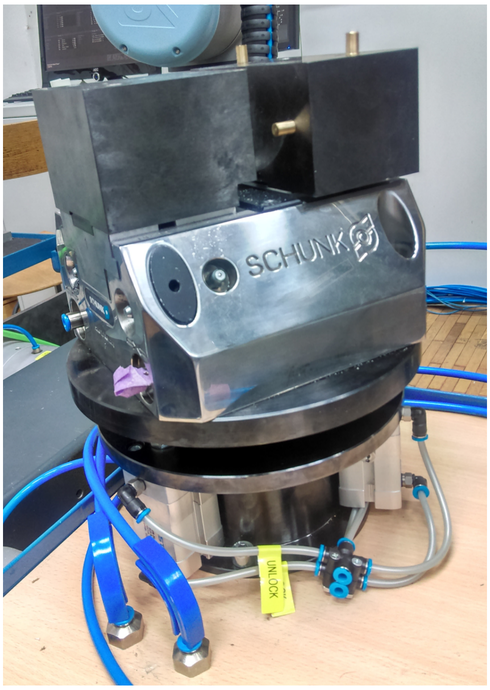

Figure 10: Rotary table

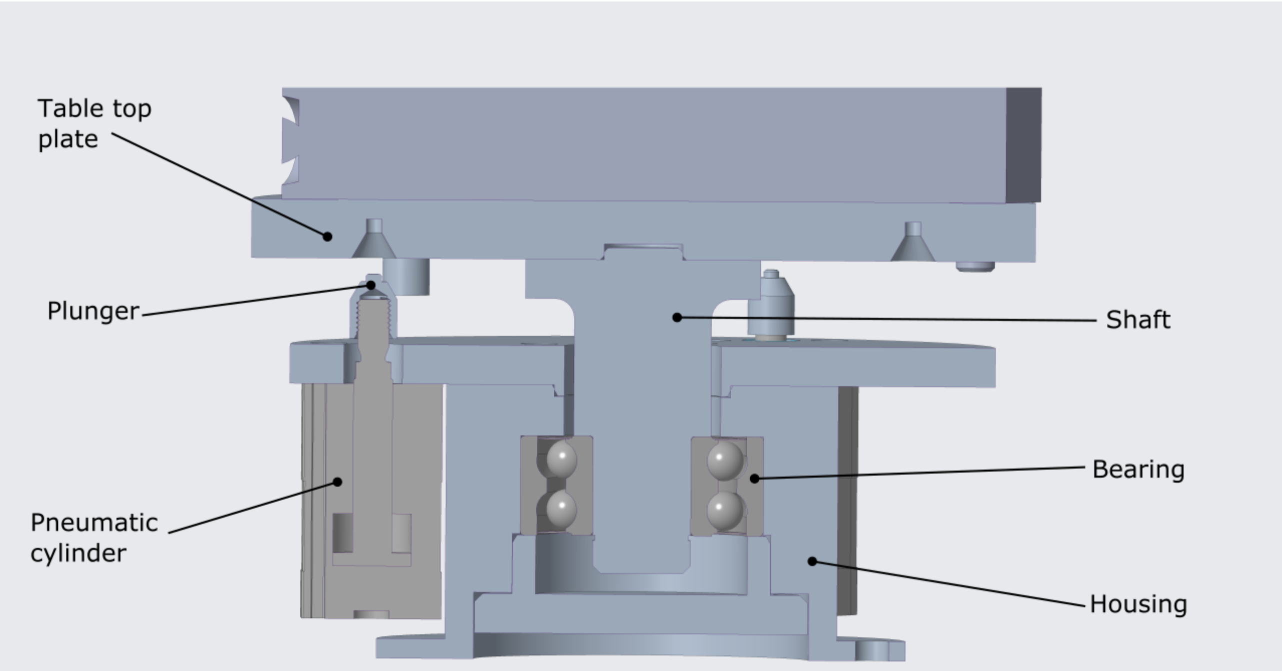

Figure 11: Cross section of the rotary table

With the basic concept of a rotary table in mind and with the goal of lower price tag, we have developed a passive rotary table (Figure 9 and 10). It consists of a housing, a shaft, and a table top plate. The housing holds the bearings and provides mounting points for the pneumatic cylinders, which are used for locking it in position. The shaft inserted into the bearings enables rotation and holds the table top plate. The table top plate has a pattern of radially distributed holes at an equal spacing of 15° at the bottom, which receives the locking plungers. This plate can also be easily exchanged with a plate having a hole pattern of different resolution or a plate equipped with a different fixture. In the Precizika Metal use case, a pneumatic vise was mounted on the table top plate. Because stiffness of the assembly is of high concern due to high repeatability requirements, all the components are made out of steel and were dimensioned using a high safety factor. Cross-section and major components of the rotary table are presented in Figure 11.

