# Requirement Oriented Reconfiguration of Parallel Robotic Systems

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## 1. Introduction

The development of industrial production is subject to a change, which is mainly caused by higher customer orientation. The possibility of an end-customer to configure nearly individual mass products results in sophisticated challenges for production. The diversity of variants is growing. In addition an increasing demand to offer a band of new products leads to shorter product life cycles. To be competitive a company has to provide the product at reasonable costs. Considering serial production lines in highly developed countries, a high degree of automation is necessary to gain economies of scale. These changes of the economic boundaries demand specific design methodologies for the production equipment. In particular reconfigurable robotic systems are promising alternatives to the purchase of new production equipment. In case of changed production organization, reconfigurable robotic systems reduce redesign efforts and do not require rescheduling of entire production lines. Major impact factors to the design of reconfigurable robots are shown in Figure 1. They are subdivided into product and production driven aspects.

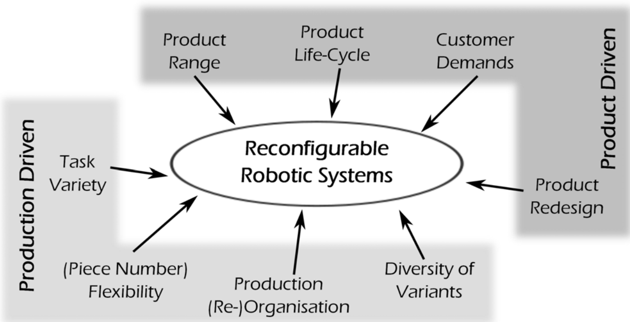



Fig. 1. Impact factors to reconfigurable robotic systems.

Regarding robotic systems, parallel robots, due to their high speed, acceleration and stiffness parameters have a huge potential to be reconfigurable systems. Several and entirely different reconfiguration strategies of parallel robotic systems can be derived based on these properties. Starting from the early design stage of requirement management, design considerations

and machine elements have to be considered in order to enable effective reconfiguration of the systems. Since development and design complexity for reconfigurable robotic systems increase necessary steps to be addressed are use case derivations, their segmentation and discretization as requirement spreads as well as the relation between the systems components and parameters of the robotic system, which are modified.
In this contribution general aspects of robotic reconfiguration approaches are shown and a methodological design procedure for reconfigurable systems is introduced. A brief literature review tends to determine the general idea of reconfiguration and the state of research of robotic reconfiguration by several approaches. As parallel robots constitute the focus in this chapter, some basics of this particular type of robots are shown. In order to develop reconfigurable robotic systems, the requirement management as the first step of the design process is significant. Therefore, paragraph 4 discusses the modeling of complex requirements and requirement spreads using SysML. In the following, static and dynamic reconfiguration approaches of parallel robots are presented and applied exemplary. Since the suitability of each reconfiguration strategy depends on the restrictions of the considered use cases, a systematic assessment of reconfiguration approaches is done in section 6. The chapter closes with a conclusion and a brief prospect to further research activities.

## 2. Literature review

The field of robotic research reconfiguration is often attended by modularization, standardization of interfaces or morphology on different mechatronic levels. In order to establish a consistent comprehension the term "‘reconfiguration"’ is defined, before representatives of different concepts are described briefly.

### 2.1 General idea and term definition

The general idea in developing reconfigurable robots is to enable a system to change its abilities to fulfil various tasks. These tasks are characterized by different requirements depending on the robots field of application. In this contribution parallel kinematic robots are focused on, where handling and assembly tasks are typical. Hence, a suitable definition for reconfiguration is given by Setchi (2004):

*"‘Reconfigurability is the ability to repeatedly change and rearrange the components of a system in a cost-effective way"’.*

In literature a wide spread understanding of reconfigurable robots is existent (see Figure 2). In the following section different approaches and realization examples are introduced in order to distinguish the scope of this contribution.

### 2.2 Classification of reconfiguration approaches

Many approaches for the reconfiguration of robotic systems have been proposed in literature but are not yet established in industry. These approaches can be considered as either online or offline. While online reconfiguration is performed during the use of a robot without switching it off, offline reconfiguration demands a shut-down of the robot (see Figure 2). The following literature review helps to gain a deeper insight into the possibilities to realize reconfigurable robots that can adapt to external environments.

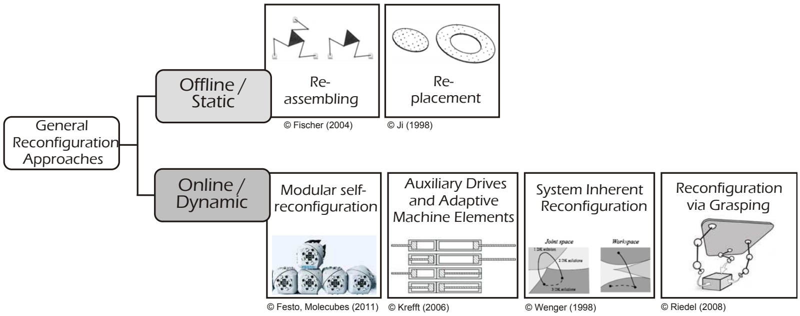



Fig. 2. General classification of reconfiguration approaches to adapted parallel robots to external environments.

#### 2.2.1 Offline reconfiguration

The mechanical structure of fully parallel robotic systems is very suitable for offline reconfiguration since those structures are actuated in parallel and therefore consists of many consistent components. Components or sub-modules of the system are replaced or the same components are mounted in different positions and orientations. Thus, various morphologies of the kinematic structure can be arranged.

**Reassembling and replacement.** Various pieces of work focus on the design of modular kinematic structures in order to enable effective reconfiguration of robot systems [Krefft (2006), Fisher (2004), Wurst (2002)]. A modular robotic system consists of a set of standardized modules, such as actuators, passive joints, rigid links (connectors), mobile platforms, and end-effectors, that can be rapidly assembled into complete systems with various configurations. In Ji (1998) a reconfigurable platform manipulator based on a HEXAPOD kinematic structure is presented. Each module e.g. leg modules of the structure can be replaced and position and orientation of the joints on the mobile platform and the base can be varied, using different sets of pattened holes. Thus, different workspace dimensions are obtained. Yang et al. (2001) propose two types of robot modules in order to simply assemble three-legged parallel robots. Using fixed-dimension joint modules and variable dimension link modules that can be custom-designed rapidly, various kinematic structures can be facilitated.

In order to develop offline reconfigurable parallel robots numerous design approaches have been presented in literature. Since modular design is a research field in engineering design, specific methodologies for modular reconfigurable parallel kinematic machines (PKM) were introduced e.g. by Jovane (2002), Pritschow et al. (2000), and Koren et al. (1999). These approaches are mostly limited to concrete kinematic structures e.g. HEXAPOD robots, so transfer of constructive realizations is narrowed down.

#### 2.2.2 Online reconfiguration

Online reconfiguration means to change the robots' properties without rearranging the mechanical parts. Hence, no shut-down of the system is essential, but particular hardware components as well as dedicated control functions are required.

**Modular self-reconfiguration.** Modular self-reconfigurable robotic systems have been topic of tradition in robotics science for years, a survey of Jantapremjit (2001) shows a variety of these reconfigurable robots. In general they are assembled by a set of identical modules with the same functional range. Each module has to carry actuation, sensing, control entities as well as energy supply, communication and offers several interfaces. In order to be self-reconfigurating the set of interlocked modules has to change configuration autonomously, which mostly imply the ability of locomotion for each module. In Yim (2007) the classification of modular self-reconfigurable robots by architecture and the way in which the units are reconfigured is provided. The control strategy of those robots can be centralized or distributed. Famous examples of this robot class are PolyBot G3 [Yim (2000)] or Molecubes [Molecubes (2011)].

