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Contents

1 Reconfigurable jigs

1.1 Motivation

Constantly increasing competition and pricing pressures in industry lead to an intensified demand for higher productivity and shorter time-to-market strategies [1]. Rising diversity and model variety and shorter life cycle times require more flexible production plants. This leads to an intensified demand for new production concepts. Current robotized plant concepts are characterized by flexible robot systems and the possibility to exchange tooling system equipment like spot welding guns, arc welding tools or grippers quickly and effectively. These tooling systems can also be made flexible [4]. However the peripheral elements are still inflexible. Currently, fixture systems are optimized for a certain work piece or piece family and exactly defined manufacturing processes. Improvements can therefore be achieved by the introduction of more flexible fixtures. Such fixture solutions have already been proposed in the automotive industry. They are called reconfigurable assembly systems and allow easy adaptability to a particular geometry of different work pieces. New modular components can be added or removed from the workcell according to the current task requirements. In this way, high flexibility of production can be achieved [2].

1.2 Design

To increase the flexibility of robotic workcells we use a reconfigurable fixture design called hexapod. Hexapods are unactuated Gough-Stewart platforms with six degrees of freedom (three translatory and three rotational). They are composed of an upper and a lower plate connected by six links. The lower plate is mounted to the robot workcell. The position and orientation of the upper plate is reconfigurable. Figure 1 shows the design of the hexapod.

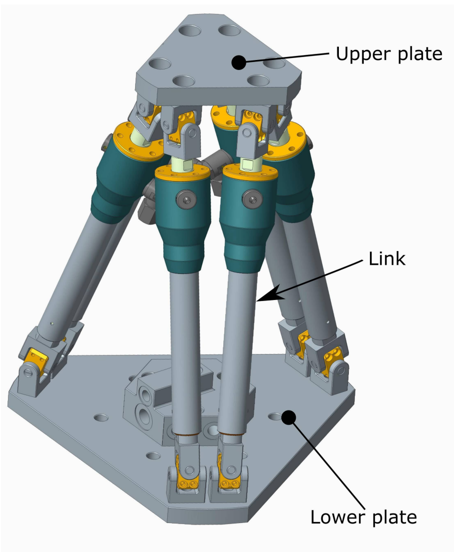

Figure 1: Hexapod

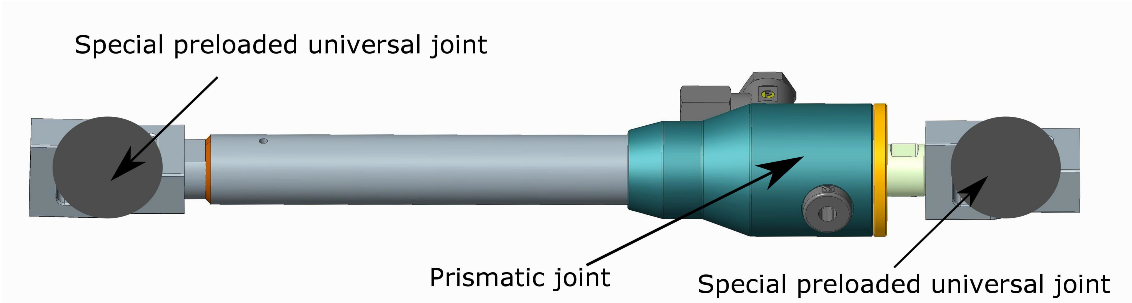

Figure 2: Hexapod links. The joints are currently being patented.

The proposed hexapod prototype is composed of standard elements. No position measuring equipment or actuators are used. The movement of the upper platform can be performed manually or by an external mechanism, e. g. a robot, which can move the upper platform from one configuration to another. The lower plate remains fixed during this reconfiguration process.

To fix the required position, a special brake system is used. The clamping force is provided by an internal hydromechanical system. Hydraulic clamping brakes that lock the prismatic joint are used for each link. The necessary force is applied by an air-oil pressure intensifier. It acts as an interface between pneumatic and hydraulic subsystems. It pressurizes hydraulic fluid that is conducted via hoses to each link. It acts as a safety device normally applying hydraulic pressure. To release the brakes pneumatic pressure is used. Figure 3 shows the block diagram for hexapod control.

The proposed hexapod system was adopted for use in our experiments. The current design is based on extensive research done previously [6]. Some crucial parts of the hexapods, i. e. joints, are currently in the process of being patented. Flexible jigs have not been used before for the assembly of automotive lights, robot components and smart furniture motors, which are ReconCell use cases.