The rotation of the rotary table is accomplished by a robot grasping the work piece and rotating it into the desired position. At that time, three plungers mounted on the pneumatic cylinders, mounted on the housing under the rotating portion of the table, are pushed upwards into the the holes, located at the bottom surface of the table top, thus locking the table into a desired orientation. Thanks to the conical design of the holes and plungers, the locked position is very repeatable even if position of the robot is a bit wrong.

The operation of the rotary table can be seen in the video available at

`http://www.reconcell.eu/content/space/videos/rotation_table_bottom.mp4`

2 Manual reconfiguration

This section of the deliverable describes the reconfigurable elements of the cell that allow for major reconfigurations of the cell layout and periphery. While the the automated reconfiguration is most times welcome as it can be faster and without human intervention, they are limited to rather small scale reconfigurations. The elements described in this section allow for major reconfiguration of the cell layout.

2.1 BoxJoint system

The BoxJoint system is used to assemble the workcell frame. It uses a combination of metal plates, special nuts and bolts to connect square beams of different sizes together. They are commercially available and the solutions used in the ReconCell project are described in deliverable **D1.1**, Section 2.1 "BoxJoint system". This system proved to be extremely usefull to shorten the time needed to assemble a modular robotic workcell and for any followup modifications. We observed that the assembled frame is extremely mechanically stiff and causes no position errors when robotic operations are performed.