**Auxiliary drives and adaptive machine elements.** In order to adapt the configuration of the kinematic structure during operation of the robot, passive components can be substituted by auxiliary drives or adaptive machine elements. Using these components, geometries of the kinematic structure e.g. strut length and degree of freedom (DoF) are affected, thus different configurations are achieved. Adaption of the strut length is carried out using auxiliary linear motion devices such as linear motors, hydraulic jacks, air cylinders, or lead screws driven by rotary actuators. An approach to select suitable components for reconfiguration of manufacturing systems is introduced by Lee (1997). However, a requirement oriented consideration of component parameters is not made. In Krefft (2006) a concept to vary the length of struts in discrete steps by means of air cylinders is introduced. This geometric reconfiguration results in workspace as well as stiffness variations. Approaches to affect systems DoF are presented e.g. by Theingi et al. (2007). Here, belt drives are used to couple joints and therefore reach new kinematic configurations as well as passing singularities within the workspace. O'Brien (2001) proposes a kinematic control of singularities applying passive joint brakes to affect the kinematic DoF.

Main difference of the described approaches is the impact to the robots' performance. Adding auxiliary drives, the performance is mostly influenced negatively. For instance system weight raises because of higher component weight. Hence, adaptive machine elements which offer basic function as well as additional ones are focus of this contribution. Other aspects such as the realization of redundant actuated mechanisms are not considered.

**System inherent reconfiguration.** Due to the fact that within the workspace of parallel robots singularities occur (see section 3), system inherent reconfiguration without demanding particular mechanical components is feasible. Several research works focus on passing through or avoiding singularities within the workspace [Budde (2010), Hesselbach et al. (2002), Wenger (1998)]. Passing actuator singularities, workspaces of different assembly modes can be combined to a larger workspace [Krefft (2006)]. Hesselbach et al. (2002) firstly introduced an approach to cross singularities using inertia of the Tool Center Point. A comprehensive procedure for the passing of singularities as well as the concerning control issues is described in Budde (2008).

**Reconfiguration via grasping.** The last approach to be considered in context of online reconfiguration of parallel robots is, that separate manipulators constituting an entire mechanism by grasping an object. In Riedel (2008) a reconfigurable parallel robot with an underactuated arm structure is presented. After grasping, the contact elements at the end of the underactuated arm mechanisms are connected to the object which forms a closed loop mechanism similar to the architecture of parallel manipulators. Each arm mechanism is a combination of a five-bar-linkage with a parallelogram arrangement, a revolute joint around the vertical axis and a spherical wrist joint [Riedel (2010)]. Consequently, different configurations of the entire system can be arranged to face specific requirements (workspace dimension, process forces, stiffness) of the current task.

Based on this brief literature review in the following section particular properties as well as design aspects of parallel robots are introduced. Subsequently, requirement management for reconfigurable robots is introduced in section 4. Further considerations will also focus on offline and online reconfiguration. Here, the use of adaptive machine elements as well as system inherent reconfigurations are considered.

## 3. Parallel robotic systems

Parallel robots constitute a special class of robotic systems mainly for industrial applications. The characteristic property of parallel robots, in comparison to their serial counterparts is the closed-loop kinematic chain referring to the kinematic structure. The constructive advantage of this robot architecture is the possibility to assemble the drive near the frame, which implicates very low moving masses. This specific design leads to several significant benefits in the robots' performance, such as high stiffness and high dynamic properties. Due to these aspects, parallel robots are employed for an increasing amount of handling and assembly tasks [Merlet (2001)]. The most famous example of a parallel kinematic structure is the Delta robot of Clavel (1991) (see Figure 3). Here, a four DoF Delta robot is shown, where three translational DoF are provided by the rotary drives mounted at the frame. The load transmission is carried out by the three close-loop chains, where the constant orientation of the end-effector platform is provided by the parallelogram structure in the mechanism. The middle axis offers an additional rotary DoF by the application of a length variable connecting shaft.

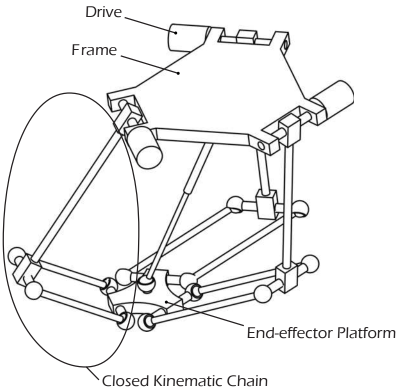



Fig. 3. Delta structure as famous example for parallel robotic systems.

The rather low market penetration of parallel robots (except the Delta kinematic) is reasoned by specific drawbacks. The unfavorable workspace-to-installation space ration in comparison to serial robots is the main aspect. Furthermore, the presence of diverse singularities within the workspace, which lead to a degeneration of the robots' manipulability. In addition, these singularities result in challenging tasks in control design. In Park (1998) singularities are classified as

1. configuration space singularities at the boundaries of configuration space
2. actuator singularities, where the DoF of the robot varies
   (a) degenerate types: links can be moved, even if the actuators are locked
   (b) nondegenerate types: internal forces are generated

3. end-effector singularities, in which the end-effector frame loses DoF of available motion.

Mathematically, the mentioned singularities occur, if one of the Jacobian Matrices $J_{A,B}$ with

$$J_A = \frac{\delta f}{\delta X} \vee J_B = \frac{\delta f}{\delta q} \quad (1)$$

where X represents the Tool Center Point (TCP) coordinates $X = (x, y, z)^T$ and q the actuator variables $q = (q_1, q_1, ..., q_n)^T$, becomes singular. Whereas, a configuration space singularity appears if,

$$det(J_A) \neq 0 \wedge det(J_B) = 0. \quad (2)$$

Actuation singularities are conditioned by

$$det(J_A) = 0 \wedge det(J_B) \neq 0. \quad (3)$$

The singularity analysis is hindered by the structural complexity of parallel mechanisms, which is attended by an extensive kinematic description. Due to reconfiguration approaches of parallel robots, singularity detection, avoidance or passing is especially focused in paragraph 5.2.

For the systematic design of parallel robotic systems different approaches have been proposed in literature e.g. [Frindt (2001)]. The parameter space approach proposed by Merlet (1997) considers requirements such as workspace and the articular velocities and leads to possible sets of robot geometries that satisfy these requirements. These first design solutions are sampled to identify the best compromise with regard to other requirements, i.e. accuracy. Following the cost function approach [Bourdreau (2001)] the robot geometries are arranged in the way that workspace dimensions are as closely congruent as possible with the prescribed as possible. Based on this demand the design problem becomes a multi objective optimization problem. Whereas these approaches consider only one use cases of the robotic system they lead to "'static"' solutions, which can hardly be adapted to other use cases. Therefore, the proposed approach can be seen as an addition to these approaches. It ensures the design of reconfigurable robotic systems in order to satisfy temporal changes of requirements which are caused by different use cases.

This brief overview of the properties of parallel robotic systems shows the benefits and drawbacks of these systems. With regard to the aforementioned aspects of reconfiguration parallel robots are suitable systems to be reconfigured, as their extensive dynamic, accuracy and stiffness parameters. Hence, they can cover a huge range of requirements. For this reason a specific methodical approach for the requirement management e.g. under consideration of the identification of requirement spreads is needed.