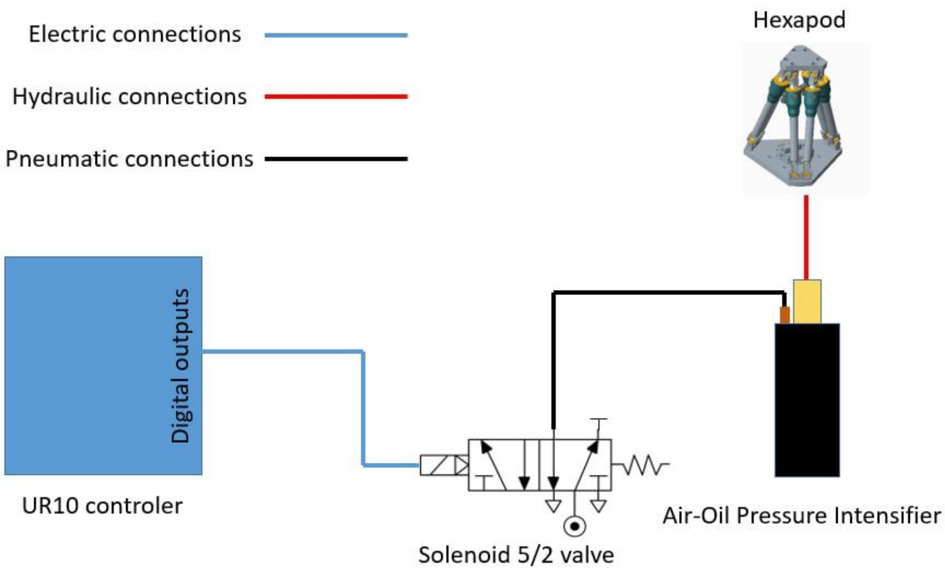

Figure 3: Schematic control diagram

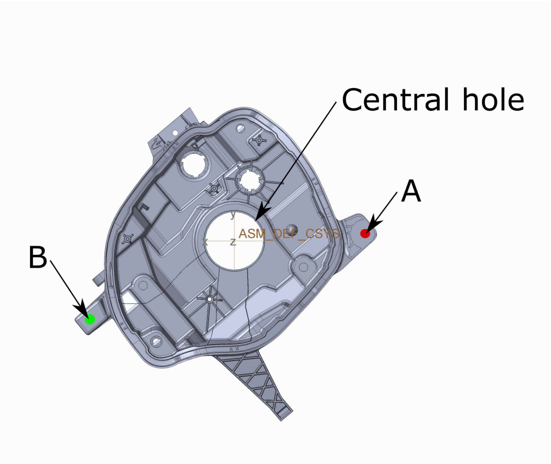

Figure 4: Light housing X07 left

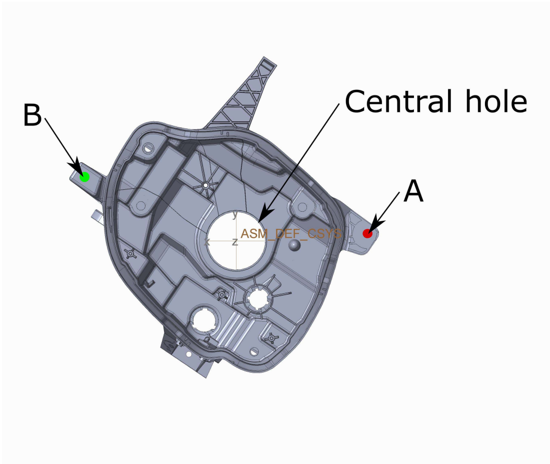

Figure 5: Light housing X07 right

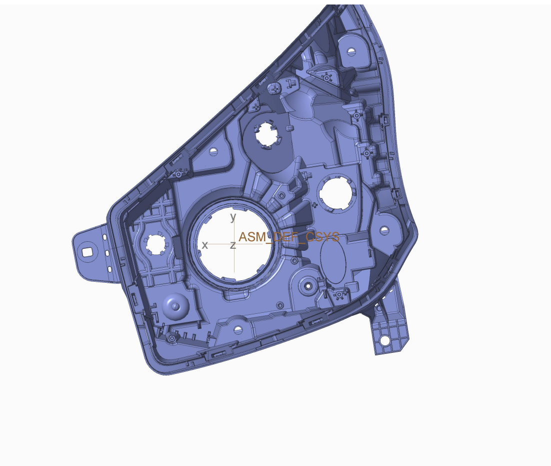

Figure 6: Light housing X82 left

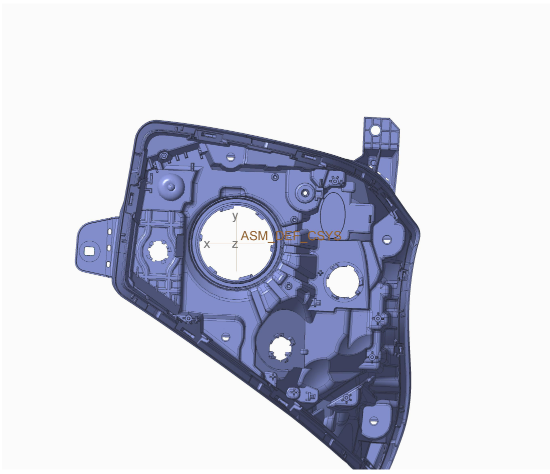

Figure 7: Light housing X82 right

1.3 Hexapod mounted clamps and supports

Because of the elastic structure of the ELVEZ light housings, it is sensible to support them at at least three points. Further analysis has shown that the the central and mounting holes are the features exhibiting the smallest variance in position and geometry between different models. These features are therefore the most appropriate points to be supported by reconfigurable jigs. The light housings are therefore clamped at the two mounting holes and supported by the central hole. Figures 4 to 7 show the ELVEZ light housings in their relative clamping positions. Holes A and B (Figure 4 to 7) were chosen to be the most appropriate features for clamping. The numerical coordinates of mounting holes positions and their diameters are given in Table 1. The origin lies in the middle of each piece's central hole. The working area of the hexapod has been confirmed to be big enough to reach each of the target points (either A, B or central hole) for both housing models and their left and right variation.

To achieve the best position accuracy it is convenient to use centering pins when positioning light housings on jigs. The pin tips are conical which compensates for any inaccuracies caused by the robot motion. The problem is that different light housing models have different hole diameters that the pins have to fit. The central hole has besides the different diameter also some

Table 1: Positions of the centers of mounting holes relative to the center hole.

Light model	Hole	x [mm]	y [mm]	z [mm]	Diameter [mm]
X07 left	A	-160,8	-8,4	-113,4	10,0
	B	177,3	-97,555	-185,8	9,6
	Central hole	/	/	/	71,4
X07 right	A	-160,8	8,418	-113,4	10,0
	B	186,5	78,5	-185,8	9,6
	Central hole	/	/	/	71,4
X82 left	A	-185,4	-118,6	-10,83	12,0
	B	0	10	35	10,0*
	Central hole	/	/	/	91,5
X82 right	A	-171,2	138,3	-10,8	12,0
	B	180,7	-10,0	-215,3	10,0*
	Central hole	/	/	/	91,5

*The given dimension is of the centering pin as the hole is rectangular

additional, model-specific features. To overcome this problem we designed the centering pins and the central supports to be exchangeable by robot. Figures 8 and 9 show the exchangeable centering pin and the central support subassembly.

The exchangeable centering pin and exchangeable central support work in the same way.

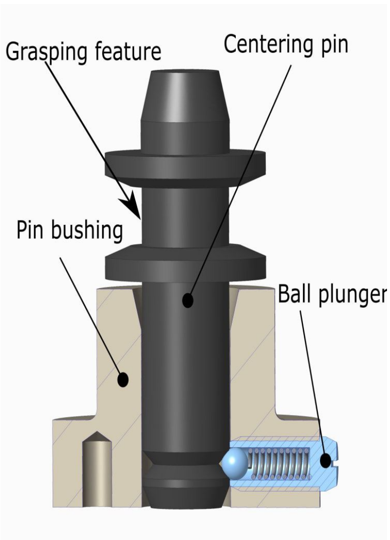

Figure 8: Exchangeable centering pin subassembly

Figure 9: Exchangeable central support subassembly

Figure 10: Light housing X07 central support

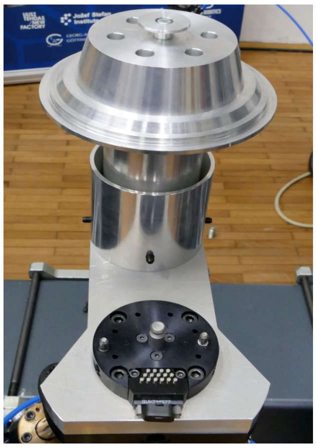

Figure 11: Light housing X82 central support

The centering pin is inserted in a bushing and held in place by a ball an spring plunger. To change the pin or central support, we simply grasp it by a specially designed grasping feature and pull it out of the bushing. The centering pins and the central support were designed to have the same grasping feature so that they can be changed using the same gripper fingers. Central supports for X07 and X82 light housings were produced (Figure 10 and 11) as well as centering pins with nominal diameters of 9.6 mm, 12 mm and 10 mm.

To clamp the light housing, a Destaco 8732 pneumatic clamp controlled by a Festo 5/2 solenoid pneumatic valve is used. The valve is connected to the UR10 control box's 24V digital output. The clamp's upper leaver arm was redesigned because the stock one was too short. We have also modified the tip by drilling a hole in it to accommodate the tip of the centering pin.

As explained before, the robot is used to reposition the hexapods. The Destaco QC-30 pneumatic tool changer is used to connect the tip of the robot to the hexapod. The tool changer is composed of two parts that can be locked together. One is attached to the robot and the other to the upper plate of the hexapod. Figure 12 shows the implementation of the reconfigurable jig clamping the ELVEZ light housing.