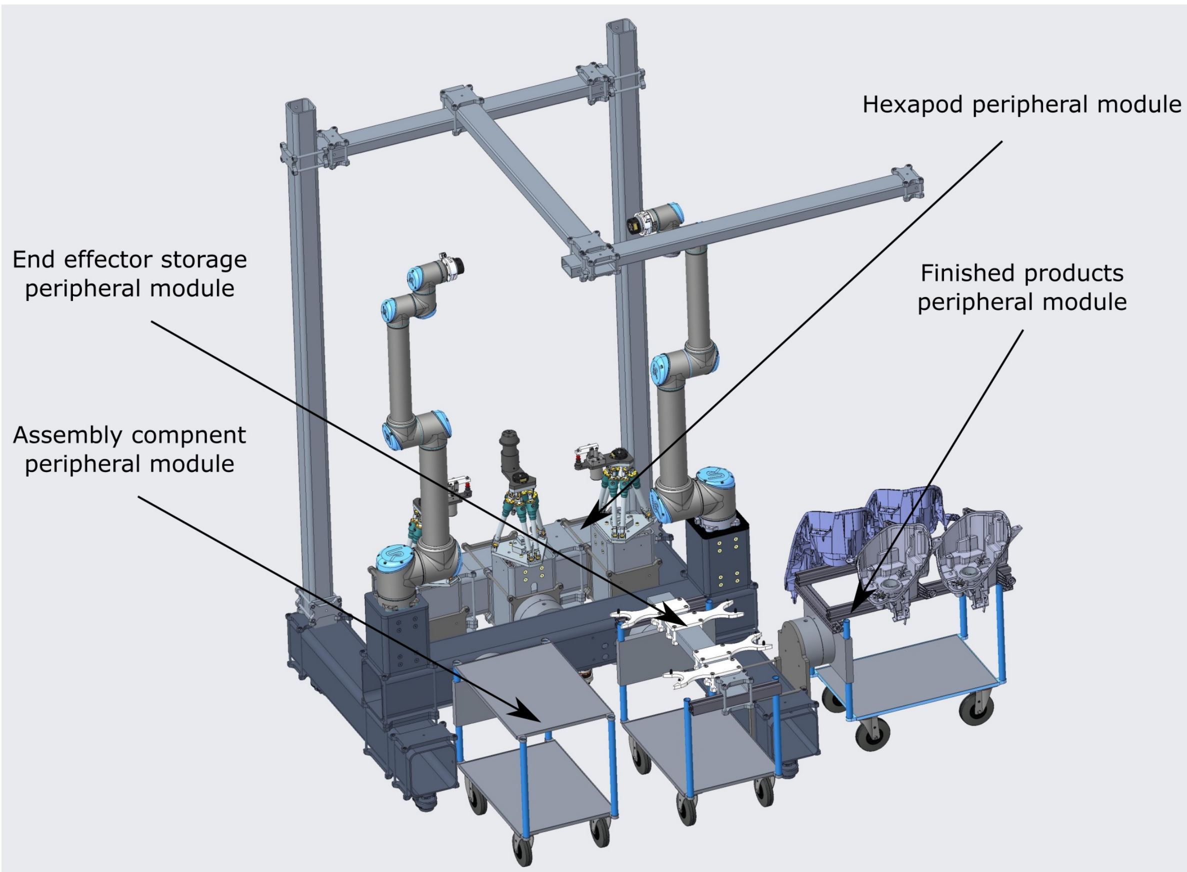

Figure 12: ELVEZ use case peripheral modules

2.2 Peripheral modules

Peripheral modules are crucial for the operation of the ReconCell system. The minimum workcell by itself can not perform any production task. The capabilities specific to the task are added in form of peripheral modules such as fixtures, end-effector storage, material flow management, and other application-specific equipment. The peripheral modules can be equipped with computational capabilities that store coordinates of points of interest, maintenance data, control pneumatic valves, and other application-specific hardware. In general, all peripheral modules are designed to be self contained units.

The peripheral modules are connected to the cell whit Plug and produce (PnP) connectors. They are connectors developed in the ReconCell project that mechanically couple peripherals to the main cell frame as well as pass through pneumatics, power, and Ethernet communication. The details of the PnP connector are described in deliverable **D1.1**, Section "Plug & Produce connector design".

In the ELVEZ use case we used 4 peripheral modules as seen in video

`http://www.reconcell.eu/content/space/videos/elvez_assembly_x07.mp4`

A peripheral module comprised of three hexapods was used for fixating the workpieces, another two peripheral modules were used for assembly components and finished products, and the last one for the storage of end-effectors. They are shown in Figure 12.

Logicdata, Precizika Metal, Ivamax and HOP Ubiquitous production tasks used additional specialized peripheral modules. In the Logicdata use case, we implemented a clamp fixture peripheral module shown in Figure 13. In the Precizika metal we implemented a peripheral module equipped with a vise mounted on the rotary table from section 1.5. This specialized peripheral module is shown in Figure 14. This module was later used in the Ivamax use case

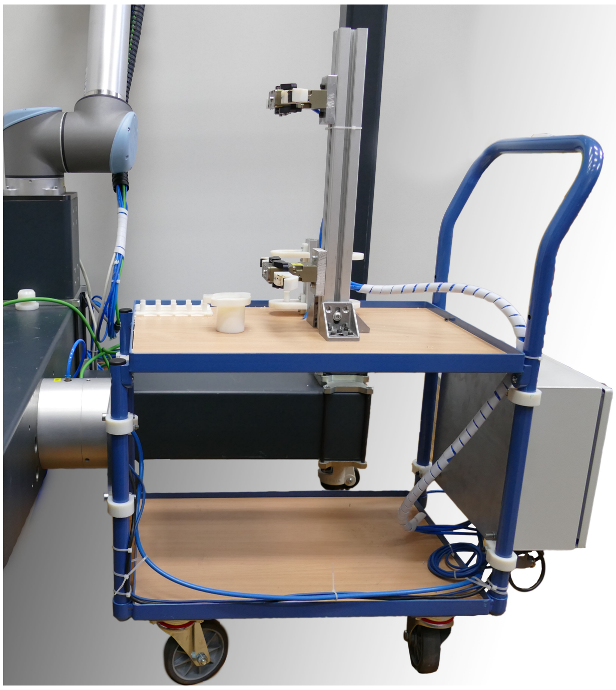

Figure 13: Logicdata clamp module

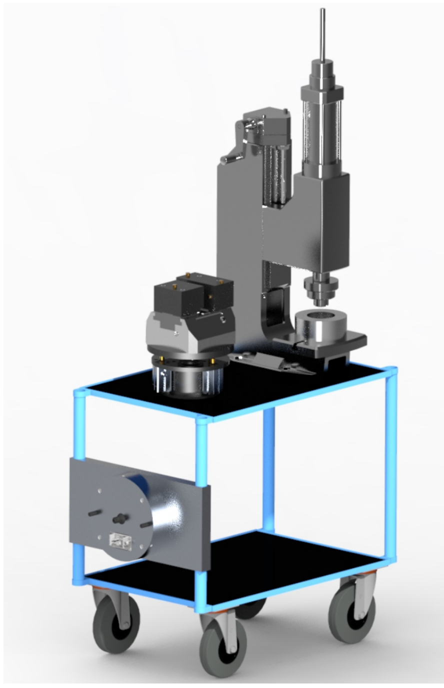

Figure 14: Precizika peripheral module

with modified jaws. Another specialized module (Figure 15) was developed and used in the HOP Ubiquitous use case. This module is used to hold the fixture on which the backplate is placed during the assembly. It also contains a mirror, onto which the assembled product is placed for the final vision inspection. This enables us to perform the inspection using only one camera.