## 4. Requirement management for reconfigurable robotic systems

The development of reconfigurable robotic systems demands detailed analysis of the product surroundings and relevant use cases during each life-cycle phase (e.g. operation, maintenance). As a result of this analysis numerous requirements are refined to forecast claimed system properties. In order to enhance life-time and performance of the system several target values for one requirement have to be fulfilled. For instance, different use cases require different workspace dimensions. These varying values for one requirement we call *requirement spread* [Schmitt (2009)]. In order to identify spreading requirements and derive reconfiguration scenarios, a structured model of the expected life-cycle as well as the desired

system properties is needed. Nevertheless, a consistent model is essential to facilitate domain specific views on the gathered information and therefore enable an efficient treatment of the development task.
In this section an object oriented approach to work out a requirement model is introduced. In order to identify reconfiguration parameters a methodical procedure is presented.

### 4.1 Modeling requirements

The modeling of requirements is carried out in order to provide a functional, comprehensive, complete, operational, non redundant and minimal set of requirements, which can be used as a pattern for the whole development process [Roozenburg (1991)]. Analysing the requirements and their relations reconfigurations scenarios for the robotic system can be derived and estimated. Requirement management for reconfigurable robotic systems focuses on three aspects [Stechert (2010)], namely: Surroundings, structure, and relations. Based on these aspects an analysis can be arranged in order to indentify reconfiguration parameters and develop reconfiguration concepts.
**Surroundings.** As one of the first steps in the development process the surrounding of the robotic system has to be respected in order to recognize important requirements for the involved domains. Therefore, each life-cycle phase has to be taken into account including different scenarios (e.g. Anggreeni (2008), Brouwer (2008)) or use cases with all related actors, surrounding environment and possible disturbances. A systematic documentation helps to identify and to use gathered requirements and constraints. It further shows which requirements derive from what surrounding element.
**Structure.** In order to handle the gathered information in the following development steps, it has to be structured [Franke (1999)]. Requirements can be hierarchical structured such as goal, target, system requirement and subsystem requirement. Furthermore, they can be allocated to the respective domain and to the purpose in the development process. In progress of the development process requirements can be allocated to concerning subsystems. Assignment of certainty and change probability helps to focus on most relevant requirements during each development step.
**Relations.** Elements of complex models are related among one another. A basic classification for relations was presented in earlier work [Stechert (2009b)]. This classification helps to declare relations associated to development steps, granularity, support, direction, linking and quantifiability. Representing these relations within the requirement model helps designers to understand the influences of changes (e.g. change of rack radii), point out goal conflicts and highlight interfaces to other disciplines. However, the modeling of relations is the basis for the analysis of the requirement model, discussed in section 4.2.
Within the work of the Collaboration Research Centre (CRC) 562 "'Robotic Systems for Handling and Assembly - High Dynamic Parallel Structures with Adaptronic Components"' a SysML-based requirement model was developed [Stechert (2010)]. Since the Systems Modeling Language (SysML) uses parts of UML (Unified Modeling Language) it is a widely known notation in the fields of software development, electronic design and automation. In recent years it has become more and more popular in mechanical engineering e.g. Woelkl (2009). Using SysML a product can be modeled out of different viewpoints and on different levels of abstraction [Weilkiens (2008)]. However, within the introduced requirement model the above mentioned aspects are picked up in order to provide a coherent product model.
Major elements of the requirement model are "'Requirements"' and "'Surroundings"' [Stechert (2009a)]. The requirements are hierarchically distinguished into "'Goals"', "'Targets"', and

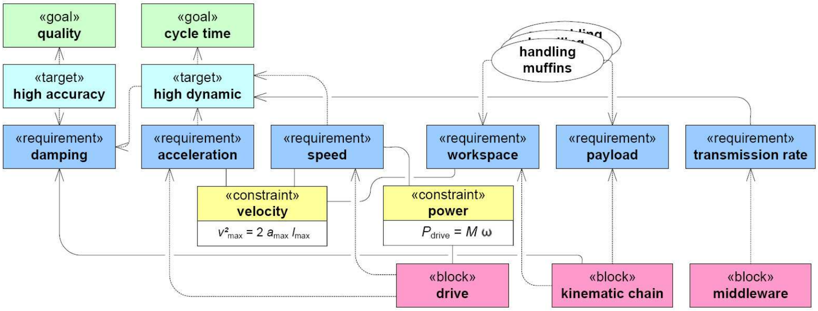



Fig. 4. Elements of an extended requirements diagramm based on SysML.

"'Technical Requirements"'. Within the element "'Surronding"' "'Product Environments"' (e.g. neighbor systems) and "'Use Cases"' are defined. These use cases are related to the product life-cycle and describe e.g. the handling of muffins within the use-phase of the robot. Figure 4 shows an excerpt of the hierarchical structure as well as different use cases. Pointing out the relations between use cases and requirements, several requirements are refined concerning their target values. For instance, the use case "'handling muffins"' correlates amongst others with the requirements "'workspace"' and "'payload"'. In addition, the requirements are linked to components of the robotic system (e.g. drive). Indicating constraints, correlation between components and requirements as well as requirements among each other are specified. In this way the requirement speed correlates with the component drive (constraint *power*).

### 4.2 Identification of reconfiguration parameters

Based on the introduced requirement model a systematic analysis can be carried out in order to identify meaningful scenarios and relevant requirement spreads for reconfiguration scenarios as well as their particular impact on the whole robotic system. By linking requirements which vary for different use cases with corresponding product parameters, reasonable reconfiguration concepts can be derived. Reconfiguration parameters can be systematically detected following the two steps shown in Figure 5. These two superordinated steps; *identify resonable reconfiguration scenarios* and *assess possible reconfiguration concepts*; constitute five working steps which are described below, following earlier work [Schmitt (2009)].

Initially, possible applications of the robotic systems and the corresponding use cases (e.g. handling muffins, PCB assembly) have to be considered. With regard to tasks (e.g. pick-and-place, feeding, high precision assembly) on the one hand and branches of trade (e.g. food industry, material processing, ICT) on the other hand, the identified use cases are structured. In addition, the reconfiguration of the robotic system is considered as a use case itself. Subsequently, relations between use cases and requirements are established. Using the relation "'refine"' each requirement is stated more precisely by an use case. As a result of this refinement a new sub requirement is created. For instance, the use case handling muffins refines the requirement workspace width to the exact value 500 mm. Assuming different use cases within the life-time of the robotic system it becomes evident, that diverse sub requirements for the same parent requirement occur.

Within the second step a hierarchical goal-system is developed. Based on the requirements considered before, traces are followed to superordinated targets and goals. Furthermore,

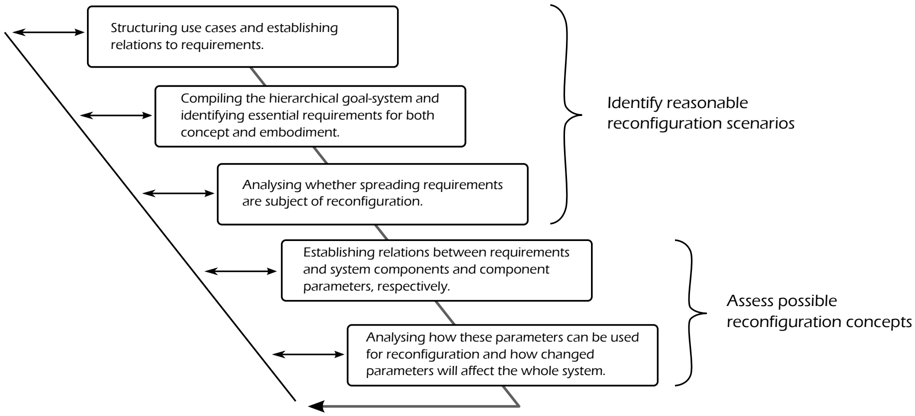



Fig. 5. Working steps for the identification of reconfiguration-relevant parameters.

the derived requirements have to be analysed to determine whether they are relevant for reconfiguration of the robot. First of all, concept-relevant requirements (e.g. DoF) are analysed. Based on the definition of concepts, embodiment related requirements have to be considered. For instance, different payloads and process loads lead to the relevant requirement operation forces, while accuracy leads to elastic deformation. Both are related by the structural stiffness of the kinematic structure.