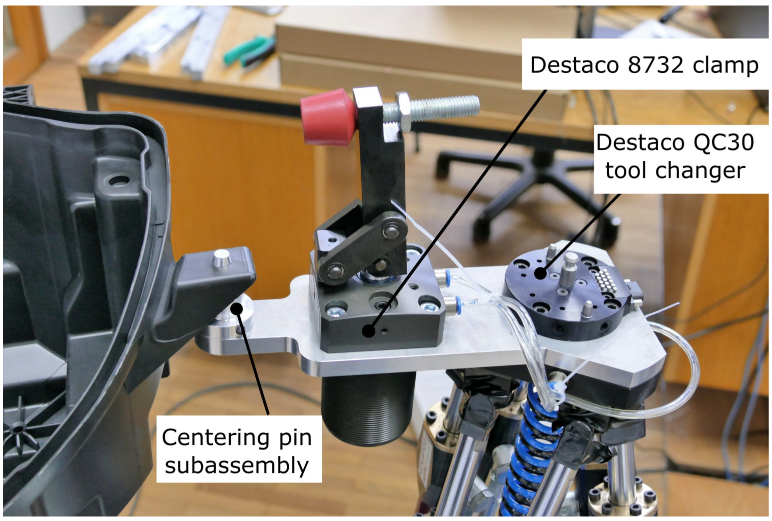

Figure 12: Hexapod mounted clamp subassembly

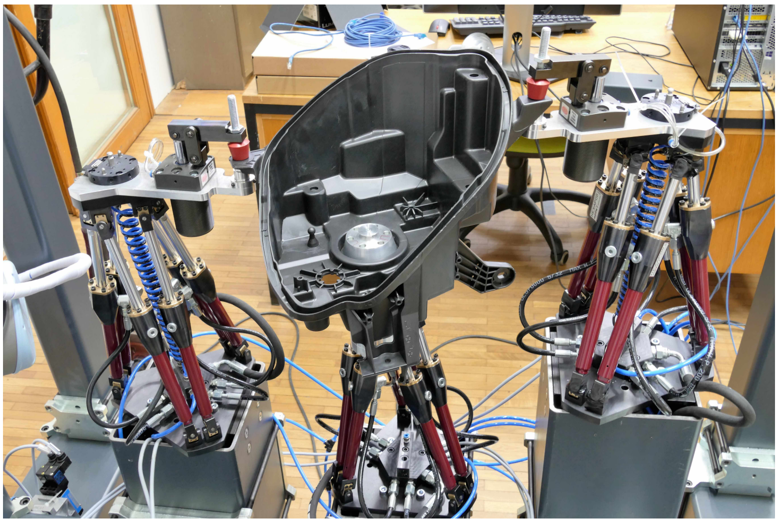

Figure 13: Reconfigurable fixtures for the ELVEZ use case

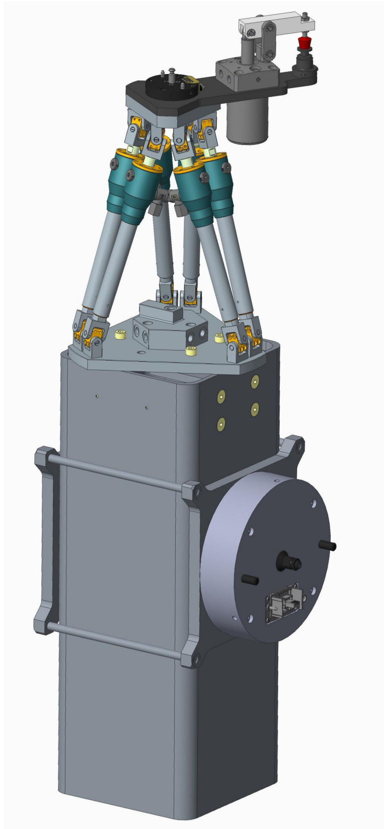

Figure 14: Reconfigurable jig module

Lastly, the hexapod, the hexapod mounted clamp, the valves and the air-oil pressure intensifier were combined in a self contained peripheral module. This module can be connected to the main cell with the Plug & Produce connectors (see Section 3). The module is self-sufficient, which means that once connected to the Plug & Produce connector it is ready to use with no additional configuration. Figure 13 shows the application of reconfigurable jig elements in the ELVEZ use case, while Figure 14 shows the details of the reconfigurable jig module.

Hexapod is an enabling technology adopted and further developed by JSI in order to develop and build the modular reconfigurable jig concept. It was developed as an optional feature of the proposed workcell. The reconfigurable module is designed for use in SMEs as a flexible fixture for the production of small batches of highly personalized products. Its application can reduce the costs arising due to the manufacturing, development and storage of application-specific jigs. The modular approach to workcell configuration and robot-guided reconfiguration are innovative concepts developed by JSI. These concepts are important to increase the flexibility of robotic workcells.

2 Reconfigurable frame

The frame of the robotic workcell is a structure that connects the robot with the peripheral modules. The main design requirement for the frame is to be as stiff as possible. This is important for robotic workcells because even small frame deformations can cause errors in the position an orientation of the robot end-effector. This can result in failures that impair throughput rate and product quality [3].

When a change in the production process occurs, we want to be able to keep most of the workcell intact and either add the necessary components or reconfigure existing elements to perform a new task. Thus the frame has to be reconfigurable and allow the adaptation of the workcell configuration. In addition, the frame has to be shaped in a way that makes adding and removing peripheral elements as simple and fast as possible. To achieve this we applied the Plug & Produce connectors (see Section 3) mounted to the frame. An important requirement for the frame is also to be affordable. This means that it should be constructed from inexpensive materials and without high-precision machining operations.

To comply with the above requirements, we decided to construct the frame of the cell using square steel beams connected with BoxJoint elements. Steel beams provide good stiffness while the BoxJoint system keeps the frame simple to build and reconfigure.

Since our main goal is to build a robot workcell frame that can be for different use cases, we decided to first design a separate frame for each of the three use cases and then unify the resulting frames.

2.1 BoxJoint system

As mentioned above, the beams are connected using the BoxJoint system. This system uses metal plates, nuts and bolts to connect rectangular beams together. The main advantage of the system is its simplicity and affordability. Many different configurations can be constructed using BoxJoint system just by bolting the connecting elements. No welding is required. Another advantage is that the joints can be disassembled. This mean that in the case of an upgrade or change in the workcell configuration, we can reuse most of the materials. The resulting joints are also very stiff. The stiffness of the BoxJoint system is comparable to welded joints.

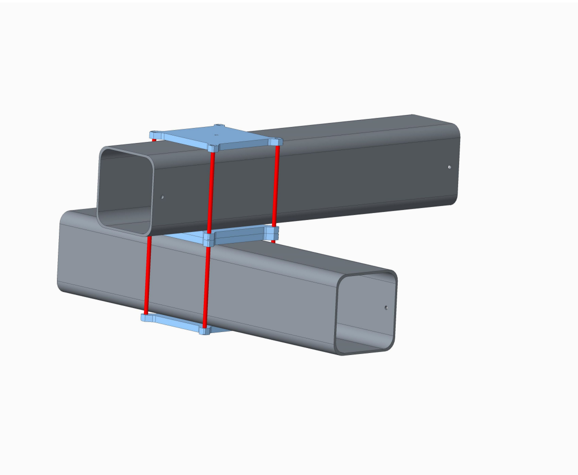

Figure 15: Double box joint

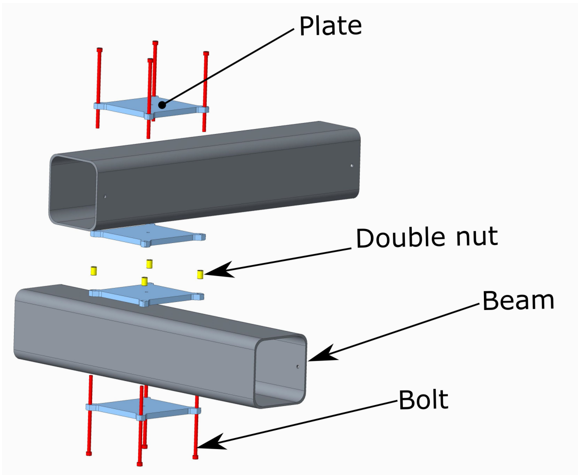

Figure 16: Double box joint structure

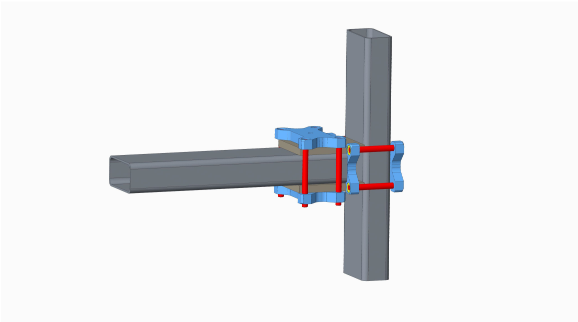

Figure 17: T-joint

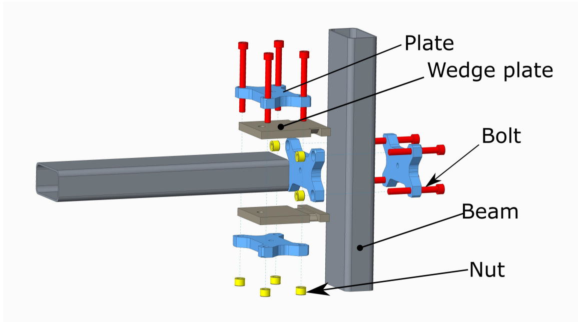

Figure 18: T-joint structure

The most frequently used BoxJoint solution in the frame was the double box joint. It is used to connect two beams together either in parallel or perpendicular to each other. It is composed of 4 plates, 8 bolts and 4 double nuts. The double box joint and its structure are shown in Figure 15 and 16.