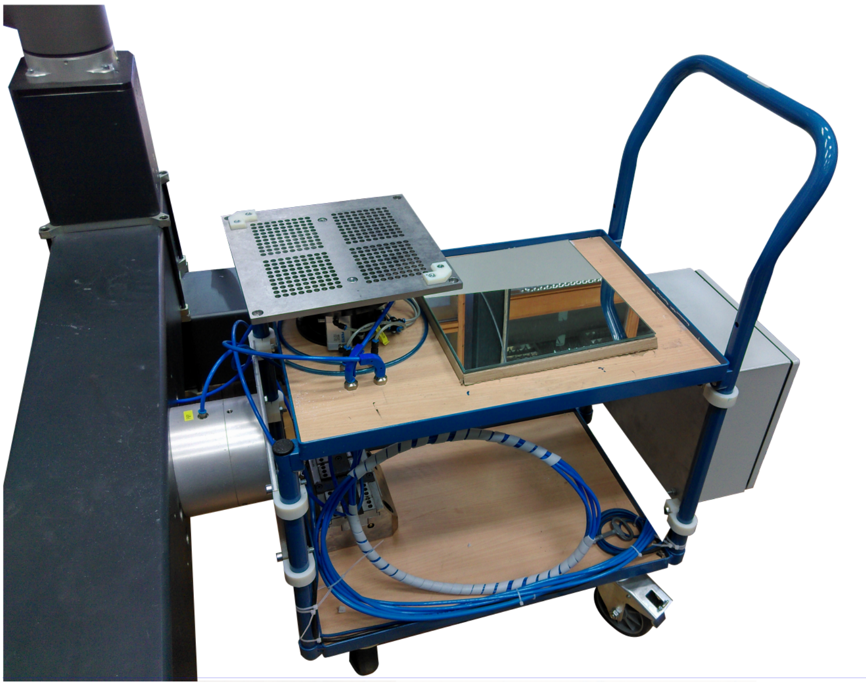

Figure 15: HOP Ubiquitous peripheral module

3 Optimal (re)configuration

The optimality of workcell configuration and reconfiguration was experimentally evaluated using the system designed for Ivamax use case, which is described in deliverable **D6.4**. The aim of the experiment was to show the dependency between consumed energy (Joules) and part position.

The experiment consisted of the robot arm picking up the metal casing from the part delivery trolley and placing it to the vise. Experiment setup can be seen in Fig. 16. The vise was on a predefined position, while the position of the part was changing. In every iteration of the experiment, the part was placed at a new position on the trolley and localized using the computer vision system described in deliverable **D3.2**. The robot motions proceeded in following steps:

1. The robot starts from the fixed initial joint configuration to grasp the object localized by the vision system.
2. The robot moves the object from the trolley to the fixed position above the vise.
3. The robot moves the object back to the same position on the trolley where the object was initially picked up.
4. The robot moves back to the starting position.

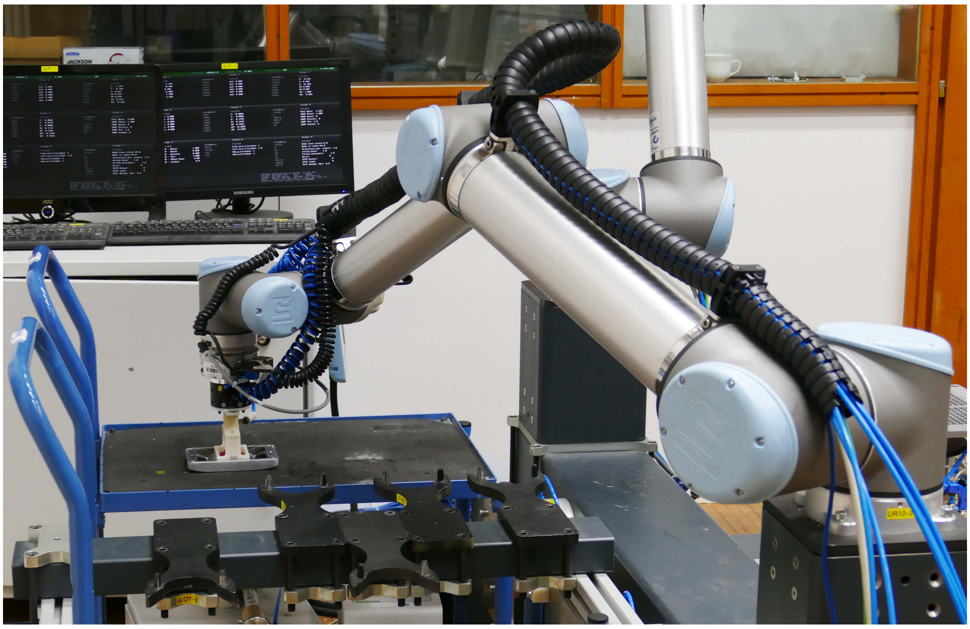

Figure 16: Experiment setup. Robot picking up a casing from an example position.