The object of the third step is to estimate whether spreading requirements are subject of reconfiguration. It is obvious, that a reconfiguration is not probable between every use case. A robot used in the chemical industry first will not be sold to a company from the food industry, reconfigured and reused for pick-and-place tasks. However, a pick-and-place robot in the food industry might handle muffins first and convert to packaging of croissants in the same company later. Additionally the influence of requirement changes to other requirements have to be considered. The DoF at the gripper for instance might be subject of a wide spread. However, extending a fully parallel structure with an additional DoF causes a completely new control program. Therefore, it becomes obvious that not every requirement spread is a meaningful basis for reconfiguration concepts. Costs and engineering complexity are major limits. A detailed analysis of the goal-system leads to a lean set of essential reconfiguration-relevant requirements for robotic systems [Schmitt (2009)]:

- enabling object handling
- provide workspace
- enable operation forces
- provide degree of freedom
- assure high accuracy
- provide performance
- enable low lifecycle costs

These general requirements are specified by different use cases. For instance, the DoF is refined by the number of possible movements and the orientation of rotation (e.g. $\xi = \pm 25$).

In the fourth step, requirements are related to system components. System components can be hard- or software and are related to other components (e.g. information flow, geometric surfaces). For instance, the requirement workspace dimension is satisfied by the kinematic structure. More precisely the system component strut and its parameter strut length fulfill this requirement.

As a last step reconfiguration scenarios are developed and analyzed. Therefore, traces from a requirement to the involved parameters are followed and detected relations are described in a qualitative or - if possible - in a quantitative way. For instance, relation between strut length and workspace dimension can be described by kinematic problem, see section 3. Furthermore, it is necessary to determine the influence of the identified reconfiguration parameters to other requirements and detect possible goal-conflicts. It is obvious, that an extension of the strut length will lead to a higher moved mass, which might decrease the performance of the robotic system.

## 5. Reconfiguration approaches for parallel robotic systems

In Paragraph 2.1 general approaches for reconfigure robotic systems were introduced, in case of parallel robots for industrial applications three reconfiguration approaches are of major relevance. These different concepts are discussed in detailed, following the classification proposed by Krefft (2006):

- *Static reconfiguration (SR)* requires switching off the robot and rearranging machine parts such as drives, struts, or joints as well as complete sub-assemblies manually (see section 2.2.1).
- *Dynamic reconfiguration type 1 (DR I)* is carried out during operation of the system. Physical dimensions are not changed, but different configurations of the kinematic structure are used. Here singularities of type 1 have to be passed by the robot (see paragraph *system inherent reconfiguration*).
- *Dynamic reconfiguration type 2 (DR II)* is realized during operation of the system. The changing of kinematic properties is effected by the adjustment of geometric parameters such as strut length or modification of the DoF by joint couplings in order to avoid or replace singularities (see paragraph *auxiliary drives and adaptive machine elements*).

Table 1 illustrates the description of *SR*, *DR I* and *DR II* by characterizing the robot status and the configuration chance. The detailed discussion of the concepts is made in the following sections, whereas section 5.4 points out two case studies of reconfigurable parallel robots.

| Reconfiguration Approach | Robot Status | Configuration Change |
|---|---|---|
| **Static (SR)** | off | manual rearrangement of components/ subassemblies |
| **Dynamic Type I (DR I)** | on | usage of different configuration by passing through singularities |
| **Dymanic Type II (DR II)** | on | adjustment of geometries by machine components |

Table 1. Reconfiguration approaches for parallel robotic systems.

### 5.1 Static reconfiguration

According to the term of definition of static reconfiguration, the rearrangement of mechanical components is the objective to deal with. Based on a starting concept, the introduced methodology supports identification of reasonable reconfiguration modules $(RM_i)$ of the parallel robot. Within this modularization it is possible to allocate several requirements to the system components. In this way it can be sorted out, which key property of the system is affected by what reconfiguration strategy. Figure 6 shows the $RM_{1...3}$ and their interrelation as well as the interfaces between single machine components of parallel robots.

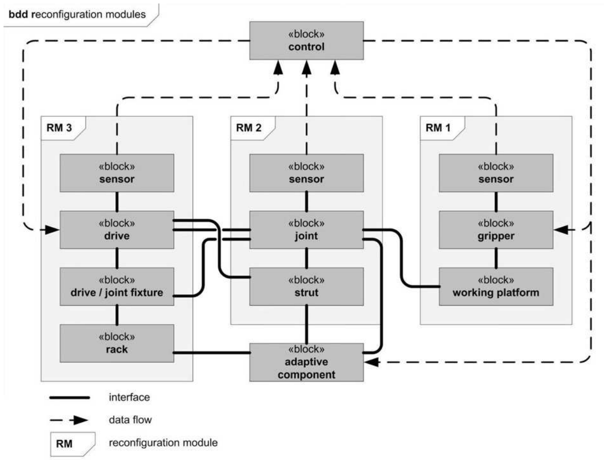



Fig. 6. SysML model for the modularization of the system components of a parallel robot.

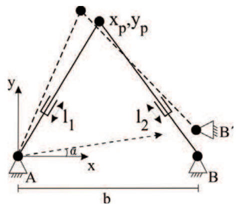
The application of different grippers $(RM_1)$ according to the requirement spread accomplishes the type of requirement, that result from the variation of the manufactured product. In this case, the workpiece size, geometries, surface or material properties are meant. The workspace or the required structural stiffness are only slightly influenced by the gripper. To integrate different kinds of grippers, e.g. mechanical or pneumatic ones, adequate constructive and control interfaces have to be designed. Furthermore, the changing manner of energy supply must be considered e.g. at the mobile platform. The change in mass and moments of inertia influences operation forces, accuracy and performance.

The strut/joint assembly $(RM_2)$ can be reconfigured through the installation of different strut kits. Here, diverse strut length results in variations of the position and dimension of the workspace. In addition, changes in strut length affect performance and accuracy due to changes in moved masses and transmission ratio of the kinematic chain, thence possible acceleration, maximum speed and eigenfrequencies. In terms of a modular construction kit, the interfaces between modules have to correspond with one another.

In general the drives are the base of the characteristic kinematic chain of a parallel robot and represent the 3rd reconfiguration module $(RM_3)$ together with the drive/joint fixture. They are assembled at or near the frame platform and are distinguishable between rotational and translational DoF. According to static reconfiguration, the specific properties such as weight or number and accessibility of the application points, must be observed during the design process for reconfigurability. Therefore, the frame can determine the ability for the static reconfiguration of parallel robots. If the frame provides a set of patterned holes to assemble the drives or base assembly points of the struts, the workspace dimension and position as well as stiffness can be influenced according to the identified requirement spread.

In order to show the benefits of static reconfiguration concerning the variation of the workspace position and dimension, a simple 2-DoF parallel mechanism is considered. The kinematic 2-R$\underline{P}$R structure consists of passive rotary joints (R) at the base and the end-effector platform and active prismatic joints ($\underline{P}$) (see Fig. 7).