The limitation of the double box joint is that it is impossible to make a coplanar frame. One of the beams connected by the joint has to lie outside the plane of the other. To overcome this limitation, we use the T-joint. Here we connect the end of one beam to an arbitrary position of the other so that all beams lie in the same plane. The downside is that this joint is less stiff in comparison with the double box joint. The T-joint and its structure is shown on figure 17 and 18.

2.2 Frame design

2.2.1 ELVEZ use case frame

For this frame configuration, the first task was to do determine the robots' relative positions. Since two robots are going to be used, it is sensible to position them so that their workspaces overlap. This is important when handing work objects form one robot to another or performing jig-less operations. Different jig placements were also considered to find the best compromise between the robots' reaching space and compact size. The whole family of ELVEZ automotive lights including all their assembly parts were analyzed to find optimal solutions.

The design of the cell frame was done by JSI in close collaboration with ELVEZ. Weekly meetings with ELVEZ representatives were organized in order to get their input regarding the progress. The good design, good discussion, good dissection (GD^3) methods were utilized. The design of the workcell was an iterative process with many iterations where each iteration improved the shortcomings of the previous. The last iteration was to consider the frame requirements of all use cases and synthesize a common frame design.

Figure 19 shows the first draft of the ELVEZ workcell. The two spheres represent the workspace of the two robots. They have a diameter of 1300 mm. The central cylinders have a diameter of 300 mm and represent the area where robot operations should be avoided. The right robot is mounted on a linear rail (see section 4). The minimal horizontal distance between the robots is 1500 mm and the vertical distance is 285 mm. Most of the beams were square tubes, 100 by 100 mm in cross section with the wall thickness of 5mm. The beams are connected using BoxJoint squeeze boxes (see Section 2)

In the next iterations (one of which is shown in Figure 20) we added more details. We added

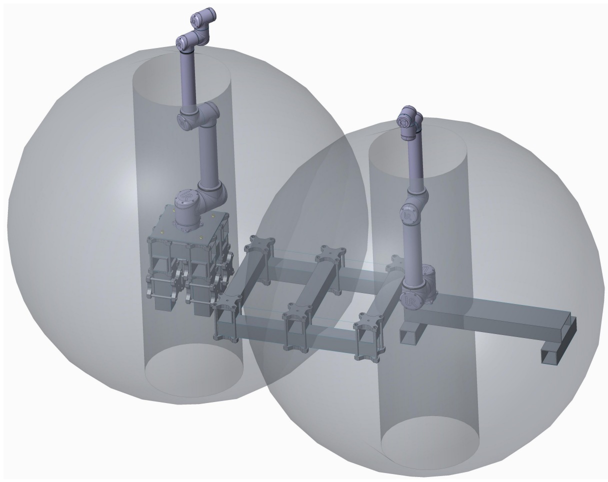

Figure 19: First draft of the ELVEZ workcell design.

ELVEZ light housings mounted to reconfigurable fixtures. A frame for mounting vision sensors was added. The minimum distance between the robots' bases was reduced to 1200 mm. This resulted in a larger common workspace with more possibilities for robot-robot collaboration. The cross section of the beams was increased to generate a stand on which the fixed robot is mounted. The cross section of the lower square tubes measures 200 by 200 mm, with the wall thickness of 6 mm. The cross section of the rectangular tubes measures 200 by 100 mm with the wall thickness of 4 mm. These beams are connected by a combination of squeeze box and double box joints. The vision system's frame beams measure 100 by 100 mm with wall thickness of 4 mm. They use two T-joints (see Section 2.1).

In the final iteration we further diminished the minimum distance between the tow robots to 1050 mm. We fully developed the fixed robot stand. It is now made of a 8 mm thick 200 by 200 mm square tube, at the top of which the robot's mounting plate can be attached. The upper

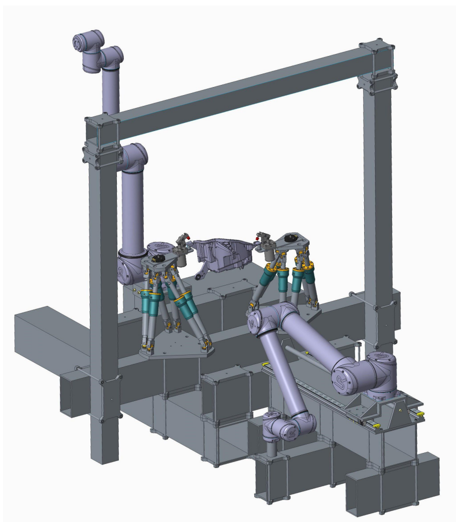

Figure 20: Intermediate iteration of the ELVEZ workcell design.

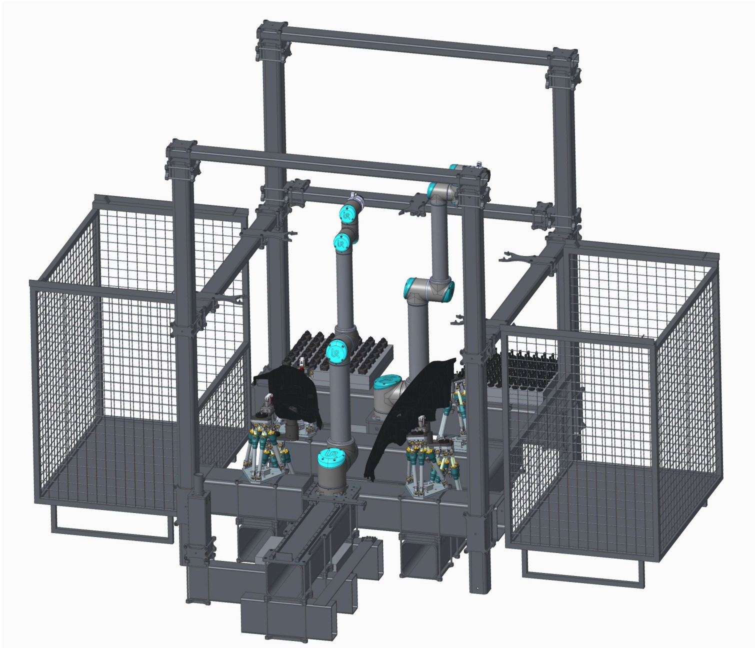

Figure 21: Final iteration of the ELVEZ workcell design

part of the frame has been expanded and now offers the possibility to store robot end-effectors (besides cameras). This has been achieved by attaching tool hanger modules (see Section 2.4) to the frame. The tool hanger modules are attachable to any 100 by 50 mm horizontal rectangular beam by a combination of BoxJoint standard and custom made parts.