During the experiment we captured the data from the ROS system using the `rosbag record` function. This allowed us to capture all data regarding the robot that performed the movements. The Universal Robot robots broadcast data of the electrical current going to each of the robot's servo motors $I_j(t)$, where j denotes each of the robot's six degrees of freedom. The consumed electrical energy for each joint (E_j), i.e. motor, and the overall system can be calculated from with:

$$E_j = U \int_0^T I_j(t) dt, \quad (1)$$

$$E = \sum_{j=1}^{6} E_j, \quad (2)$$

where U denotes constant voltage, which is $48V$ for all motors on a UR10 robot, while T represent the duration of the robot's task.

The results are divided in two sets of motions: part picking (step 1 and 2) and part placing (step 3 and 4). The results showing the relation between the consumed energy and the part position can be seen in Fig. 17 for picking and in Fig. 18 for placing, respectively. The part position is defined relative to the base of the robot. As can be seen from the results, the closer the object is to the base of the robot, the lower the total energy consumption is. While this could be expected, we can extract additional information from the results. We can observe the energy consumption rises faster along the Y axis of the object position. In case the closest position is not available to place the object, it is better to move it along the X axis than the Y axis.

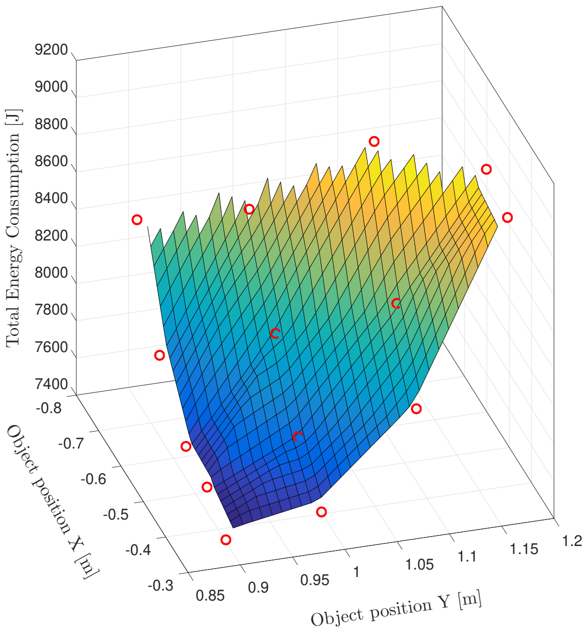

Figure 17: Total energy consumption for object picking task. Object was picked up from 14 different locations on the plane. They are marked with red circles. The results in between were numerically interpolated for better visualization.

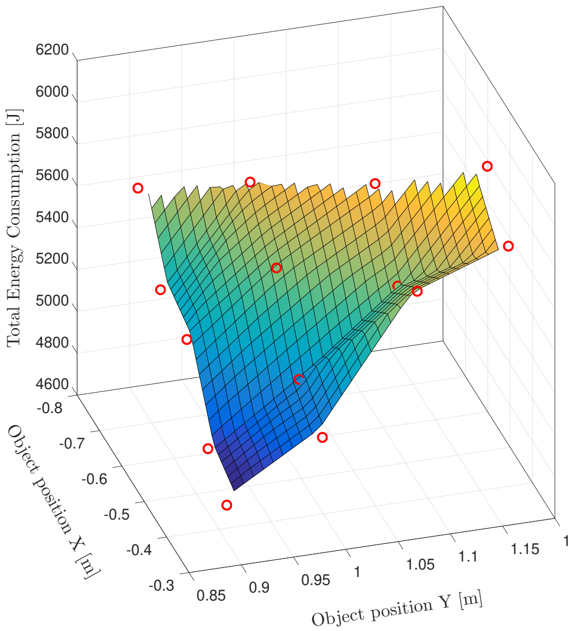

Figure 18: Total energy consumption for object placement task. Object was placed to 14 different locations on the plane. They are marked with red circles. The results in between were numerically interpolated for better visualization.