The point of origin is fixed at base $A$ and the Tool Centre Point (TCP) is defined by the vector $X = (x_p, y_p)^T$. The distance between base $A$ and $B$ is given by b. The vector




a) Kinematic structure of the RPR mechanism.

$$q_1 = \begin{bmatrix} x_p \\ y_p \end{bmatrix} = \sqrt{x_p^2 + y_p^2} \quad (4)$$

$$q_2 = \begin{bmatrix} cos(\alpha) \cdot (b - x_p) \\ sin(\alpha) \cdot b \cdot y_p \end{bmatrix} = \quad (5)$$

$$= \sqrt{cos(\alpha) \cdot (b - x_p))^2 + (y_p + b \cdot sin(\alpha))^2} \quad (6)$$

b) Relations for kinematic analysis.

Fig. 7. Kinematic structure and relation for kinematic analysis of the considered RPR mechanism.

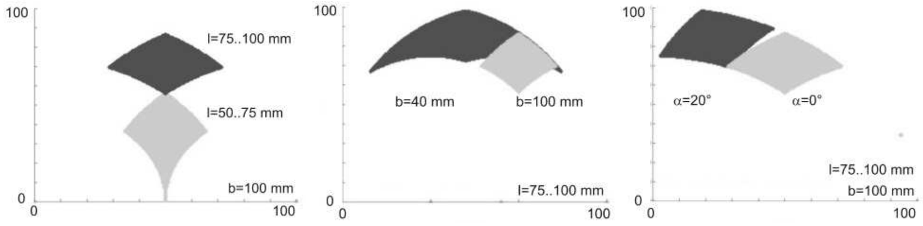
$q = (q_1, q_2)^T$ includes the actuated strut variables, whereas each strut can be moved between the intervals $[q_{min}, q_{max}]$. The parameter $\alpha$ describes the angular displacement $B$ of base $B$ to $A$. For the kinematic analysis the solution of the relation between end-effector coordinates and drive parameter ($f(X, q) = 0$) is essential. Here, the direct and inverse kinematic problem constitutes the motion behavior constrained by the geometric dimensions. The direct kinematic problem calculates the position and orientation of the TCP out of the given drive displacement. If the TCP coordinates are defined, the inverse kinematic problem assesses the actuator displacement. The relation given in Figure 7 b) is important for kinematic analysis.
In paragraph 3 the existence and kinematic influences of singularities of parallel robots were discussed briefly. In case of the shown planar 2-DoF parallel mechanism the configuration space singularities can be associated with the boundary of the respective workspace. Actuation singularities are existent for the condition

$$|q_1| + |q_2| = b. \quad (7)$$

Referring to the kinematic structure in Figure 7 a) a workspace analysis to point out several reconfiguration concepts was done using MATLAB. First, the variation of the interval $[q_{min}, q_{max}]$ can be associated as a change of strut kits. Here length range can be varied according to the boundary of each requirement in the chosen use case. The second reconfiguration concept is to reposition the assembly points. This can be shown by the variation of the parameter b in a way that the distance between $A$ and $B$ is in- or decreasable. Furthermore, the change $\alpha$ expresses the repositioning of $B$ not only in x-, but also in y- direction to $B$. The following Figure 8 demonstrates the possibilities of workspace repositioning by changing the drive assembly points and varying strut length. In field (a) the range $l$ with respect to $[q_{min}...q_{max}]$ of the actuated struts is changed. Illustration (b) shows the repositioning of the drive carrying struts in x-direction. In the kinematic model this is equivalent to the adjustment of parameter $b$. Furthermore in (c) the reconfiguration of the base assembly points in y-direction by varying the angel $\alpha$ between the drives is shown.

### 5.2 Dynamic reconfiguration type I

Dynamic reconfiguration of type I focuses on the passing through singularities during operation without adding specific components. Therefore, it also can be constituted as a system inherent ability of the parallel robot to reconfigure itself. Based on the works of *Budde* [Budde (2010), Budde (2007)] this reconfiguration approach is introduced in detail, using the TRIGLIDE structure as an example.
As pointed out before, workspace dimension is an essential system parameter, which has




(a) (b) (c)

Fig. 8. Influence of the reconfiguration parameter on the position and dimension of the workspace: a) varied strut length $l_1$, $l_2$; b) varied frame diameter $b$ and c) varied angle $\alpha$ at the frame connection level.

to be varied to fulfil different tasks. Since the main drawback of parallel mechanisms is the small workspace-to-installation-space ratio, dynamic reconfiguration type I facilitates the passing of singularties. Hence, several workspaces are combined during operation and the useable overall workspace is enlarged. The different workspaces are mathematically defined by different solutions of the direct kinematic problem (DKP) (assembly modes) or the indirect kinematic problem (IKP) (working modes). Each mode constitutes its own workspace. The workspaces of different working modes are divided by configuration space singularities, where assembly mode workspaces are distinguished by actuator singularities. In order to determine each of the possible configurations a vector **k** of binary configuration parameters (+1 or -1) has been established by Budde (2008) with

$$\mathbf{k} = (k_1, k_2, ...) = (\mathbf{k}_{IKP}, \mathbf{k}_{DKP}), \tag{8}$$

where $k_{IKP}$ expresses the different solutions of the IKP and $k_{DKP}$ denotes the different set of drive positions (solutions of the DKP). Each sprocket chain has two solutions of the IKP. Hence, a parallel mechanism with $n_{SC}$ sprocket chains and $n_{DKP}$ solutions of the DKP can have $2^{n_{SC}} \cdot n_{DKP}$ theoretical configurations, whereas not every solution is a real one and therefore relevant for the reconfiguration strategy. In order to use different workspaces or configurations generally (several) change-over configurations has to be captured to reconfigure the mechanism.

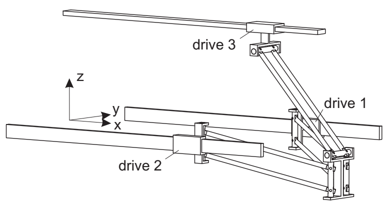



Fig. 9. Kinematic structure of the TRIGLIDE robot.

The described approach of DR I (passing through singularities to enlarge the workspace) should now be demonstrated using the example of the CRC 562 TRIGLIDE robot. The robot is based on the Linear-Delta structure. It consists of three linear driven kinematic chains, which guide the working platform. Each chain has a parallelogram structure in order to keep the end-effector platform in a constant orientation. This arrangement allows three DoF, additionally a fourth rotary axis can be mounted at the end-effector platform. Thus, a hybrid kinematic structure occurs. In Figure 9 the kinematic structure of the TRIGLIDE robot without the rotary axis is shown.

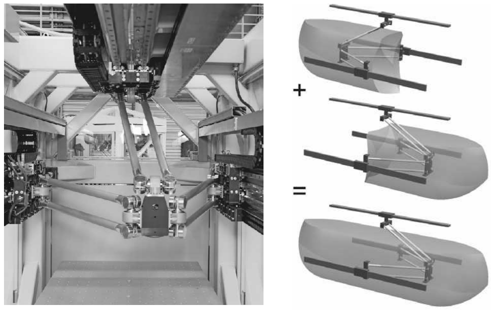


Fig. 10. Prototype of the TRIGLIDE robot (left); Usable working-configurations and resulting overall workspace (right).

In case of the TRIGLIDE robot the change between different configuration workspaces is accomplished by passing through singularities. Implemented strategies to go through the different singularity type are described in Budde (2010). In Figure 10 the prototype of the TRIGLIDE robot is shown as well as the desired main-workspaces and the resulting overall workspace.
As mentioned before the so called change-over configurations have to be captured in order to reach the main-workspaces, which are mostly capable to fulfil requirement spreads regarding to workspace. Several configurations are shown in Figure 11. The presented approach to reconfigure the TRIGLIDE robot leads to challenging tasks in control. The necessary steps and the adapted control strategy is explained in Maass (2006).
To complete the explanation of the named reconfiguration approaches for parallel robots, the next paragraph deals with *DR II* with a focus on adaptive machine elements.