The upper part of the frame is made of 3 mm thick 50 by 100 mm horizontal rectangular tube and 6 mm thick 100 by 100 mm vertical beams. They are connected using T-joints. The upper and lower parts of the frame are connected using a double box. The lower part of the frame is made of 6 mm thick 200 by 200 mm square beams. They are connected using double boxes. The footprint measures 1700 by 1800 mm.

This final configuration of the workcell is capable of producing left and right parts simultaneously. It has 6 reconfigurable jigs, three for each part.

The logistics is an important aspect to consider. Although providing logistic solutions is not part of the ReconCell project, the material flow in and out of the workcell is very important because the workcell has to be integrated seamlessly in the existing production line. To achieve this, work pieces have to be stored in an orderly fashion, i. e. their positions and orientations are must be known with sufficient precision throughout the whole manufacturing process.

To satisfy the modular paradigm, an innovative concept of trolleys equipped with part-specific trays was developed by JSI. These trolleys connect to the workcell via the Plug & Produce connector. They can be smart and store part properties such as type of parts, part quantity and the relative positions of individual parts (see Section 3.3.1). Our analysis showed that trolley size of 600 by 400 mm is optimal for all use cases. See Section 3 for more details.

2.2.2 Precizika metal use case frame

The Precizika metal (PRZM) use case requires the assembly of many different parts in the final product, hence applying a modular, reconfigurable workcell design is of great benefit for this

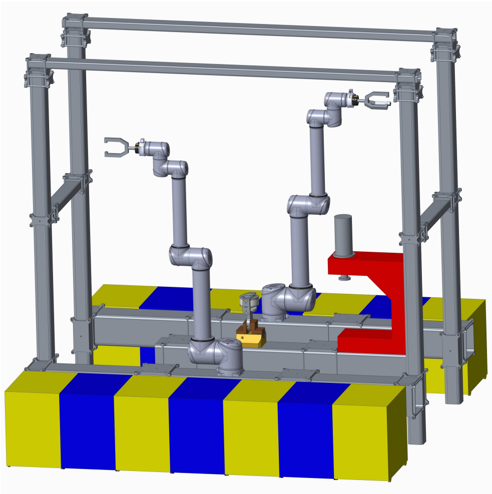

Figure 22: Firs draft of the PRZM workcell design

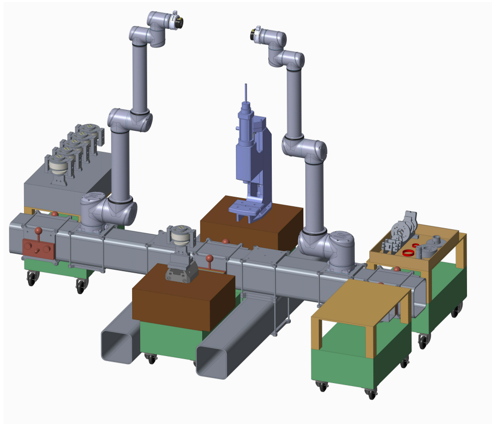

Figure 23: Intermediate version of the PRZM workcell design

use case. This type of workcell requires many P&P (Plug & Produce) connectors to connect to trolleys on which assembly components, end-effectors and specialized tools can be stored.

Figure 22 shows the first iteration. Each yellow and blue cuboid represents the mounting position for different assembly components. Because of this approach, the footprint of the workcell increases. It is composed of (same as the final ELVEZ workcell) 6 mm thick 200 by 200 mm beams, 6 mm thick 100 by 100 mm beams, and 3mm thick 50 by 100 mm beams. It uses (same as the final ELVEZ workcell) double box joints and T-joins. We used the same types of beams for the upper part of the frame as in the ELVEZ workcell design.

In the next iterations we changed the way how assembly components are stored. In the first iteration, each component had a separate storing area and could not be be quickly changed. Hence in later iterations we decided to store on a trolley all specialized tools and all parts needed to assemble the final product. This saved a lot of space. This made the frame more flexible. Figure 23 shows an intermediate iteration of the PRZM workcell. The upper part of the frame is not shown because we focused on the lower part first. The lower part is made of 6 mm thick 200 by 200 mm beams.

In the final iteration we added the upper part of the frame. It is made of 3 mm thick 50 by 100 mm horizontal and 6 mm thick 100 by 100 mm vertical beams. Here all the connections are

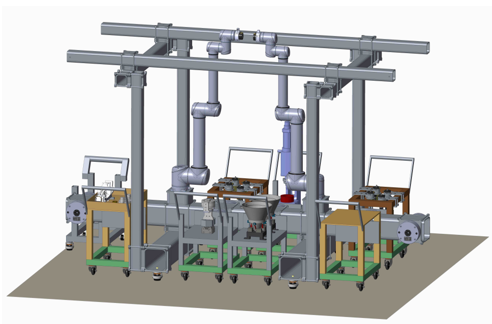

Figure 24: Final version of the PRZM workcell design

realized using double box joints. The tool hanger modules that are part of the upper part of the frame are not visible in the model. The hight of the upper frame has not been determined yet. The final configuration is shown in Figure 24.

While constructing the optimal frame for the PRZM workcell, we also analyzed how the PRZM product can be designed appropriately for robot assembly. To achieve this, an extensive workshop was organized where JSI proposed concepts how to design parts appropriate for robot assembly. Changes included the unification of bolt sizes due to the high cost of robotic screwdrivers, the introduction of centering chamfers, replacement of dowel pins with spring pins that are easier to insert and part geometry optimization in terms of robotic grasping.

2.2.3 Logicdata use case frame

The Logicdata (LDT) frame is the simplest to determine as it is jig-less. We used the same frame as for the PRZM workcell, the only difference being that different parts and end-effectors are used. It is shown in Figure 25.

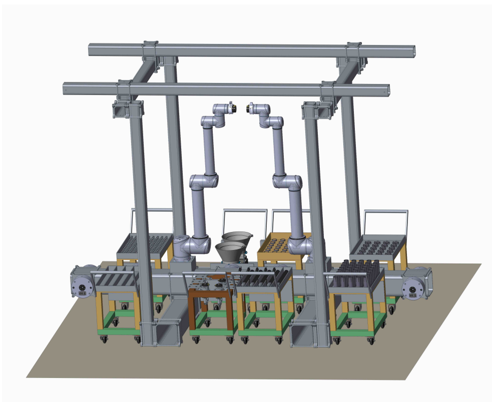

Figure 25: Final version of the LDT workcell design

2.3 Unified workcell frame

Finally, we analyzed all three use case specific frames. We determined each experiment's attributes such us the required number of robots, trolleys, application-specific tools, Plug & Produce connectors, human resources and other elements that affect the design of the workcell frame. In conjunction with the design of experiment-specific workcells, we started to work towards a unified workcell. After each iteration parameters such as frame cost, footprint size, weight, flexibility and functionality were assessed. Finally, when all of these criteria were satisfied, the resulting workcell configuration was selected as a unified workcell.

The biggest challenge was the integration of the ELVEZ workcell. The PRZM and LDT workcells are simpler and required only a couple of iterations to unify. The ELVEZ workcell required more space because of the reconfigurable fixtures. After many iterations, the optimum size of the footprint of the unified workcell was determined to be 1200 mm by 1600 mm. It has 10 Plug & Produce connectors.

The unified workcell frame is shown in Figure 26. The ELVEZ workcell configuration constructed from the unified workcell frame is depicted in Figure 27.

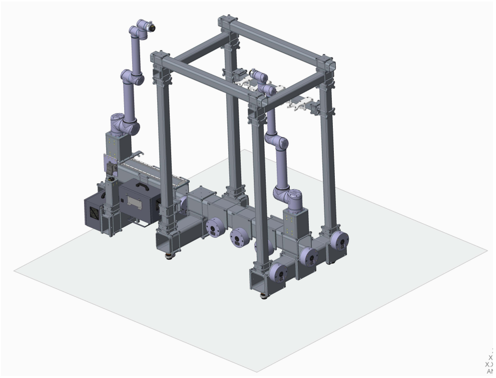

Figure 26: Unified workcell frame applicable to all three use cases.