### 5.3 Dynamic reconfiguration type II

Unlike the aforementioned reconfiguration strategies, the adjustment of geometric parameters is the subject of *DR II*. Here, the variation of strut length or the modification of kinematic DoF by joint couplings or lockings e.g. in order to avoid singularities or dislocate them are reasonable reconfiguration scenarios. Since this reconfiguration strategy demands no shut-down of the system, specific machine elements are required. In Schmitt (2010) an adaptive revolute joint is presented. Besides the basic functions of a passive joint, this revolute joint enables adaption of friction and stiffness. This functionality is based on the so-called quasi-statical clearance adjustment in the bearings using piezoelectric actuators Stechert (2007). This clearance modification between the inner and outer ring leads to an adaption of friction and stiffness (see Fig. 12 a)). Depending on the previous friction moment caused by the preload of the bearings the realized prototype enables continuous locking of rotary DoF by friction magnification of 440 percent [Inkermann (2011)]. In Figure 12 the first prototype of the adaptive revolute joint is illustrated.
In order to demonstrate a reconfiguration strategy of parallel mechanisms in the sense of *DR II* with an adaptive machine element a simple $\underline{\text{R}}$RRR$\underline{\text{R}}$-mechanism is further considered, following Schmitt (2010). The $\underline{\text{R}}$RRR$\underline{\text{R}}$-mechanism is a fully closed-loop planar parallel

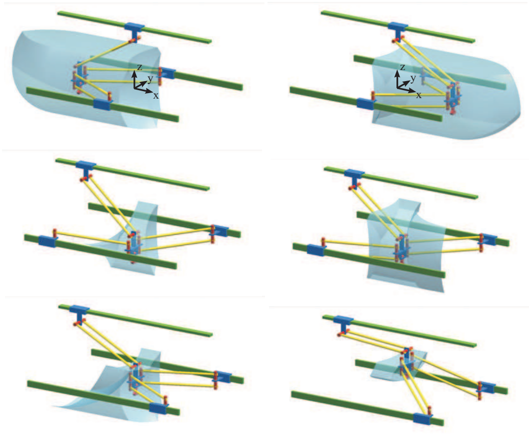


Fig. 11. Main-workspaces in working configuration (top); Selected changeover configurations (middle, buttom) of the TRIGLIDE robot.

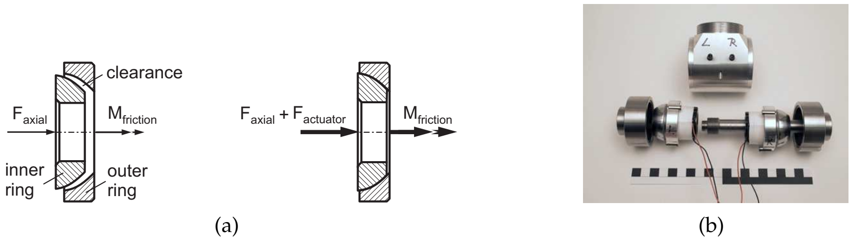



Fig. 12. Effect principle and realized prototype of the adaptive revolute joint used for dynamic reconfiguration type II.

manipulator with two DoF. The cranks at the base points $A_1$ and $A_2$ are actuated. The two passive rods $L_{12}$ and $L_{22}$ are coupled to each other by a passive revolute joint in the end-effector point C. The kinematic chain originating at base $A_1$ and the corresponding crank is connected by the described adaptive revolute joint, which is marked by $\otimes$ (see Figure 13).

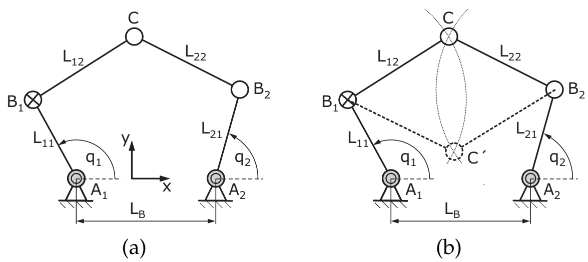



Fig. 13. Kinematic scheme and geometries of the <u>R</u>RRR<u>R</u>-mechanism (a) and solutions of the DKP (b).

The kinematic description of the mechanism with its two closed loop chains $i = 1,2$ can be geometrically done with the cartesian end-effector coordinates $\mathbf{X} = [x_c, y_c]^T$, the base coordinates $\mathbf{A} = [x_{Ai}, y_{Ai}]^T$, which can be derived by $L_B$, the actuator angles $\mathbf{q_i}$ and the given geometric parameters $L_{ii}$ with respect to the base frame $\{0\}$. In eq. 9 the kinematic describtion of the mechanism is given, considering the parameters and variables shown in Figure 13 (a).

$$\mathbf{F} = \left[ \begin{bmatrix} x_c \\ y_c \end{bmatrix} - \begin{bmatrix} x_{Ai} + cos(q_i) \cdot L_{i1} \\ y_{Ai} + sin(q_i) \cdot L_{i1} \end{bmatrix} \right]^2 - L_{i2}{}^2 = 0. \tag{9}$$

Expression 9 provides a system of equations which relate the end-effector coordinated $\mathbf{X}$ to the actuator coordinates $\mathbf{q_i}$. The equation for the direct kinematic problem (DKP) has two solutions, in case of the R̲RRRR̲-mechanism. They constitute to different configurations of the mechanism (see Figure 13 (b)). Changing these configurations an actuator singularity occurs, when moving from position $C$ to $C'$. In general actuator singularities can occur in the workspace or separate workspaces into different areas.
In order to reconfigure the mechanism or to use these different workspaces adequate strategies have to be developed, in case of *DR II* using the adaptive revolute joint. Assembling the adaptive revolute joint in point $B_1$ (see Fig. 13 (a)) and blocking it entirely, it is possible to treat the mechanism as a R̲RRR 4-bar structure, with one actuated revolute joint at base point $A_1$. According to the theorem of GRASHOF different kinds of 4-bar mechanisms exist, depending on the geometric aspect ratio of the links [Kerle (2007)]:

$$\begin{aligned} l_{min} + l_{max} &< l' + l'' \quad \text{ability to turn around} \\ l_{min} + l_{max} &= l' + l'' \quad \text{ability to snap-through} \\ l_{min} + l_{max} &> l' + l'' \quad \text{no ability to turn around.} \end{aligned}$$

$l_{min}$ and $l_{max}$ are the lengths of the shortest and the longest link in the structure and l′, l″ are the lengths of the remaining links. In case of the shown 5-bar mechanism with the adaptive revolute joint, one link length can be adjusted according to the desired mechanism property. The resulting length $L_R$ can be calculated by

$$\mathbf{L}_R = \sqrt{L_{12}^2 + L_{11}^2 - 2 \cdot L_{12} \cdot L_{11} \cdot cos(\Theta_1)}. \tag{10}$$

Beside the aforementioned possibility to reconfigure the robot, it is feasible to develop strategies to pass through an actuator singularity in an assured manner by blocking and releasing the mechanism at point $B_1$ by means of the adaptive revolute joint. This reconfiguration strategy is shown in Fig. 14.
The aspect ratios in the example are chosen by $L_{i1}/(L_{i2}, L_B) = 3/4$. If the mechanism is close to a singular position (Fig. 14.1), the adaptive revolute joint will be locked, ($\theta_1 = 40°$). The resulting 4-bar mechanism moves on a path, which is defined by a segment of a circle of radius $L_R$ with center at $A_1$ through the singular position (Figure 14.2). Subsequently, the mechanism is in another configuration, which is not a singular position (Fig. 14.3) and the adaptive joint can be released.

### 5.4 Case studies

In the previous paragraphs different approaches to reconfigure parallel robotic systems were explained on a theoretical level. In order to give examples and fields of application two

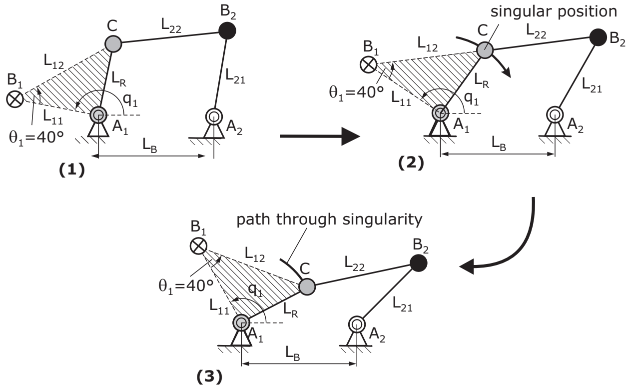



Fig. 14. Strategy of passing through singularity by blocking the adaptive joint.

case studies are explained and the benefits of reconfigurable robots are shown. The first one deals with the reconfiguration of a pick-and-place robot to an assembly robot, using the approach of static reconfiguration. Another case study is the classification of solar cells under consideration of their efficiency. This case study will illustrate an example of dynamic reconfiguration of type I.

#### 5.4.1 Example I - reconfiguration of a "‘pick-and-place"’ robot into an assembly robot

In order to highlight the introduced procedure and the concept of static reconfiguration in this section case study is presented. Therefore, a "‘pick-and-place"’ robot should be reconfigured for an assembly task, while handling object and DoF of the system remain the same. To demonstrate the reconfiguration concept the kinematic structure described in section 5.1 is used. The use case assembly is characterised by a small workspace. However, higher process forces and accuracy are required. At the same time the performance (in this case numbers of assembly cycles per minute) compared with the "‘pick-and-place"’ task is not such important. The lifetime cost should be minimal. With regard to the introduced reconfiguration modules (see section 5.1), a change of the rack radius $(RM_3)$ leads to a meaningful reconfiguration concept.

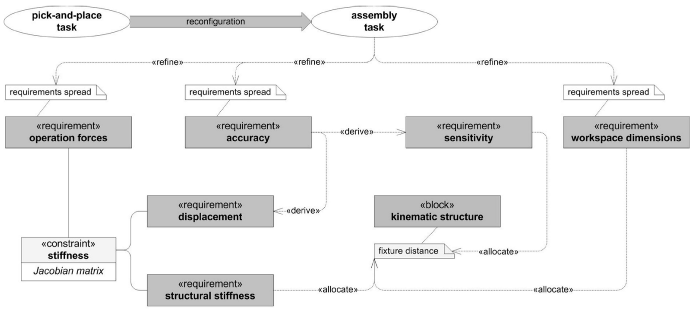



Fig. 15. Relation network for the static reconfiguration of a tow DoF parallel mechanism.

As can be seen in Figure 15 with the new use case the requirements *process forces*, *accuracy* and *workspace dimension* are refined. Since the workspace is directly influenced by the rack radius, the accuracy is influenced via the sensitivity. For increasing rack radius sensitivity in x-direction also increases and leads to higher accuracy in this direction. At the same time accuracy decreases in y-direction. In addition, the accuracy is influenced by the elastic deformation of the structure. The dimension of the deformation correlates with the value of the process forces and the stiffness of the structure. For the same stiffness higher process forces result in higher deformation and, therefore, decreased accuracy. This leads to a goal conflict which can be reduced with higher stiffness of the structure. At the same time the stiffness can be increased due to an adaption of the rack radius. Here, a higher rack radius results in a higher stiffness.

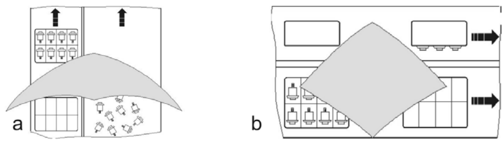



Fig. 16. Exemplary use cases for reconfiguration of a "‘pick-and-place"’ robot (a) into an assembly robot (b).

Static Reconfiguration from "‘pick-and-place"’ to assembly system in this case is carried out by increasing the rack radius. Figure 16 highlights the reconfiguration, showing the two use cases. In the first use case push-buttons are delivered via a first conveyer belt and placed into a container on a second belt. For this reason the workspace is elongated. After reconfiguration the same push-buttons are taken from a container and assembled into a casing. As the push-buttons provide a snap-in fastening operational forces in y-direction are needed and forces in x-direction might appear due to alignment deviations. Hence, the second configuration complies with the demanded changes.

#### 5.4.2 Use case II - solar cell classification

The end-of-line process-step within the fabrication of crystalline solar cells is the classification of the cells according to their efficiency. Here, the "‘flash-test"’ is conducted, where each cell is lighted by a defined flash (time, brightness per area) comparable to the sun irradiation. The result determines the quality class of a cell. In order to sort the cells according to their class after the flash-test, handling devices are necessary. Due to the high number of classes, which are physically represented as square boxes, the handling robot has to provide a relatively huge workspace. Additionally, the requirement of cycle time about 1 sec. per "‘pick-and-place"’ operation is very challenging. This combination makes the application of parallel robots feasible, if it is possible to overcome the poor workspace-to-installation-space ratio. The process flow of the classification can be summarized as following:

1. Conveying the cells to the classifying facility via feed band
2. Determination of the efficiency value (flash test)
3. Define the right box/position of the robots’ end-effector
4. Picking up the cell with the robot
5. Position the cell at the determined box according to the efficiency value

6. Drop the cell in the box
7. Pick up the next cell → return to process step 3

The values of the cell efficiency are subject to a distribution e.g. Gaussian, which means that a certain percentage rate (depends on the standard deviation $\sigma$) of the classes corresponding to the cell efficiency are distributed with a dedicated expectation value of $\mu$. The remaining classes, which belong to

$$\mu \pm n_d \cdot \sigma, \tag{11}$$

where $n_d$ constitutes the desired interval of $\sigma$.
Under this assumption the concept of DR I, the TRIGLIDE robot makes use of the two workspaces. The high frequented boxes to classify the solar cells are located in the first, the less ones in the second workspace. Due to the required time $T_R$ to change the configuration, it is not efficient to vary workspace every cycle. Therefore, the proposed box distribution according to the expectation value $\mu$ is feasible. In Figure 17 (a) the workspaces with the corresponding intervals of the Gaussian distribution and in (b) the concept of the storage boxes are shown. The indices of the boxes $c_{mno}$ describe the actual workspace (m), the column (n) and the row (o), so that the position is dedicated.