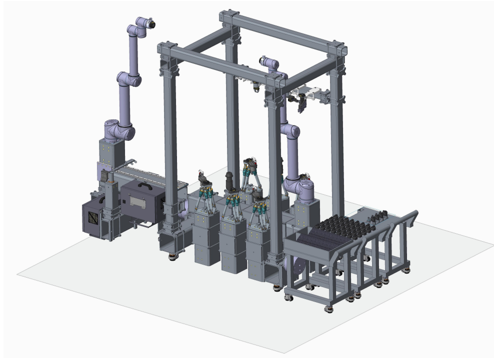

Figure 27: ELVEZ configuration constructed from the unified workcell frame.

2.4 End-effector hanger module

Despite the use of two robots in the workcell cell there is still the need to change robotic end-effectors to successfully accomplish use cases assembly tasks. To quickly and efficiently change them some way of storing end-effectors when in disuse is needed. The main requirements of such storage is to hold the end-effectors on a know position that does not change because of minor disturbances. The chance of dropping an end-effector should also be considered and minimized. It is also sensible to design the module so it can be mounted to an arbitrary position of the frame of the cell or on the trolley.

The solution we designed is shown in Figure 28. It is composed by a custom cut 14mm thick plate. In it there are two press fit 10mm DIN 6321 centering elements. They accurately position the end-effectors and keep them in place during disuse. The centering pins tops are conical to compensates for the inaccuracy of the robot and minimizing the chance of dropping the end-effector because small positional inaccuracies. The other plate is a standard BoxJoint 50mm by 100mm plate. It is, together with nuts and bolts, used to attach the tool hanger module to any horizontal 50mm by 100mm cross section beam. Figure shows the tool hanger module storing different end-effectors.

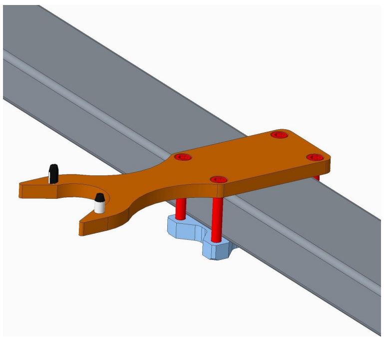

Figure 28: Tool hanger module.

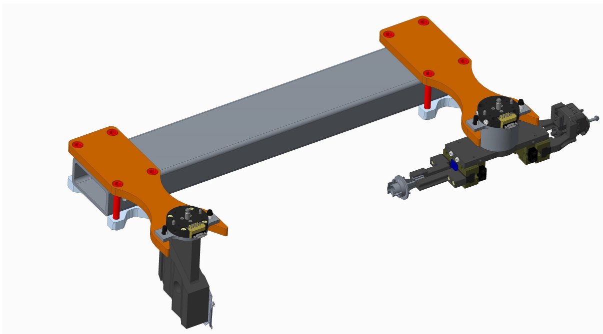

Figure 29: Two end-effectors stored on hanger modules

3 Plug & Produce approach

3.1 Motivation

The term “plug-and-play” carries an expectation of ease of use and reliable, foolproof operation. A plug-and-play product, as its name suggests, can simply be connected and turned on – and it works. The practical extension of plug-and-play products, when applied to industrial automation, has given way to the new term: plug-and-produce.

Plug-and-produce offers a practical solution to the issues of increasing competition in the global marketplace, which demands flexibility, as well as higher resource and energy efficiencies in the way goods are produced. As companies work to get products to market faster and cheaper, simple solutions are needed to enable near-immediate implementation – with no special tools or highly trained engineers or electricians required [5].

3.2 Plug & Produce connector design

The foundation of the plug-and-produce system is a Plug & Produce (P&P) connector, which standardizes how a group of modules is connected. The modules must be designed such that they can be assembled using P&P connectors only. The P&P connector to be used in ReconCell project should satisfy the following requirements:

- Cost lower than 1000 €
- Repeatability ±0.5 mm or better
- Forces: up to 1500 N in all directions
- Torques: up to 1000 N m in all directions
- Adjustment possibility: in height ±0.5 mm, in axis rotation ±1°
- Transmission of power supply: from 0.5 kW to 3 kW
- Transmission of compressed air: 6 bar, 1/2 ” pneumatic
- Transmission of ICT signals: network 8 pins
- Coupling: manually with a lever and automatically with pneumatics
- Mechanical gland: compensation of inaccuracies up to ±30 mm

After the market research we found out that none of the existing connectors meets the requirements. The commercially available tool changers could be used for this purpose. However, they do not meet the above requirements due to their high price. Each workcell will use several P&P connectors, therefore the unit price is paramount for the use of in SMEs.

PRZM therefore designed a suitable connector. The developed solution is shown in Figure 30. It is used to connect peripheral hardware modules to the main workcell. The peripheral hardware modules provide application-specific functionality. The connectors can also be used for connecting smart modules that manage material and tool flow. These smart modules have integrated computational capabilities. The shared information is used for raw material and smart tool tracking, error prevention, and error recovery.

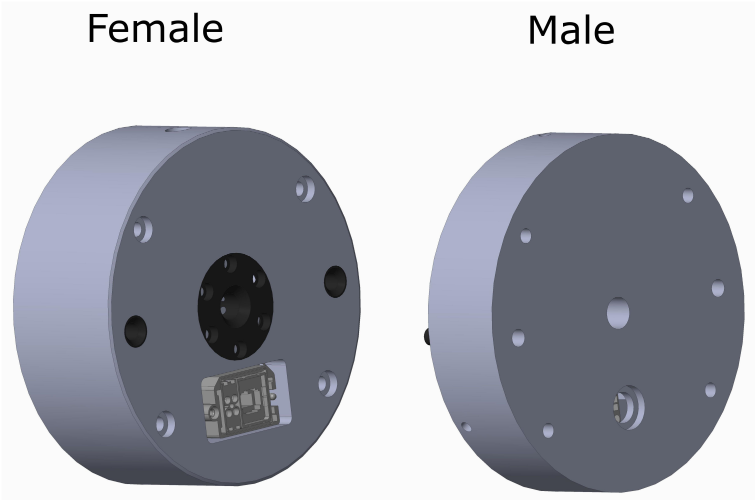

Figure 30: P&P connector prototype

3.3 Trolleys with integrated P&P connectors

As mentioned in Section 2.2.1, we developed a logistic concept for transporting of assembly parts and other equipment to and from the workcell with trolleys. These trolleys can potentially be equipped with smart functionality, although the use of smart functionality is not envisioned in the ReconCell project.

3.3.1 Trolley with parts

In the proposed trolleys, parts are stored in EuroBox containers measuring 600 by 400 mm (a quarter of a Euro-pallet). They can be palletized or in bulk. Bulk material can be sorted using robotic bin picking or vibratory feeders. The trolleys connect to the robot workcell via the P&P connector.

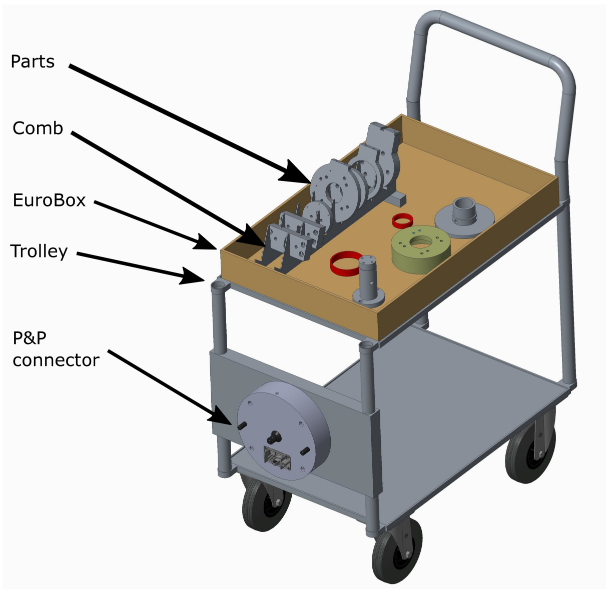

Figure 31: Trolley with parts.

In the project, manual push trolleys will be used, but the same framework can be used with automated guided vehicles (AGV). After considering all the assembly parts, tools and specialized equipment, the trolley dimensions of 600 by 400 mm were determined to be optimal. Figure 31 shows the design of trolley with parts used for the PRZM use case.

3.3.2 Trolleys with tools, end-effectors, and other specialized equipment

Fast reconfigurability and modularity of the workcell is important when producing low volumes and high variety of products in a short period of time. These functionalities can be supported by trolleys where tools, end-effectors, and other specialized equipment can be stored. The proposed trolleys make it possible to assemble application-specific modules separately while the workcell is running (off-line reconfiguration of P&P modules). The reconfiguration is achieved by simply connecting pre-assembled smart modules using P&P connectors. Downtime is therefore very short. The proposed trolleys are standardized and can be used in any cell using P&P connectors.

While it remains to be decided which trolleys will actually be used in the ReconCell project, we devised a few draft designs for trolleys that support supplying and storing robot end-effectors, clamping devices, screwdrivers, etc. Note that these devices are application-specific. Since the goal is to create a highly reconfigurable robotic workcell, an efficient and fast method for transport and storage of this equipment is required. One example is an end-effector trolley shown in Figure 32. It can be used for adding and removing end-effectors from the workcell. If the trolley is equipped with smart functionality, it can recognize and track the appropriate end-effectors and help the operator deliver them exactly where and when they are needed.

Another example is a robotic screwdriver, which is required by all use cases (ELVEZ, PRZM and LDT). To supply the screwdriver with screws efficiently, a vibratory feeder is required. The use of a feeder renders the complete system screw-specific, therefore parts of the system have to be replaced when changing screw dimensions. Each experiment uses different screws, so a fast way for changing the screwdriver with its feeder is required. This can be achieved by integrating the screwdriver in a P&P trolley module (see Figure 33).

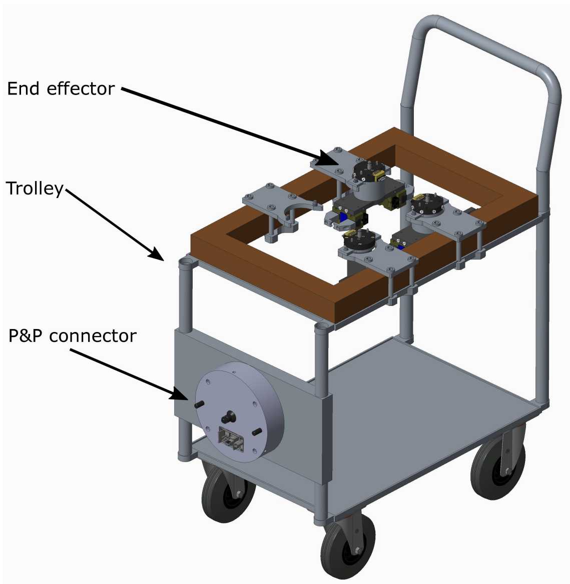

Figure 32: P&P tool hanger trolley

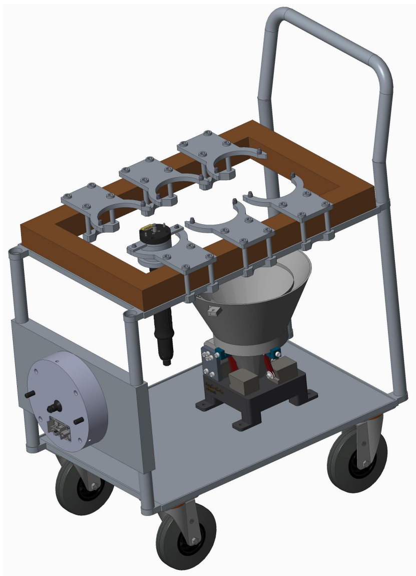

Figure 33: P&P screwdriver trolley

3.4 P&P connectors for other equipment

There is also a possibility to plug peripheral equipment, e. g. reconfigurable fixtures, directly to P&P connectors without using trolleys. In this way we can achieve a higher density of different tools in the limited space of the workcell. Figure 34 shows the reconfigurable jig module mounted on the P&P connector. Another P&P module is the linear unit, which is described in more detail in Section 4.

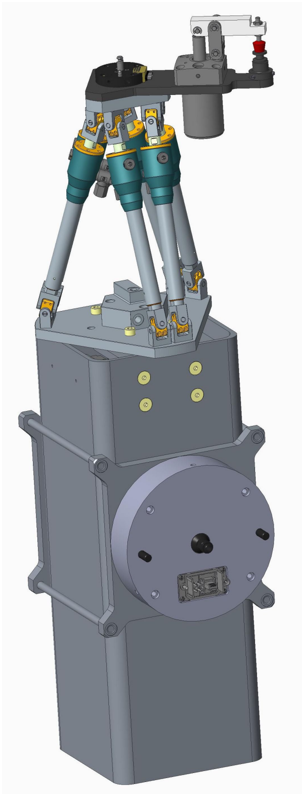

Figure 34: Reconfigurable jig module

4 Passive linear unit

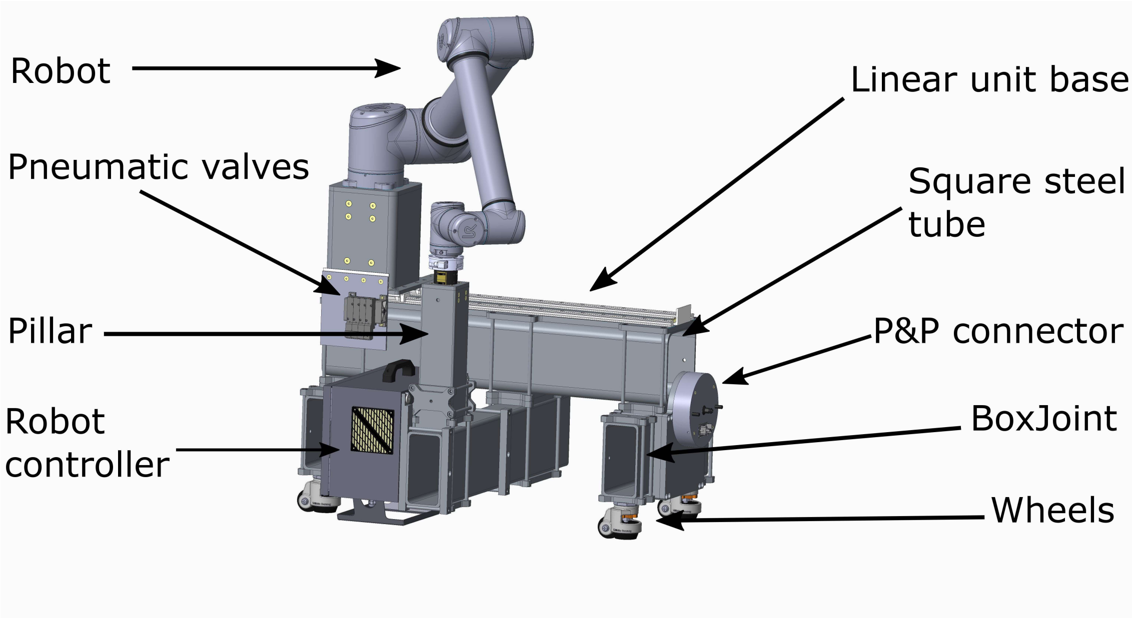

Figure 35: Integration of passive linear unit in the workcell

4.1 Motivation

Linear units allow us to increase of the robot's work envelope significantly. Usual linear units are actuated and therefore active, but this type of units are expensive. The solution proposed in ReconCell is to develop a passive linear unit, along which the robot can move using its own actuators. This simplifies the design and results in an inexpensive linear unit.