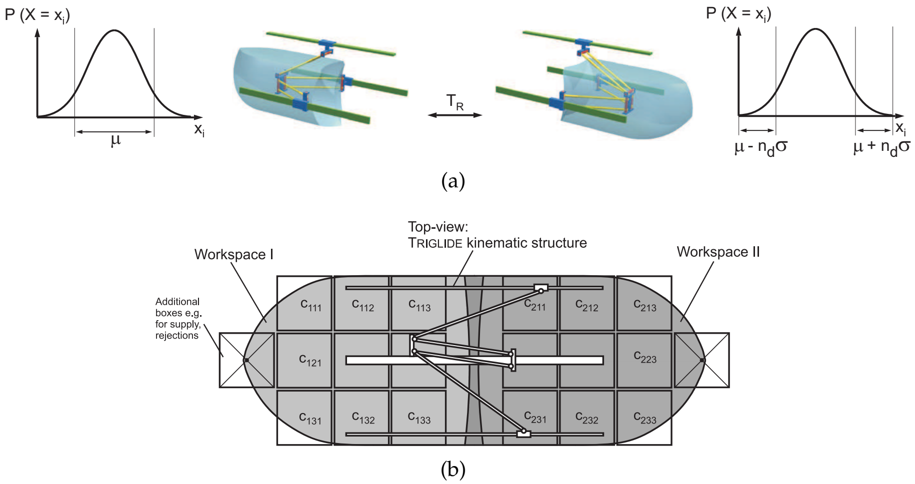



Fig. 17. Exemplarily probability distribution of supplied solar cells and used workspaces (a) and top view of a feasible conceptual design of a classification facility with the TRIGLIDE robot without periphery (b).

Since the introduced application examples highlight the advantages of reconfigurable parallel robotic systems to fulfil changing requirement, specific restrictions have to be considered in order to apply reasonable reconfiguration concepts. For this reason in the following section major aspects for the assessment and their interrelations to the presented static and dynamic reconfiguration strategies are proposed.

## 6. Assessment of reconfiguration concepts

As pointed out before the reconfiguration of robotic systems should not be considered as an end itself. It should rather follow an aim and should be subject of a systematic analysis. According to Steiner [(Steiner (1998), Steiner (1999))] changeability (reconfiguration) may not be cost efficient for systems which:

- are highly expedient, short life systems without needed product variety,
- are highly precendented systems in slowly changing markets and no customer variety,
- are insensitive to change over time, and
- are developed for ultrahigh performance markets with no performance loss allowables.

However, different use cases within the life time (e.g. handling muffins, packing croissants) and specific secondary functions (e.g. gripping principle) call for reconfiguration of robotic systems. Demands of high life-cycle times emphasize this need. In order to support the assessment of the before mentioned reconfiguration concepts a set of distinguishing aspects was derived. These aspects point out for which type of requirement spread a static or dynamic reconfiguration should be considered. Furthermore, the complexity of each reconfiguration approach is taken into account considering:

- *Duration time* characterizes the period needed to adapt the robotic systems performance, both manually and automatically.
- *Mechanical complexity* indicates the complexity of mechanical modifications and additional components, including costs to realize a reconfigurable robotic system.
- *Computational complexity* indicates the complexity of computational modifications and additional algorithms, including costs to realize a reconfigurable robotic system.
- *Parameter range* characterizes the potential of a reconfiguration approach to change several system properties e.g. workspace dimension in a wide range.
- *Robustness* indicates the vulnerability of a reconfiguration concept due to unforeseen operating conditions e.g. varying payload

The matrix in Figure 18 indicates which reconfiguration strategy is contributing to what reconfiguration-relevant requirement, see section 4.2. In applying the different approaches it is important to show up more detailed realizations. For this reason different reconfiguration concepts are stated following the introduced concepts. For instance, static reconfiguration can be realized by different strut kits and varying fixture distances. Relevant reconfiguration concepts are given for each approach.

While static reconfiguration concepts do not demand specific computational adaption and have high potencies to change several system properties such as workspace and accuracy, long time is needed to carry out the reconfiguration. The system has to be switched off, in order to rearrange several components. Thus, static reconfigurations approaches offer robust solutions since the configurations are changed manually. Regarding to dynamic reconfiguration concepts duration time is the essential advantage. However, to realize dynamic reconfiguration of a parallel robotic system specific components (DR II) have to developed or challenging control tasks have to be solved (DR I). Besides this in particular DR II features high potential to affect system properties.

This brief assessment of the introduced reconfiguration approaches should not be seen as a strict selecting tool. It rather helps to reason different concepts in early design phases of parallel robotic systems.

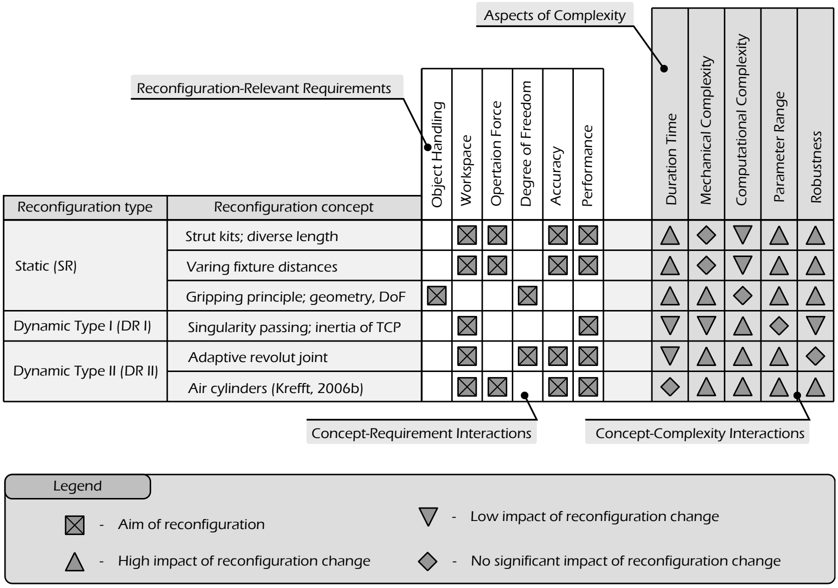



Fig. 18. Reconfiguration-approach-matrix.

## 7. Conclusion and further research

The need to increase flexibility of production systems via reconfiguration is mainly driven by the customers of the end product. Rising demands for individual products and shorter periods for product changes force the manufacturers to think about reconfigurable production equipment. In order to present ideas and strategies for reconfigurable robotic systems this contribution firstly shows the general meaning of reconfiguration and gives a brief literature review by classifying the most common types into offline and online approaches.

Such as parallel robots are in focus in this chapter, this special class of robotic systems was explained and the essential benefits as well as disadvantages, in particular the occurrence of singularities within the workspace and at its borders were introduced. Based on high potential of parallel robots to cover a huge range of requirements, an adequate requirements management referring to robotic reconfiguration has been introduced. Thereby, the identification of requirement spreads and the derivation of reconfiguration parameters were considered. The main part of the contribution examines the distinctive static and dynamic (type I and II) reconfiguration approaches of parallel robotic system. Each strategy is first discussed theoretically before two case studies are presented. In order to assess the different reconfiguration approaches, a matrix-based scheme is proposed, which serves the designer as a decision support.

Potential aims of further research activities should deal with the validation of the adapted development procedure with respect to reconfiguration issues. Further, regarding parallel robots, the proposed reconfiguration strategies should be surveyed to their transferability to other parallel structures. Another aspect, to be investigated, is the control implementation of the *SR* or *DR* concepts, in order to reduce efforts of changes. The treatment of an entirely changed kinematic structure after reassembling its mechanical components (*SR*) or the realization of passing through respectively to avoid singular positions (*DR*) are challenging research fields to deal with.

## 8. Acknowledgments

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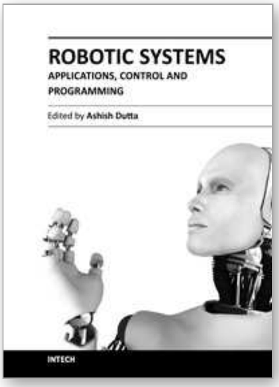


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