This solution was devised, designed and tested at JSI. The main motivation is to make a low cost way of expanding the work envelope of the robot suitable for the use in SMEs. The technology is currently being patented.

4.2 Development of linear unit base

The way a robot moves along the rail is to grasp a tool changer attached to the supporting frame. By fixing the tip of the robot, performing a linear motion parallel to the linear rails results in the motion of the base of the robot. Linear guides are used to ensure precise movement of the robot base. Pneumatic safety brakes located on the linear rails lock the movement of the robot base after the desired location has been reached. The linear unit is another module that uses the P&P connector of Section 3 to attach to the main workcell. The entire assembly is supported by height adjustable wheels which enable easy movability and high maneuverability of the module.

To choose the type of linear rails, the analysis of maximum forces and torques was performed. Forces and torques that act on the linear unit due to the lateral robot motion were calculated. They are the highest when the robot arm is fully extended and fully loaded, moving with acceleration at which the emergency stop activates. This acceleration is equal to $a = 2\,\mathrm{m/s^2}$. The moment of inertia of UR10 robot with weight of 10 kg added to the tip in configuration

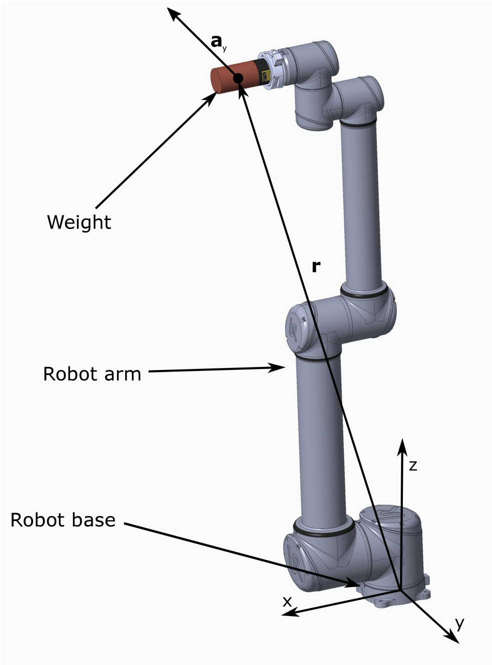

Figure 36: Worst case configuration

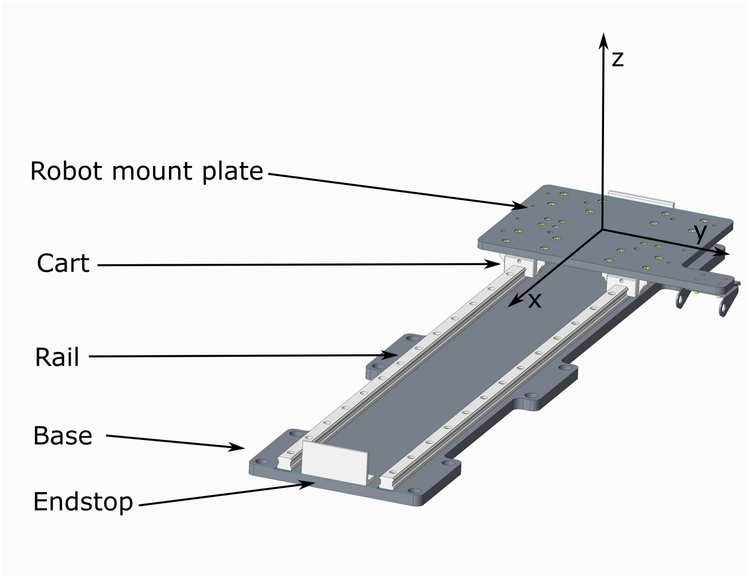

Figure 37: Linear unit base

shown in Figure 36 was calculated using a CAD program. It is equal to $J = 145\,\mathrm{kg\,m^2}$. In this case, the resulting torque at the base of the robot is calculated as follows:

$$M_x = J\ddot{\varphi} = 145kgm^2 \times 1,54s^{-2} = 223,3Nm, \tag{1}$$

$$\ddot{\varphi} = \frac{a}{r} = \frac{2ms^{-2}}{1,3m} = 1,54s^{-2}, \tag{2}$$

where r is the length of the extended robot arm, which is 1300 mm in the case of UR10. The generated force is calculated as:

$$F_y = ma = 46kg \times 2ms^{-2} = 92N, \tag{3}$$

where m = 46 kg is the total mas of the fully loaded robot arm. Eq. (3) assumes that the mass of the robot is concentrated at its tip. This is obviously not correct but provides an upper limit. The maximal prescribed load for the chosen linear guide of manufacturer TBI for model TRH 20 FL H Z1 is 21 250 N force and 369 N m torque, which is a lot more than the loads that can be caused by UR10. In addition, we selected a configuration with two rails and four carts, which is more rigid and can withstand higher forces. The configuration can be seen in Figure 37.

The most important part of the linear unit is the base shown in Figure 37. The base is attached to the workcell frame. The base of the robot is attached to the robot mount plate that slides along the rails. Note that the linear unit base can be mounted at other appropriate locations in the workcell.

4.3 Assembly of linear unit

The crucial part of linear unit assembly is to mount linear rails to the base plate. This operation requires the base plate to be made precisely. If the two rails are not parallel, the linear guides could jam. After the linear unit base has been assembled, the rest of assembly is simple and fast. Using the modular BoxJoint system described in Section 2 and square steel tubes, the frame can be assembled and the robot mounted onto the robot mount plate.

We next tested the functionality of the developed system. We started with the wheels. The linear unit is easily and accurately maneuverable by two people. The height adjustment of the linear unit is performed using the integrated height adjustment screw. We continued with the frame. The use of BoxJoints and square steel tubing made the assembly process short (under 30 minutes). The resulting unit was rigid and stable. Its best feature is its reconfigurability. It allows us to dismount the linear module and mount it somewhere else in a very short period of time. The next components tested were the linear guides. The movement was smooth and accurate. There is no backlash since the linear guides are preloaded. The brakes can also withstand very high forces, several times larger than those calculated in Eq. (3). Next the movement of the robot base was tested. For this purpose, the tip of the robot was attached to the workcell frame. Once the brakes were released, the robot was able to successfully relocate itself. After the desired position was reached, the brakes were activated and the tip of the robot was released. The forces created by the motion did not affect the linear unit in any perceivable way.

4.4 Accuracy of robot base motion

The positional accuracy of the robot base motion is primarily determined by the accuracy of the robot motion. We performed the analysis of the effect of robot base motion along the rail using an analytical friction model. This analysis showed that the major hindrance in deploying the developed linear unit lies in the limited positional accuracy of the base of the robot, which is caused by the elastic deformation of the structure of the mechanic arm.

To limit this effect, we will initially use the robot only in two extreme locations where bumpers at both ends of the rail have been placed. The robot can easily detect when these two locations are reached using a force/torque sensor mounted to the tip of the robot. The absolute position of the robot at these two locations can be determined with a suitable calibration process. The length of the rail is limited by the workspace of the selected robot. This setup is good for applications the robot does not need to relocate too often during the production process.

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